CENTER FOR INNOVATION THROUGH VISUALIZATION & SIMULATION

PURDUE UNIVERSITY NORTHWEST

STEEL MANUFACTURING SIMULATION & VISUALIZATION CONSORTIUM

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COMPUTATIONAL STUDIES AND OPTIMIZATION OF INCLUSION REMOVAL IN A STEEL LADLE

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"Where Ideas Become Reality"

OUTLINE

- Introduction
  - Objectives
  - Accomplishment
  - Outcomes
- Gas-Stirred Ladle
  - Water Model Validation
  - Industrial Ladle CFD Model
  - Parametric Study
- EMS Ladle
- Summary

INTRODUCTION

- **Current Issues**
  - Complex transport phenomena with multiple process variables
  - Difficulty in understanding the dynamic evolution of inclusions
- **Potential Impacts**
  - Process design of optimized flow condition and physical properties
  - Steel cleanliness improvement and final defects reduction

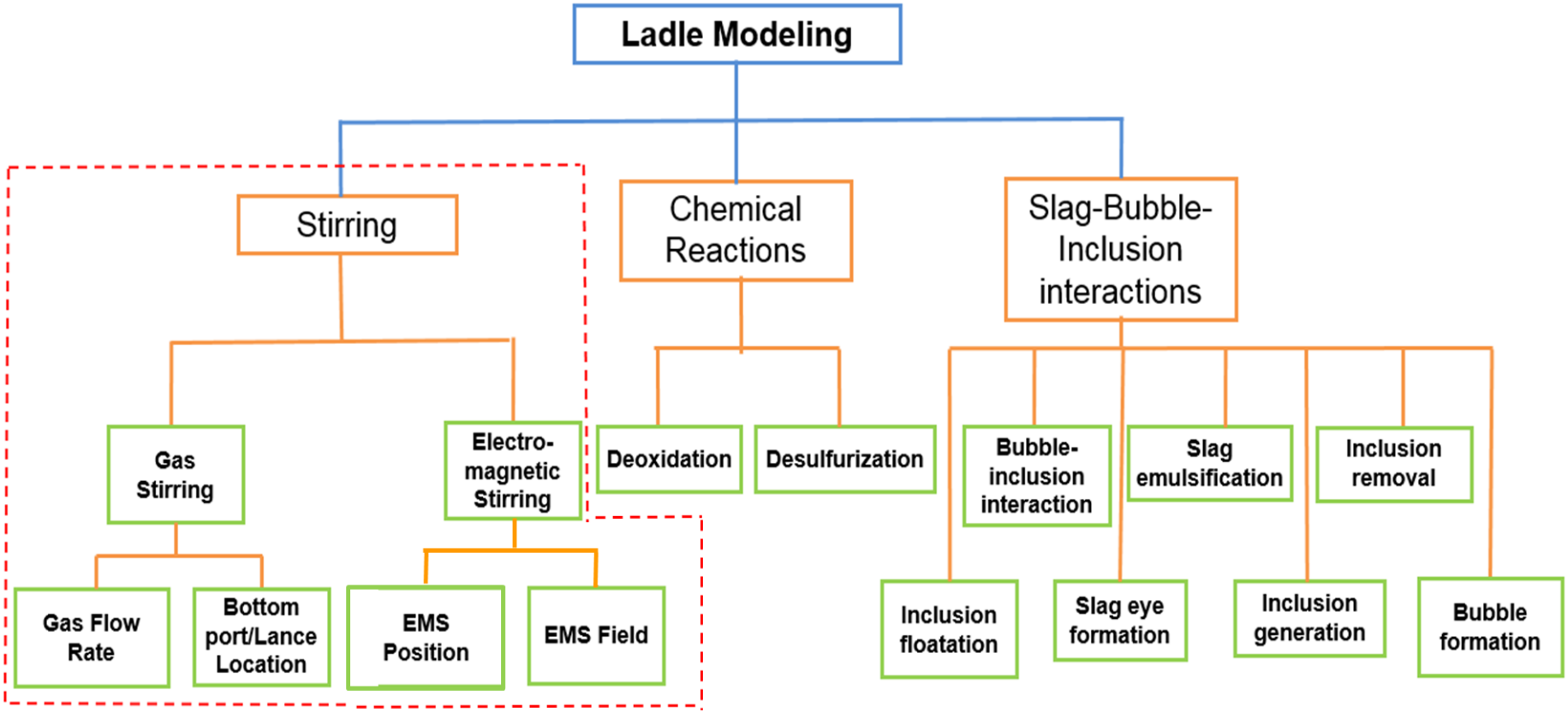
OBJECTIVES

- **Long term (5 years):**
  - Develop a comprehensive multiphase reacting CFD model of a steel ladle for process design
  - Study inclusion transport and evolution
  - Investigate effect of gas stirring conditions
  - Develop correlation between fluid flow and slag physical properties
- **Current (2nd year):**
  - Further validate the isothermal gas-stirred ladle model
  - Develop EMS ladle model
  - Add heat transfer and chemical reactions

ACCOMPLISHMENT

- **Year 1 (2016):**
  - Developed CFD model based on Nucor ladle
  - Validated the CFD model
  - Evaluated effect of bubble initial diameter on bubble distribution and slag eye size
  - Evaluated effect of argon flow rate on slag eye size, mixing time and wall shear stress
- **Year 2 (2017):**
  - Further validated CFD model with two water models and cold metal model experiment
  - Performed parametric study
  - Developed EMS model

ROADMAP


Ladle Modeling
Stirring
Chemical Reactions
Slag-Bubble-Inclusion interactions
Gas Stirring
Electro-magnetic Stirring
Deoxidation
Desulfurization
Bubble-inclusion interaction
Slag emulsification
Inclusion removal
Gas Flow Rate
Bottom port/Lance Location
EMS Position
EMS Field
Inclusion floatation
Slag eye formation
Inclusion generation
Bubble formation

GAS – STIRRED LADLE

CFD MODELS AND METHODOLOGY

All Zones: 3D, Isothermal, Transient

Slag & Melt Zones

- Multiphase flow: Eulerian-VOF
- Turbulent model: Realizable k-epsilon
- Include gravity, buoyancy and drag force.

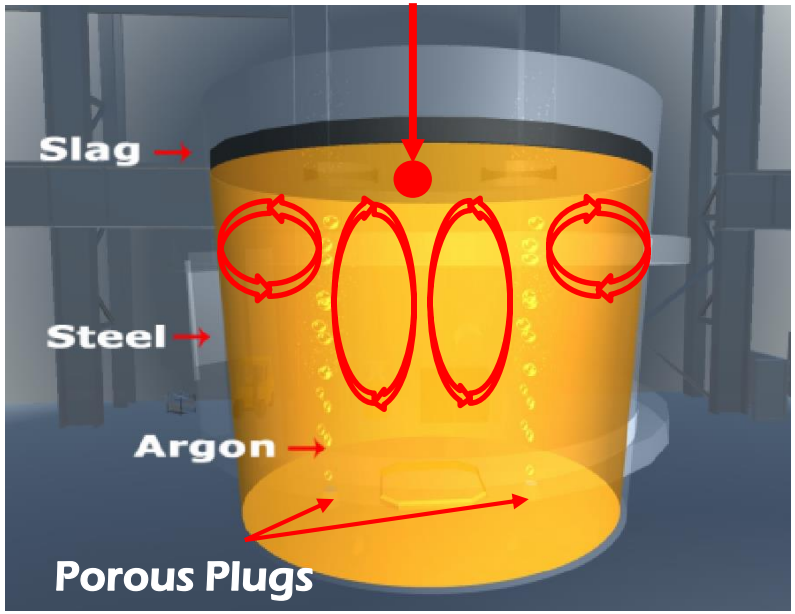
Argon Injection

- Discrete Phase Model for bubble tracking:
  - Two-way coupling
  - Discrete Random Walk
  - Include particle weight, buoyancy force, drag force, virtual mass force, pressure gradient force.

Mixing Process

- Multiphase flow: Eulerian-VOF
- Species transport

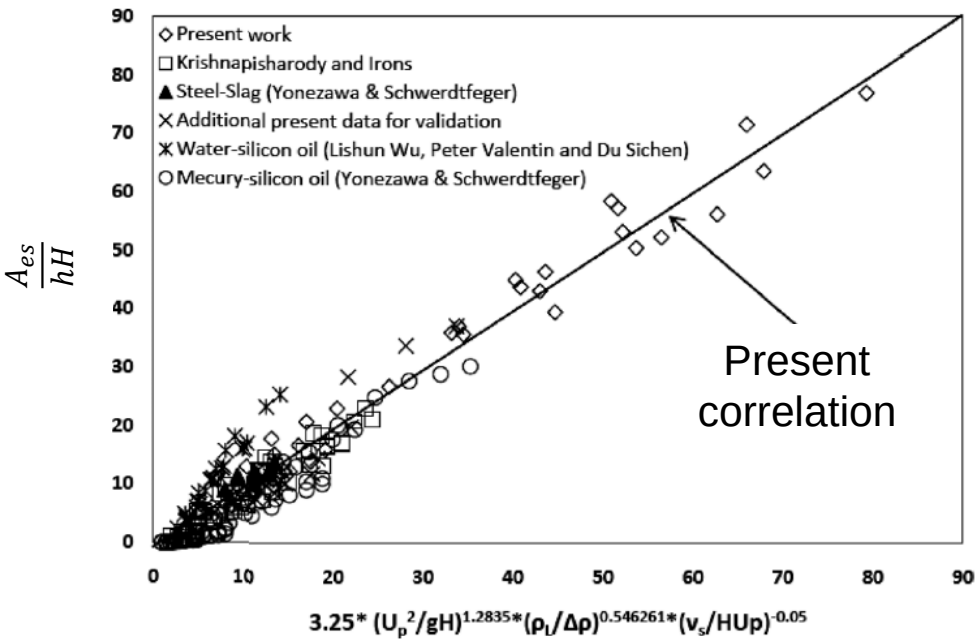
Tracer is put into the ladle

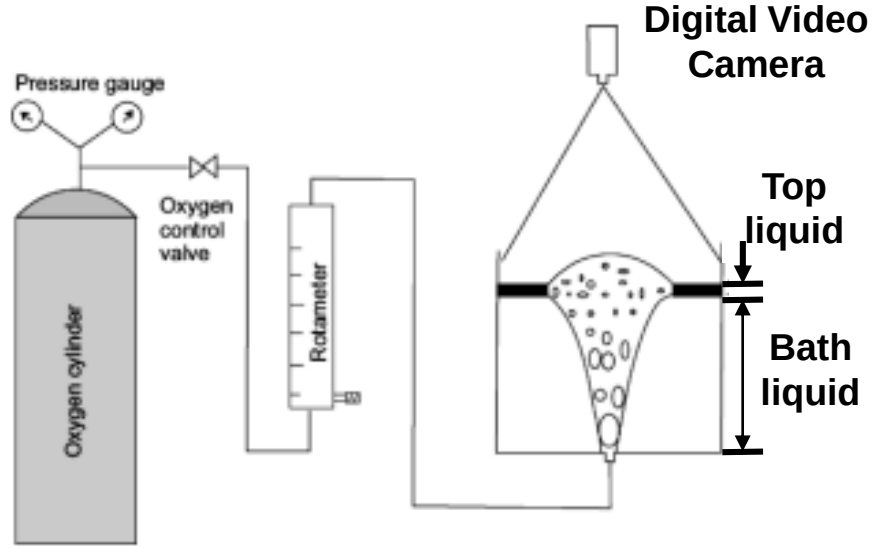


WATER MODEL VALIDATION

- Experiment by Peranandhanthan and Mazumdar investigated the effects of gas flow rate, top and bath liquid thickness, density, and viscosity on eye size.
- Derived from 1/10 scale of 150 tonne ladle on basis of geometry.

$$\left(\frac{A_{es}}{hH}\right) = 3.25\left(\frac{U_P^2}{gH}\right)^{1.28}\left(\frac{\rho_L}{\Delta\rho}\right)^{0.55}\left(\frac{\nu_s}{HU_P}\right)^{-0.05}$$





M. Peranandhanthan and D. Mazumdar: Modeling of Slag Eye Area in Argon Stirred Ladles. ISIJ International. 50 (2010) No.11, pp 1622-1631.

LIQUID PROPERTIES AND DIMENSIONS

- Experiment - bath liquid depth, diameter: 10.04in, 11.8in
- Nucor - melt depth, diameter: 105in, ~66in
- Water model 1 has density ratio closer to Nucor ladle

		Water Model 1	Water Model 2	Water Model 3	Nucor Ladle
Liquid	Upper	Petroleum Ether	Mustard Oil	Coconut Oil	Slag
	Lower	Water	Water	Water	Steel
Density (kg/m^3)	Upper	640	895	843	2786
	Lower	1000	1000	1000	7000
Viscosity (Pa.s)	Upper	0.00038	0.07	0.021	0.114
	Lower	9.125×10^{-4}	9.125×10^{-4}	9.125×10^{-4}	8.54×10^{-5}
Density ratio		0.640	0.895	0.843	0.400
h/H		0.010, 0.030	0.030	0.030	0.076

MATERIAL PROPERTIES

- Density and viscosity

	Density (kg/m^3)	Viscosity (kg/m·s)
Water	1000	0.0009125
Petroleum Ether	640	0.00038
Mustard Oil	895	0.07
Perfumed Coconut Oil	843	0.021
Air	Ideal gas law	0.000017894

- Surface tension coefficient

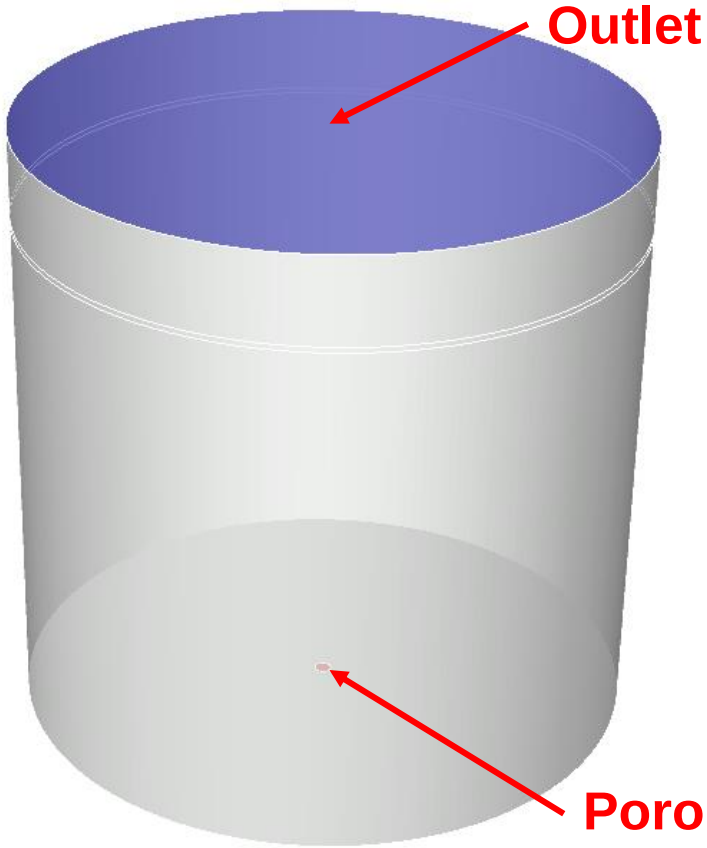
	Surface tension coefficient
Water/Air	0.07286
Water/Petroleum Ether	0.01
Petroleum Ether/Air	0.017
Water/Mustard/Coconut Oil	0.041
Mustard/Coconut Oil/Air	0.02

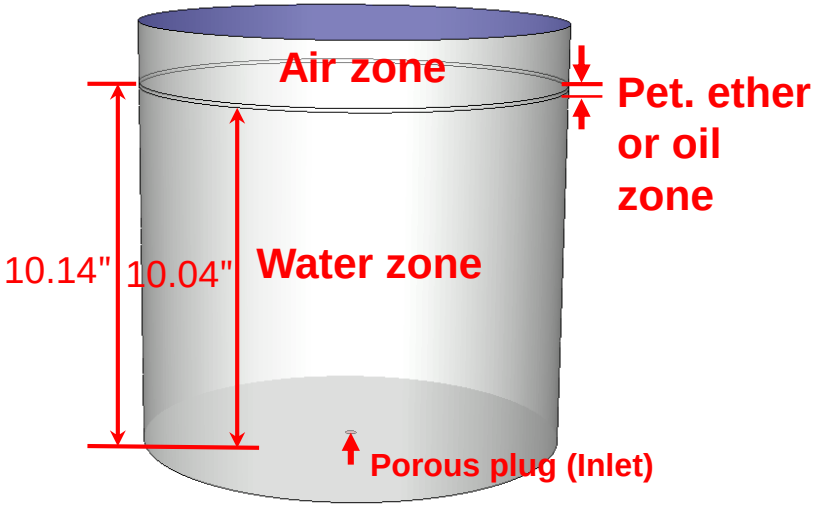
WATER MODEL VALIDATION CASES

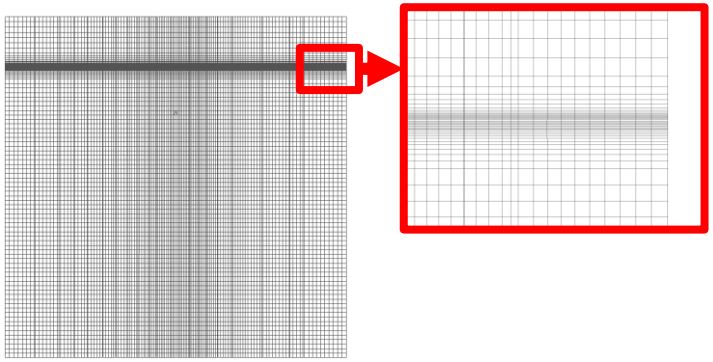
Case	Parametric Effects	Q (m^3/s)	Top liquid	Top layer height (m)	Bath height (m)
Case 1 (Base Case)	-	$5x10^{-5}$	Pet. Ether	0.0077	0.255
Case 2	Low flow rate	$3.33x10^{-5}$	Pet. Ether	0.0077	0.255
Case 3	High flow rate	$6.67x10^{-5}$	Pet. Ether	0.0077	0.255
Case 4	Thin top layer	$5x10^{-5}$	Pet. Ether	0.0026	0.255
Case 5	Top liquid density and viscosity	$5x10^{-5}$	Mustard Oil	0.0077	0.255
Case 6	Top liquid density and viscosity	$5x10^{-5}$	Coconut Oil	0.0077	0.255

GEOMETRY AND MESH

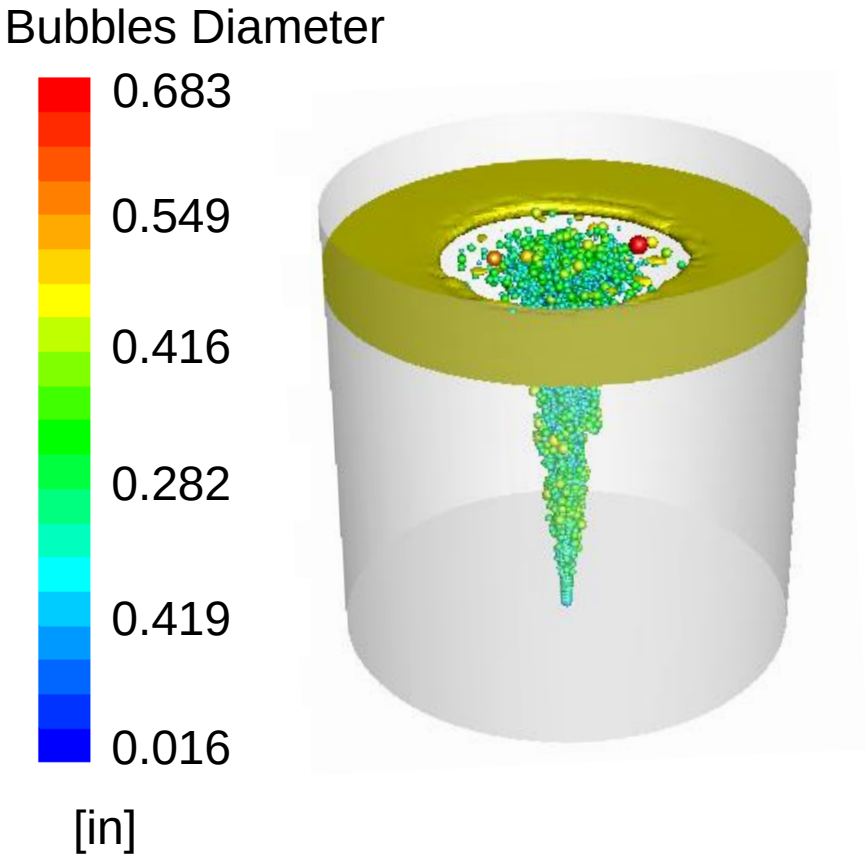
- Dense mesh around top liquid layer are used to ensure the accuracy of calculation of interface.

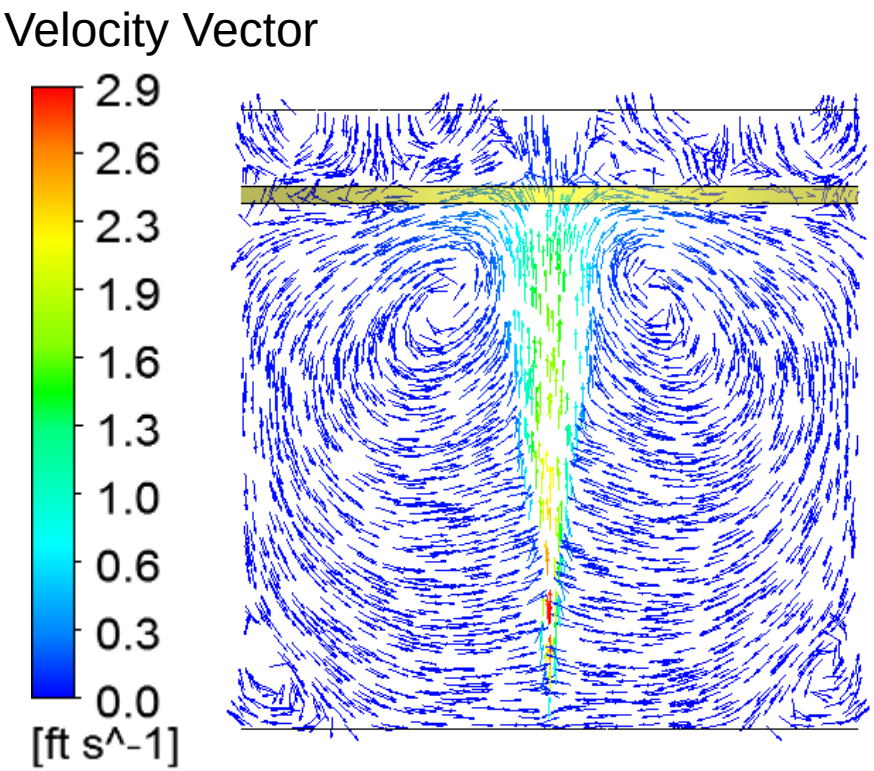






BUBBLE PLUME AND FLOW VELOCITY

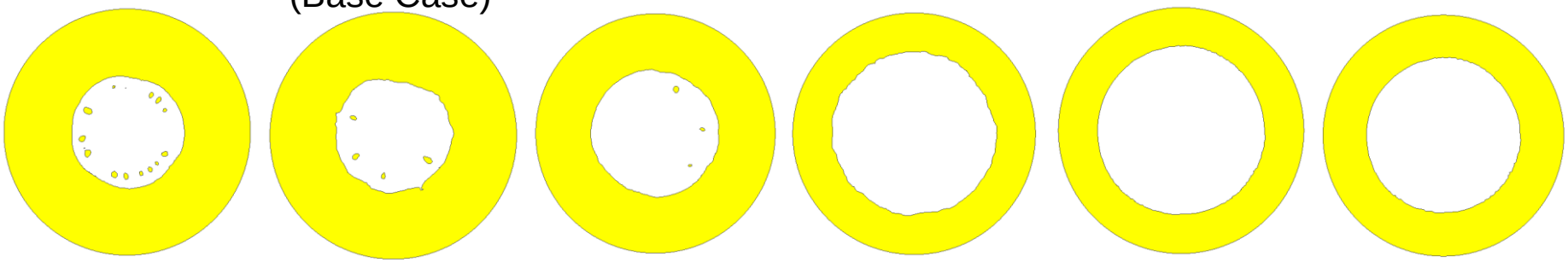




- Coalescence and breakup occur as the bubbles rise
- Recirculation formed near bubble plume

EYE SIZE

- Case 2
- Case 1 (Base Case)
- Case 3
- Case 4
- Case 5
- Case 6



Cases	Parametric Effect	Eye diameter (in)		
		CFD	Experimental data	% diff.
Case 1 (Base Case)	**-**	5.91	5.60	5.69 %
Case 2	**Low flow rate**	5.31	4.93	7.55 %
Case 3	**High flow rate**	6.22	6.19	0.65 %
Case 4	**Thin top layer**	7.95	7.45	6.67 %
Case 5	**Top liquid density and viscosity (mustard oil)**	8.03	8.94	10.05 %
Case 6	**Top liquid density and viscosity (coconut oil)**	7.56	6.88	9.95 %

RESULTS – VELOCITY PROFILE

Top-z=7.53in

Center-z=5.02in

Bottom-z=2.51in

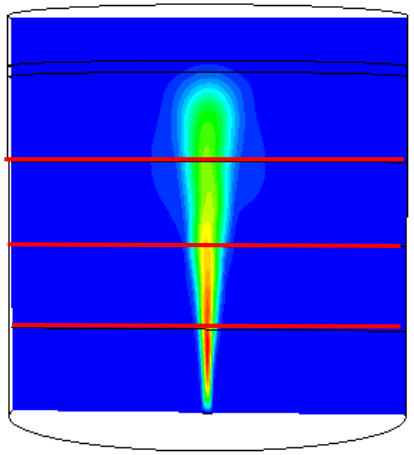
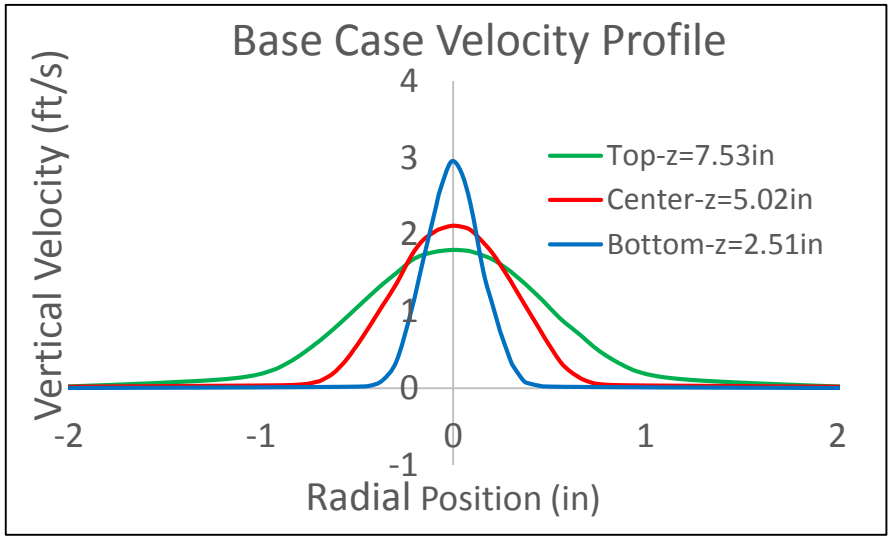
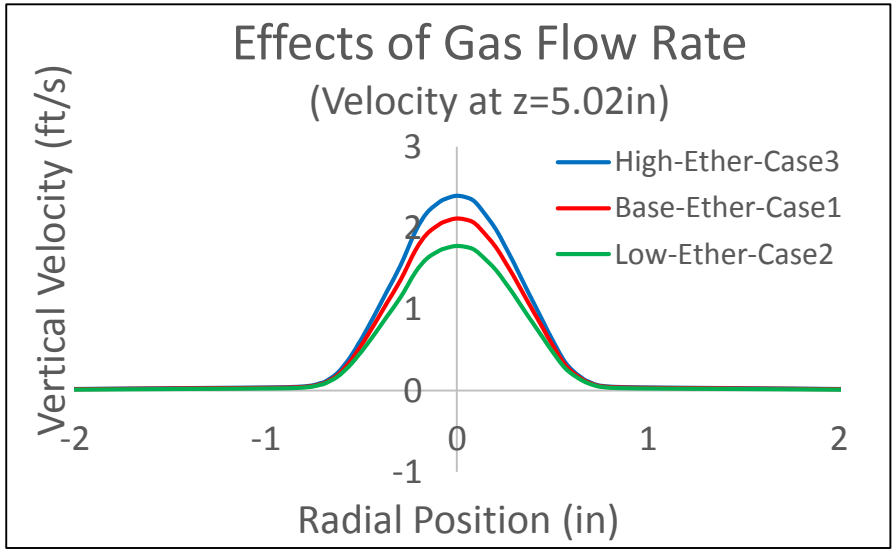


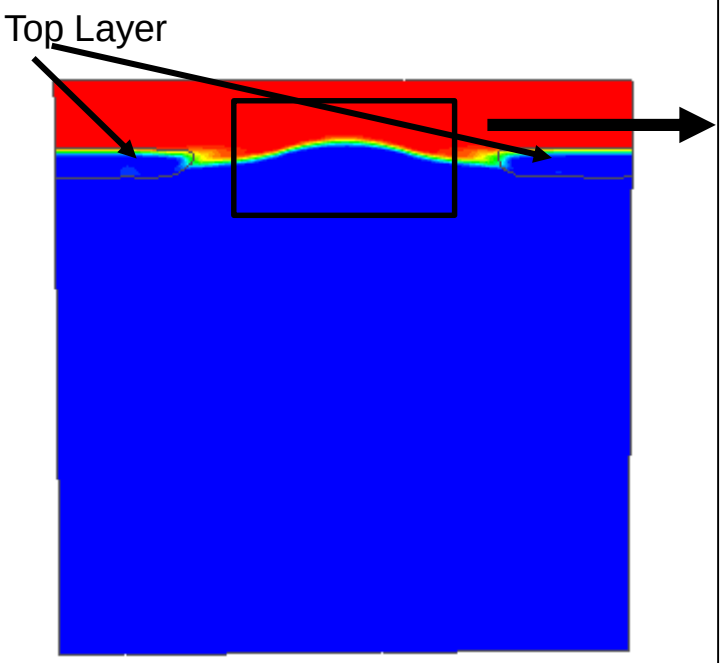
Fig: Base Case Water Velocity

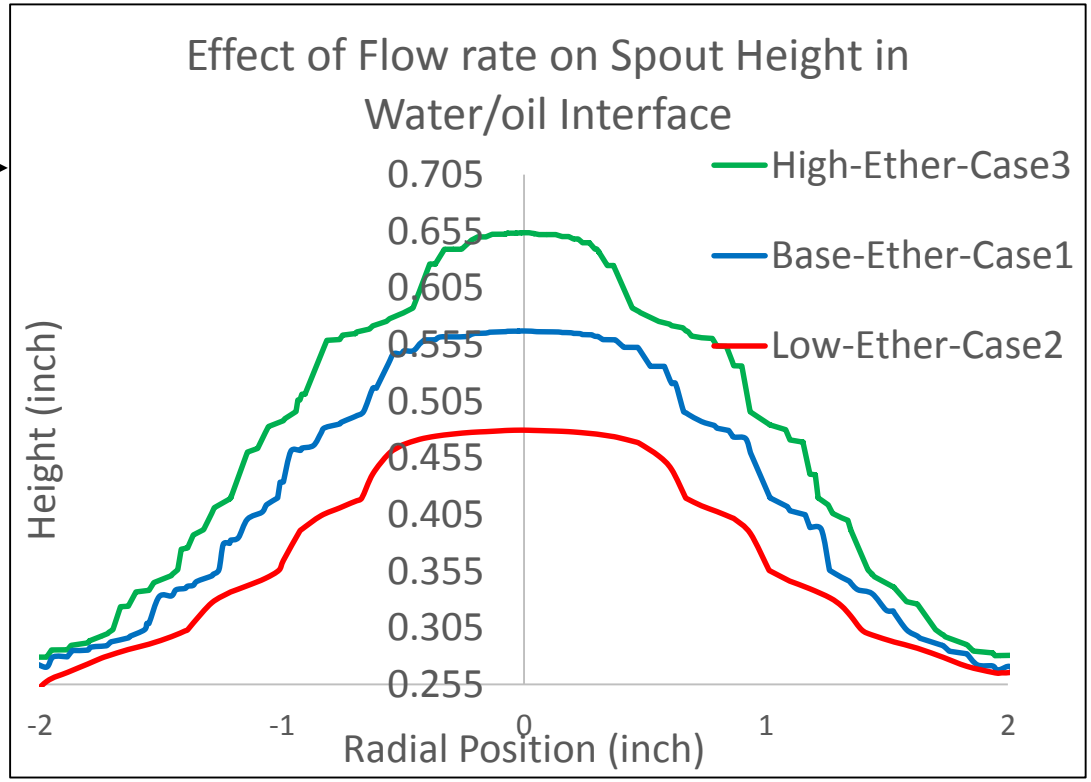




- Velocity magnitude is high initially at the bottom of ladle and its profile grows wider at the top of ladle
- High velocity magnitude at high gas flow rate

RESULTS – SPOUT HEIGHT

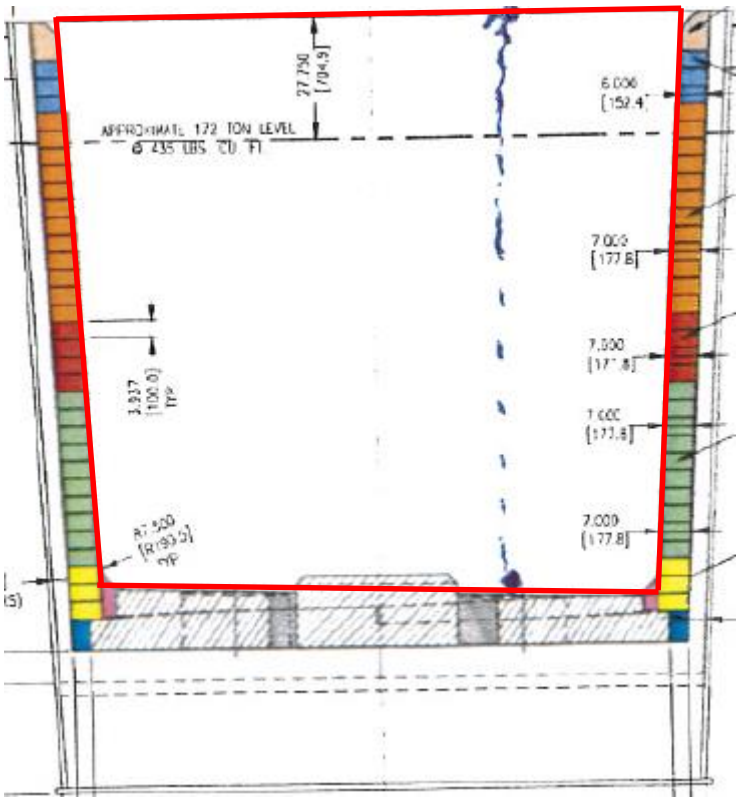




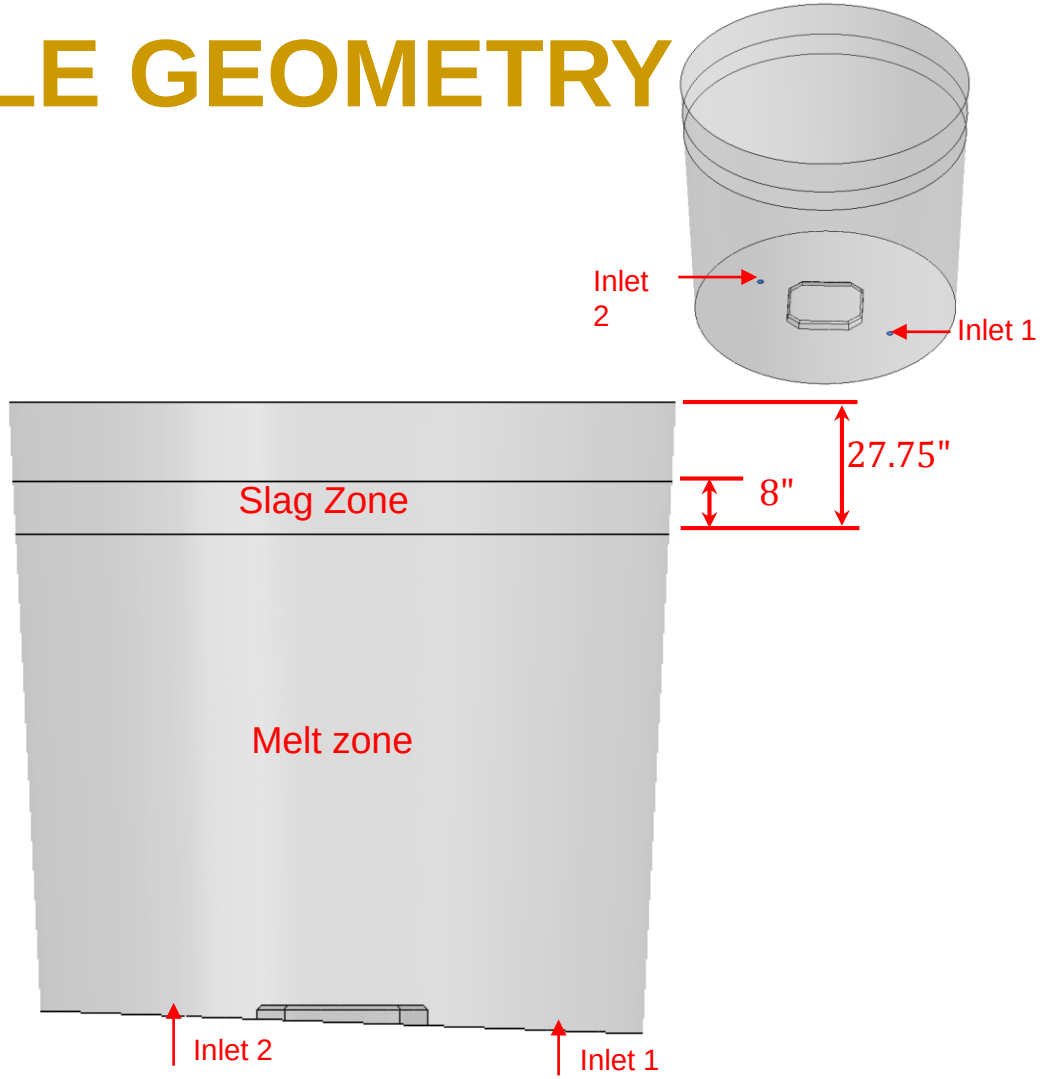
- Spout height increases with increasing gas flow rate.

PARAMETRIC STUDY

NUCOR LADLE GEOMETRY



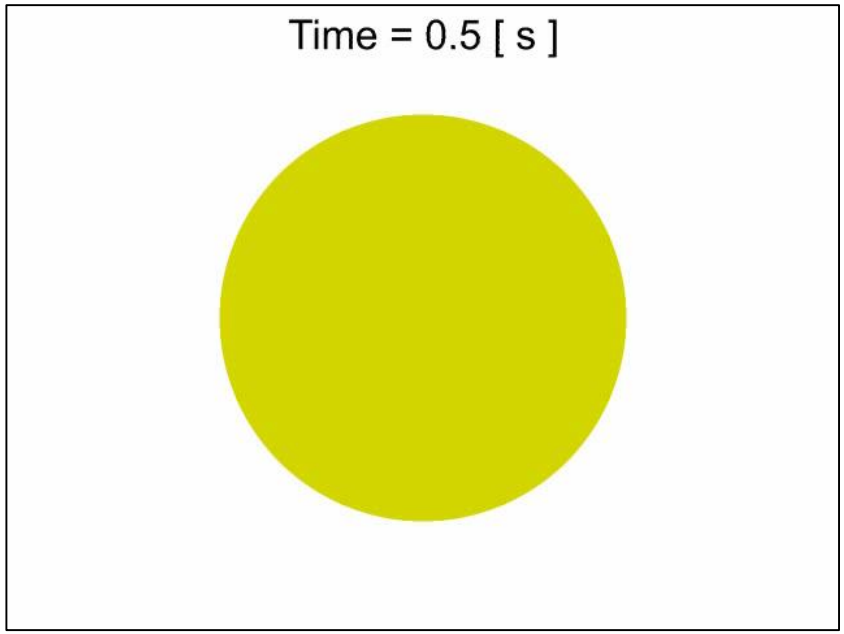
- Technical drawing from Nucor



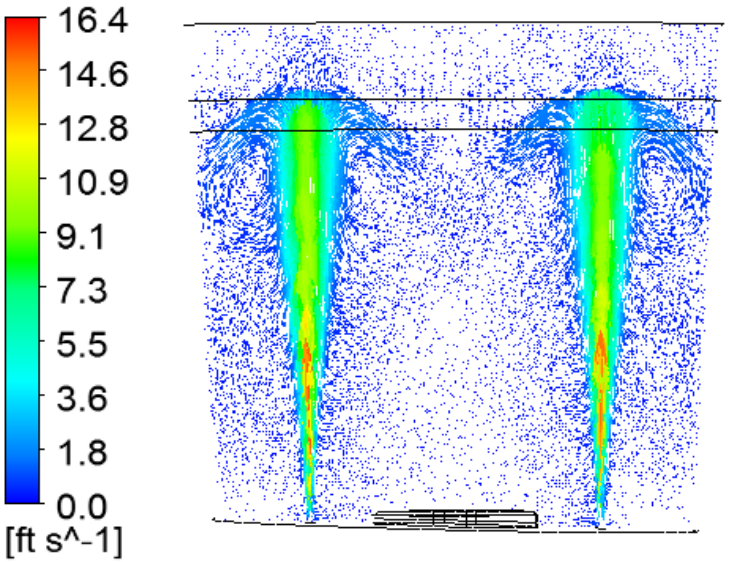
- Computational domain

BASE CASE SIMULATION RESULTS

- Slag Eye



- Velocity Vectors



- Base Case
  - Injection flow rate: 30SCFM per injection plug
  - Melt depth: 105in
  - Slag thickness: 8in

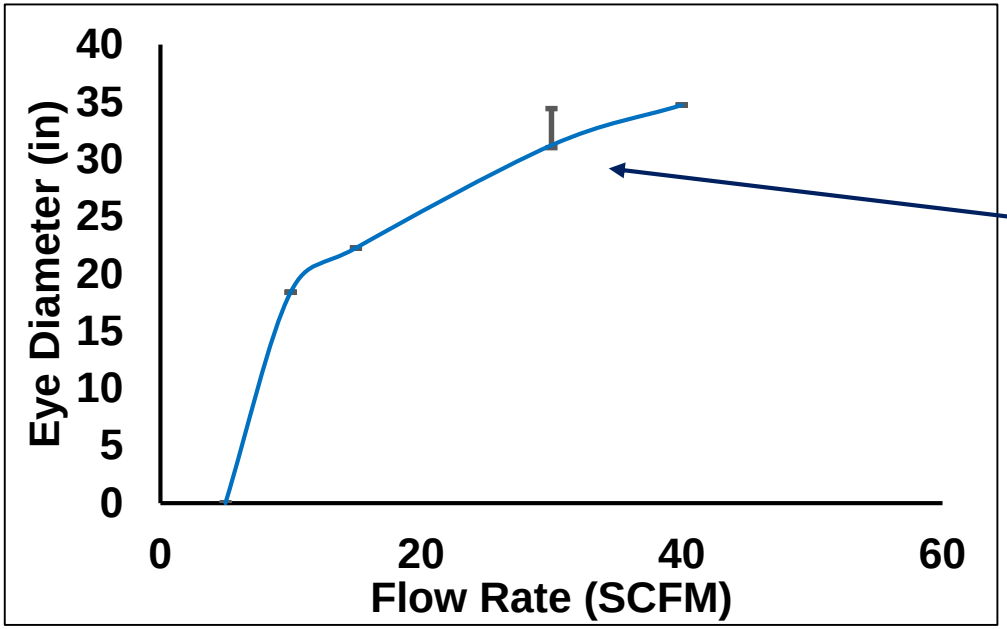
BOUNDARY & INITIAL CONDITIONS

	Case 1	Case 2	Case 3	Case 4 (Base Case)	Case 5	Case 6	Case 7
Argon flow rate per inlet (SCFM)	5	10	15	30	40	30	30
Melt depth (in)	105	105	105	105	105	105	105
Slag thickness (in)	8	8	8	8	8	4	11

* Note: Initial bubble diameter is based on 25% of $d_{bubble} = 0.35(Q^2/g)^{0.2}$, where Q is the volume flow rate of argon gas. (Aoki et al., 2004; Johansen et al., 1999)

J. Aoki, B.G. Thomas, J. Peter and K.D. Peaslee, “Experimental and Theoretical Investigation of Mixing in a Bottom Gas-Stirred Ladle”, Materials Science and Engineering, 2004

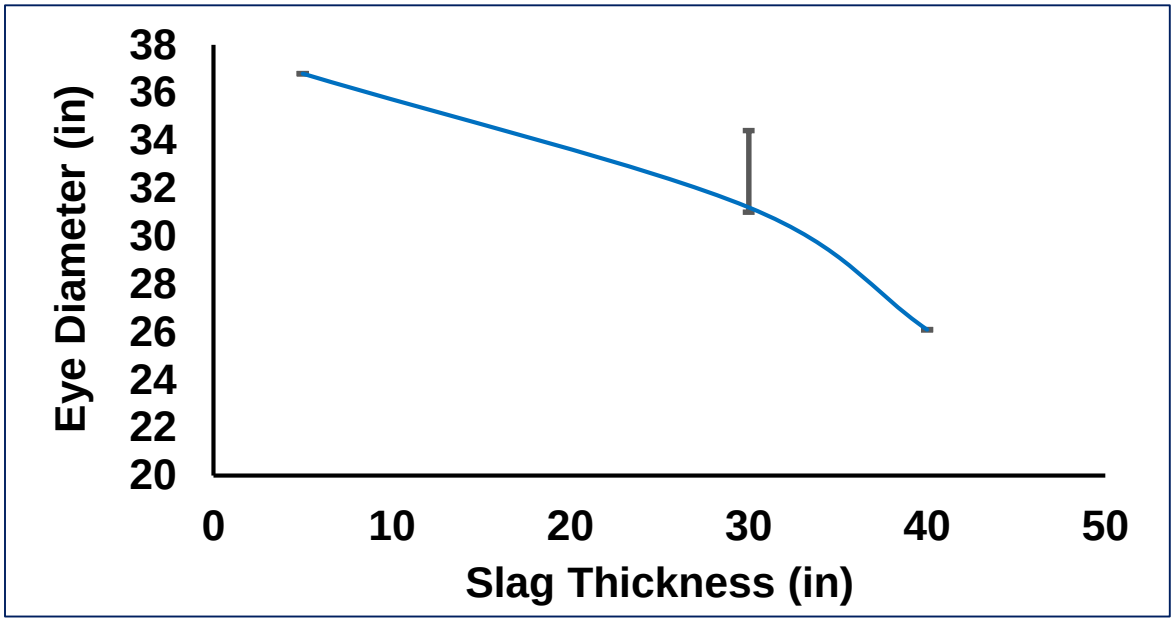
EFFECT OF GAS FLOW RATE ON SLAG EYE



- Simulated slag eye diameter is 31.2 inches
- **Measured slag eye diameter for 30 SCFM gas flow rate is in range of 28-31 inches (average ~8.71% diff.)**

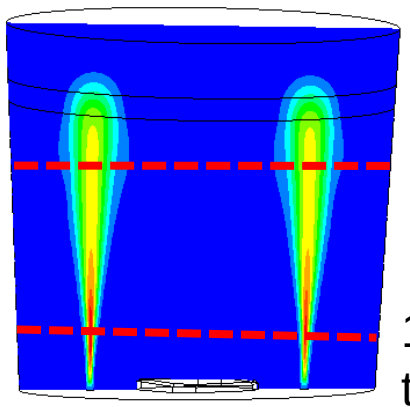
- Case 1
- Case 2
- Case 3
- Case 4 (Base Case)
- Case 5

EFFECT OF SLAG THICKNESS ON SLAG EYE

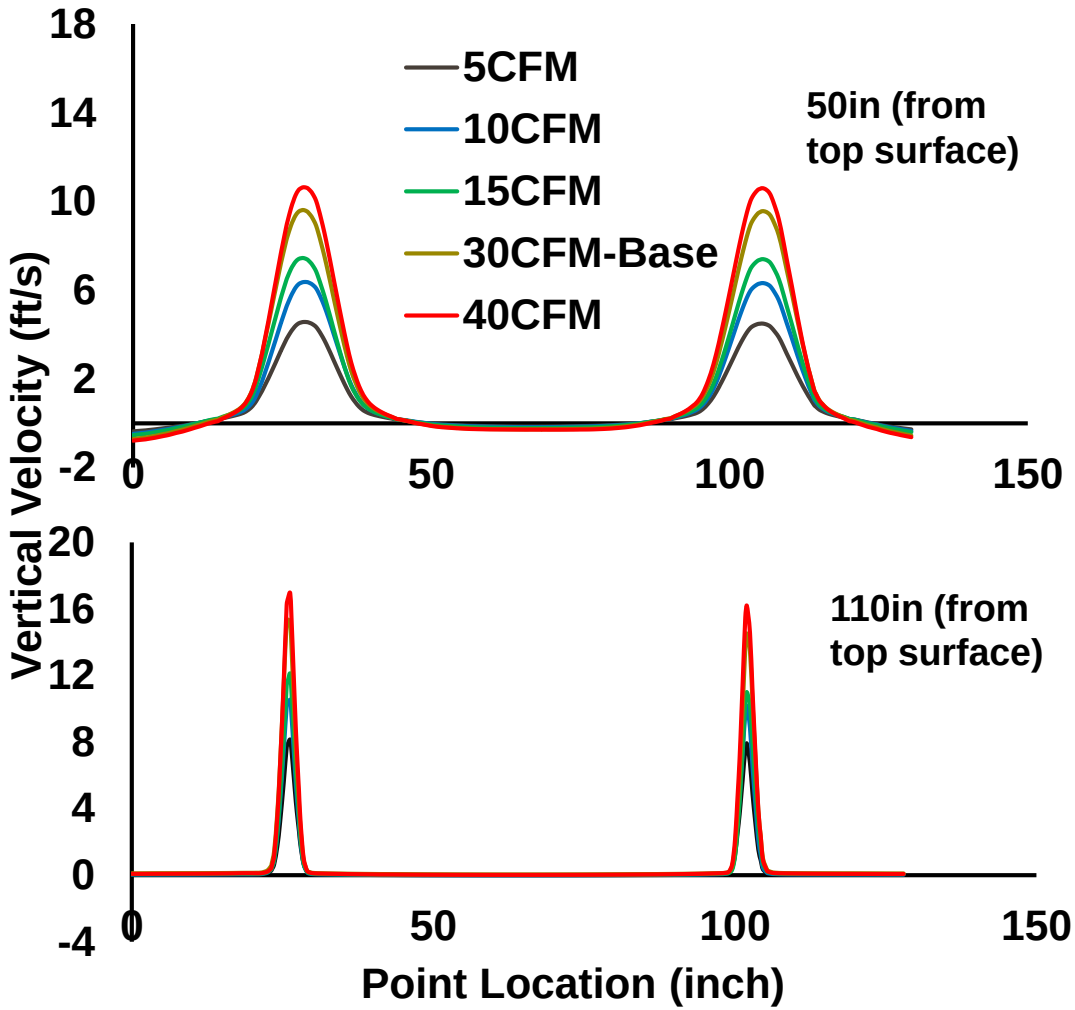


- 4 inch slag thickness
- 8 inch slag thickness
- 11 inch slag thickness

EFFECT OF ARGON FLOWRATE



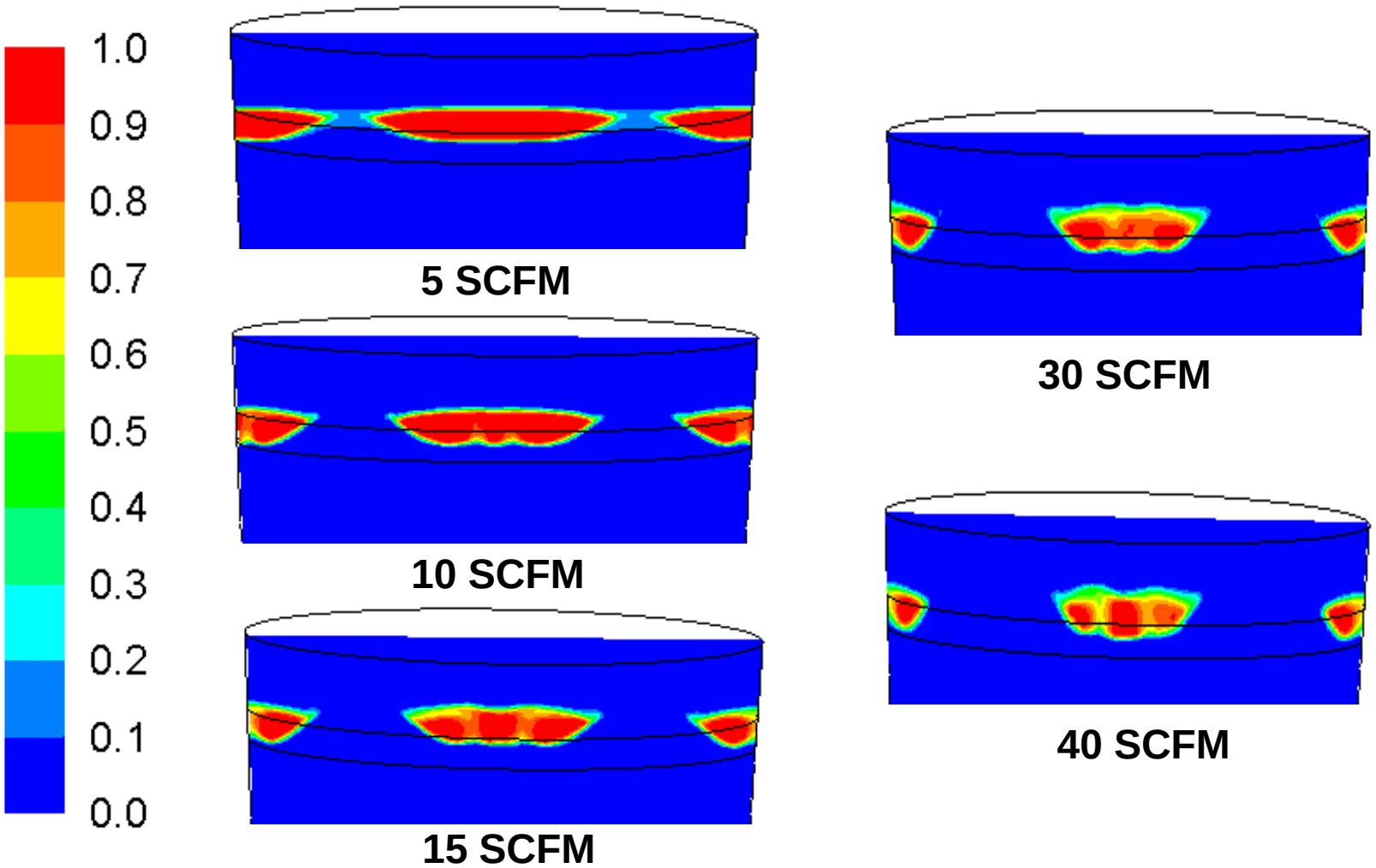
8in-30SCFM (Base Case) Velocity



- Higher and narrower velocity profile at the bottom of ladle.
- Lower and wider spread of velocity profile at top of ladle.
- High velocity magnitude for high gas flow rate.

SLAG METAL INTERFACE

Slag Volume Fraction



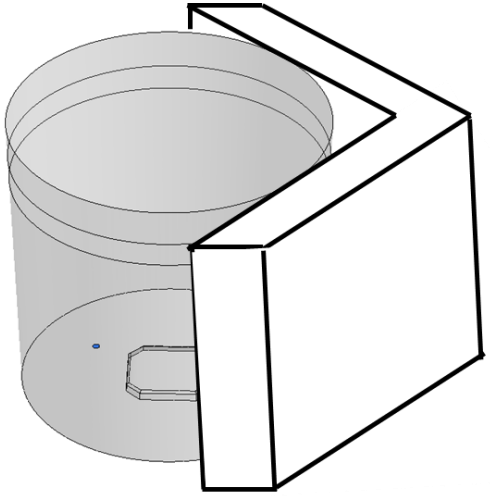
SUMMARY OF GAS STIRRED LADLE

- Water model cases and Nucor ladle model were simulated, and a good agreement is observed between experimental results and CFD results.
- Higher gas flow rate leads to larger slag eye and higher spout height.
- Slag eye is bigger when top layer is thinner and when top layer liquid density is larger.
- Velocity of center of the plume decreases as bubbles ascend.

EMS LADLE MODEL

EMS

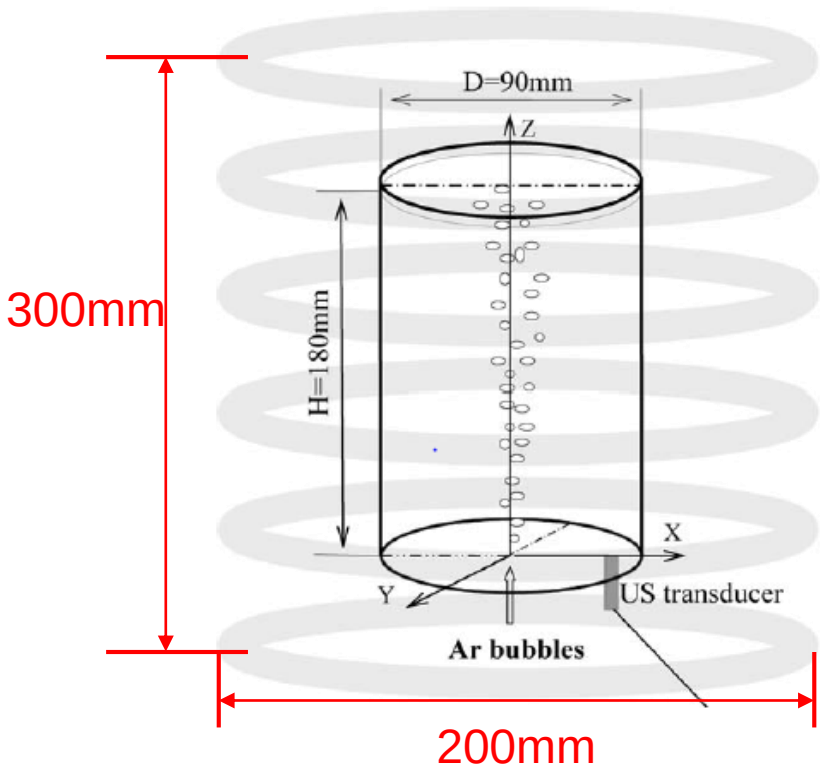
- Electromagnetic field is used to stir the liquid metal.
- The liquid flow field and the magnetic field are coupled
  - Movement of conductive fluid in magnetic field induces electric potential
  - Interaction of magnetic field with moving conductive fluid generates Lorentz force drive melt motion
- EMS can intensify heat and mass transfer and improve mixing efficiency



Induction coil

EXPERIMENTAL WORK

- Experimental configuration
- Experimental parameter



- Forcing parameter F: $F = \frac{\sigma_{el}\omega_T B_T^2 k R^5}{2\rho v^2}$

  Where $F = 1.6\text{x}10^6 \sim 2.1\text{x}10^8$

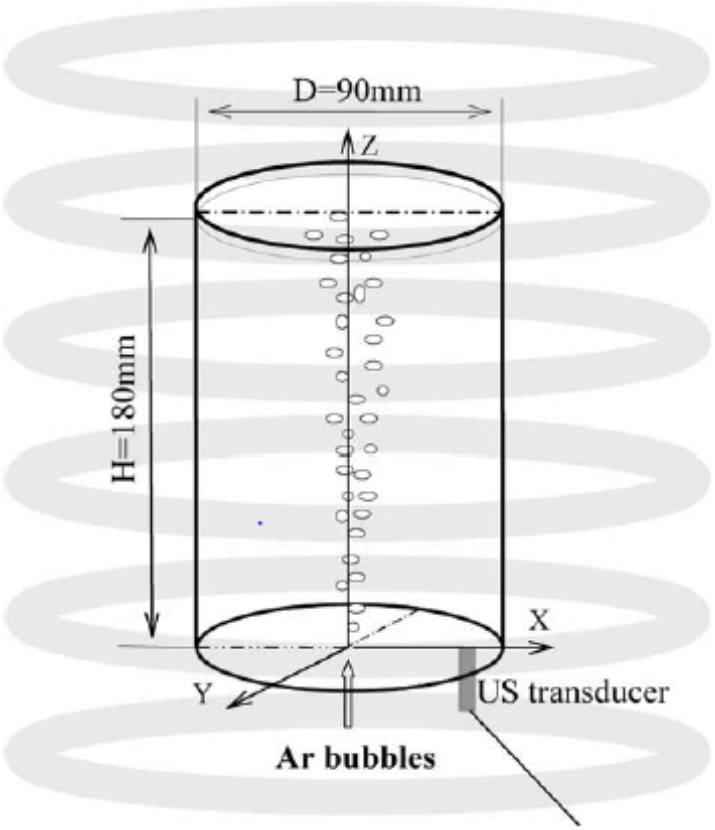
- Field frequency: $\omega_T = 2\pi f \approx 314\ \mathrm{s}^{-1}$

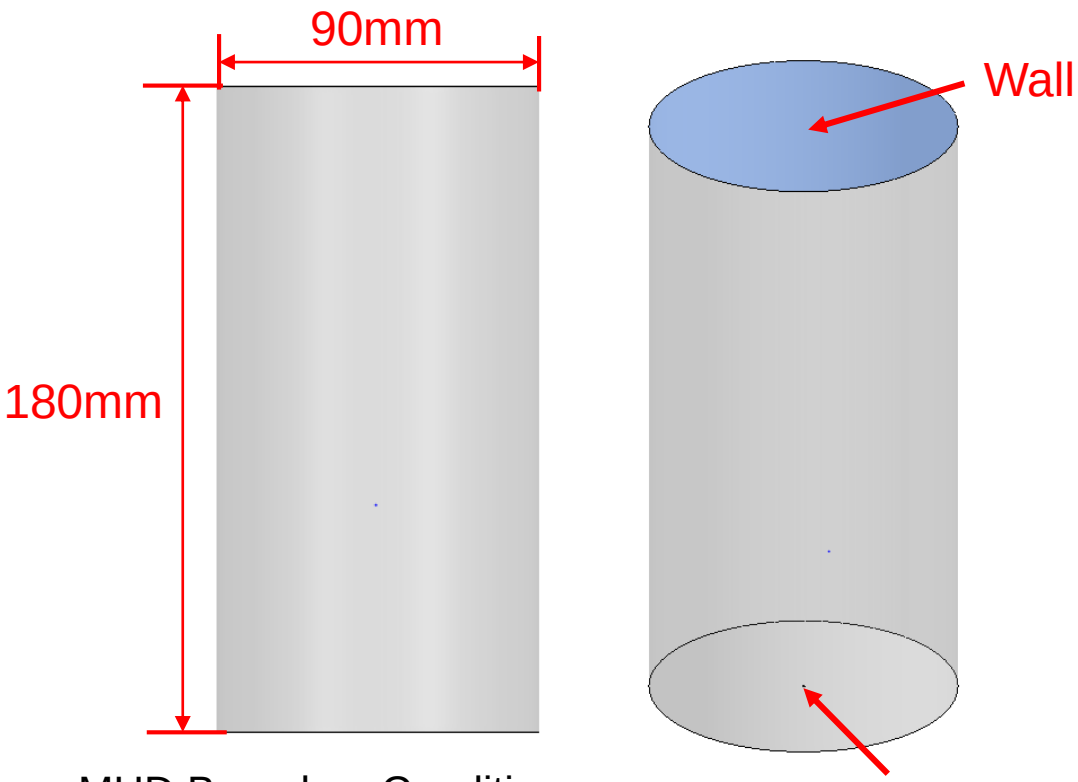
- Wave number: $k = 2\pi/\lambda = 21.8\ \mathrm{m}^{-1}$

C. Zhang, S. Eckert and G. Gerbeth, " The impact of a vertically travelling magnetic field on the flow in a cylindrical liquid metal bubble plume ", The Minerals & Materials Society and ASM International 2009.

GEOMETRY

- Experimental configuration
- Simulation geometry





MHD Boundary Conditions
Sides and Bottom: Thin Walls (5mm)
Top: Conductive (fluid surface)

CFD MODEL AND METHODOLOGY

Melt Zone (no slag zone in the experiments)

- 3-D; Transient
- Time step determined by magnetic field frequency
- Single phase flow
- Standard k-epsilon turbulence model

No Argon Injection

Magnetic field (coupling with fluid flow as forces)

- **MHD (Magnetohydrodynamic model)**
  - Alternating Current
  - Travelling magnetic field (TMF)
  - Axial direction (downward)

GOVERNING EQUATION

- Conservation of mass $\nabla \cdot \vec{V} = 0$
- Conservation of momentum $\rho\left(\frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla)\vec{V}\right) = -\nabla \vec{P} + \eta \Delta \vec{V} + (\vec{\boldsymbol{J}} \times \vec{\boldsymbol{B}})$
- Maxwell's equations $\nabla \cdot \vec{B} = 0$ $\nabla \times \vec{B} = \mu \vec{j}$
- Ohm's law $\vec{j} = \sigma(\vec{E} + \vec{V} \times \vec{B})$

Where: $\vec{\boldsymbol{B}}$ **is the magnetic fields, Tesla,** $\vec{\boldsymbol{B}} = \boldsymbol{B_0} + \boldsymbol{B}$;

B_0 external magnetic field, B induced magnetic field.

$\vec{E}$ is the electric fields, V/m;

$\vec{j}$ (A/m^2) is the electric current density vector;

μ is the magnetic permeability;

σ is the electrical conductivity of the media;

η is the viscosity.

MATERIAL PROPERTIES

	GaInSn Alloy	Container(Plexiglas)
Density (kg/m^3)	6360	1180
Kinematic Viscosity ($m^{-2}\cdot s^{-1}$)	3.4e-7	
Dynamic Viscosity (Pa·s)	2.16e-3	
Elec. Conductivity ($\Omega^{-1}\cdot m^{-1}$)	3.2e6	1e-13
Magnetic Permeability ($H\cdot m^{-1}$)	1.257e-6	6.285e-7

	Induction coil/Magnetic field properties
Frequency (Hz)	50
Wavelength (m)	0.288
Inner bore diameter (m)	0.2
Total height (m)	0.3
Angular frequency (s^{-1})	314
Axial wave number (m^{-1})	21.8
Forcing parameter (single-phase)	5.6e7
B_0 (T) (calculated from given F)	4.514e-3

MAGNETIC FIELD

- GaInSn fluid exposed to an external travelling magnetic field (TMF)

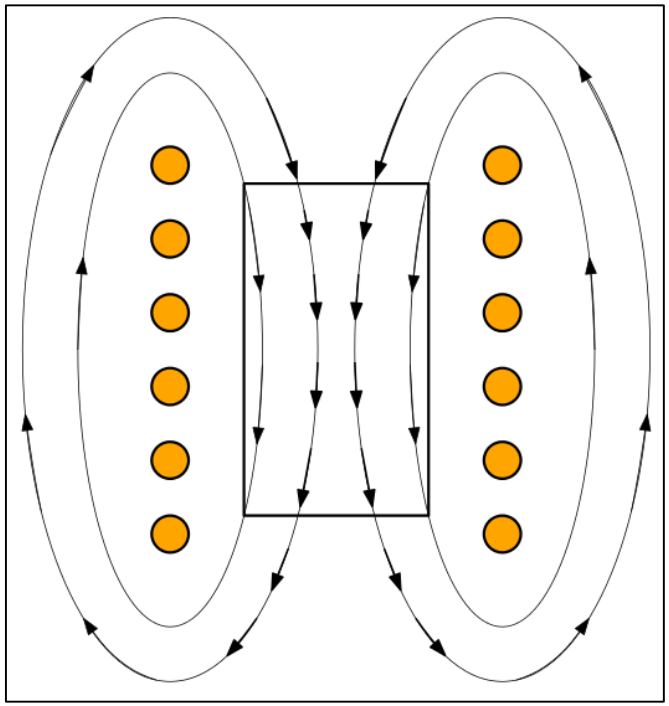
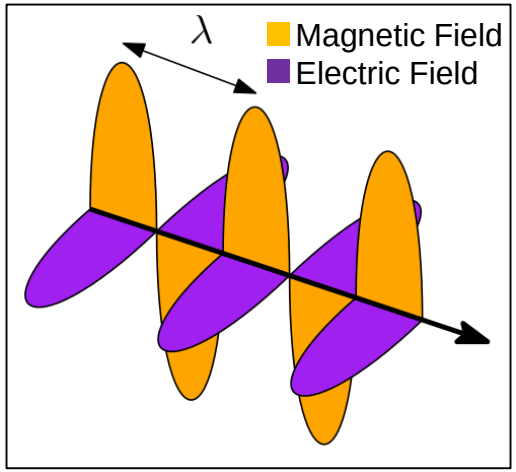
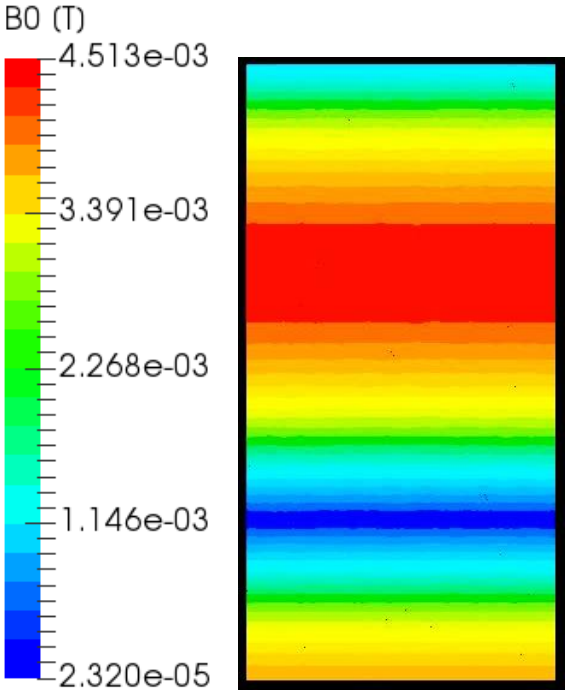


Diagram of travelling magnetic field from experimental setup

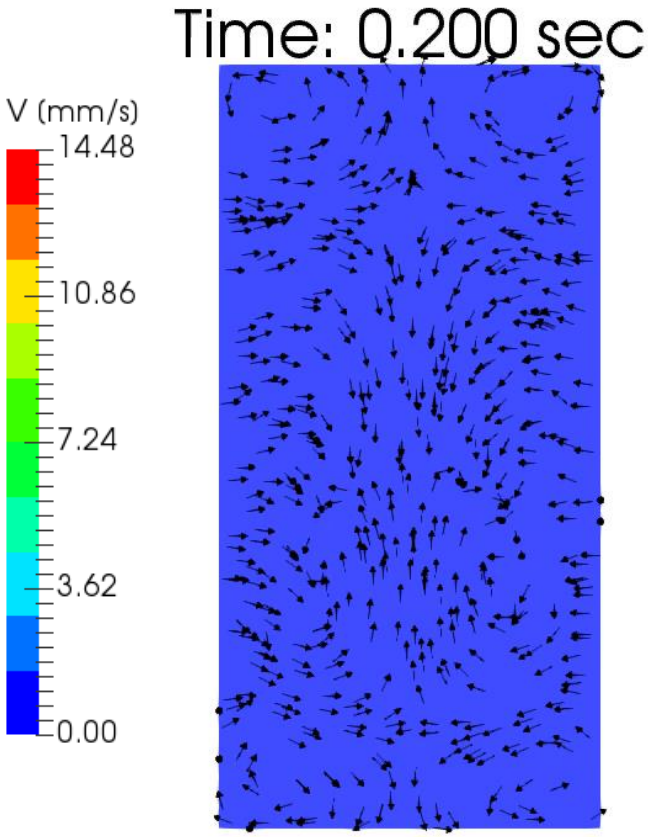


Travelling EM wave with wavelength λ

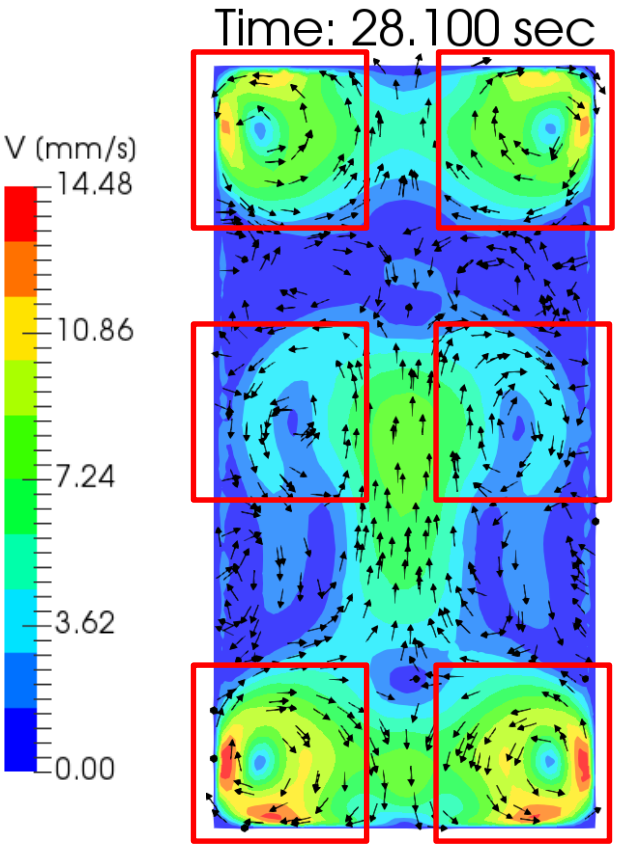


Animation of applied downward magnetic field B_0 at 50Hz at the center plane

PRELIMINARY RESULTS - VELOCITY PROFILE



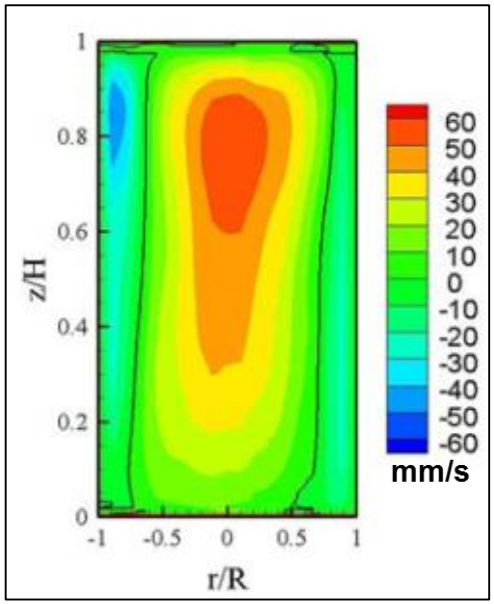
Animation of flow development across the center plane



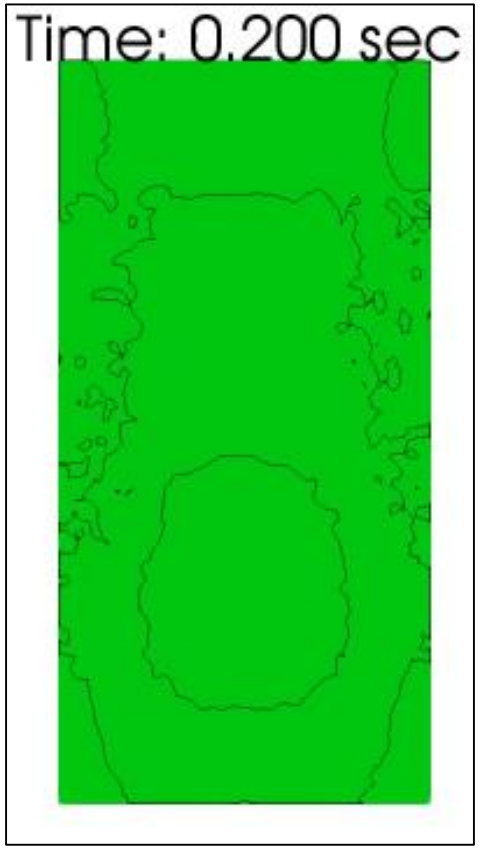
Counts of center plane velocity. Red boxes show recirculation zones

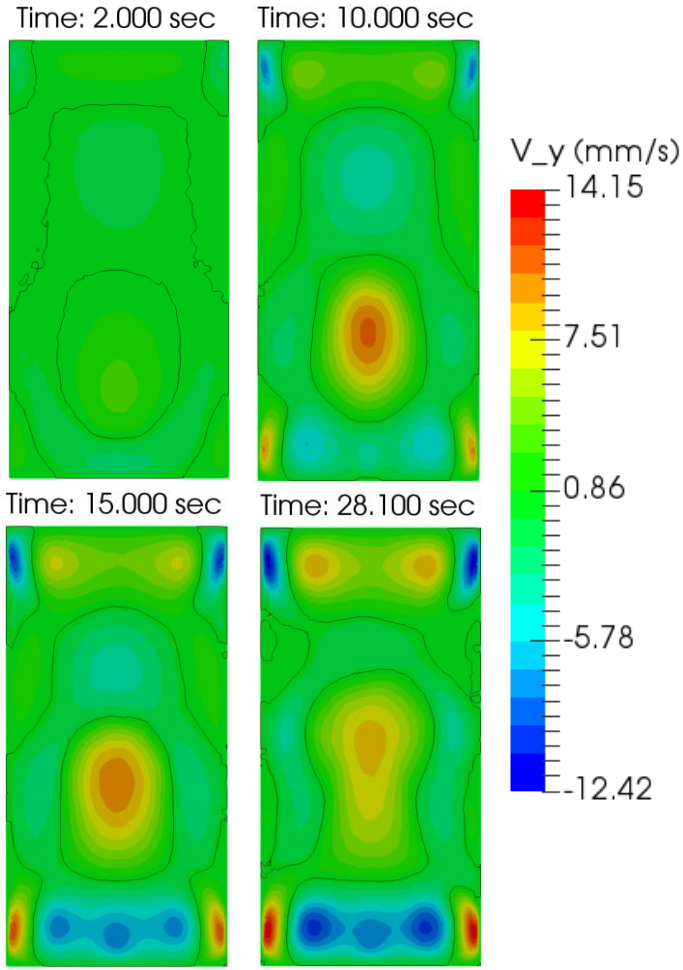
VERTICAL VELOCITY PROFILE

- As of 28 seconds, fluid has reach only roughly ¼ predicted speed of experiment (below)



Exp. velocity at 300s





Contours of vertical velocity. Black lines represent 0mm/s

SUMMARY OF EMS

- CFD models have been developed based on an existing experimental work.
- The effect of EM field on the flow of an alloy liquid is being studied.
- Global recirculation enhances the flow mixture.
- EMS induces flow motion throughout liquid domain.

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LADLE SIMULATION VISUALIZATION

CENTER FOR INNOVATION THROUGH VISUALIZATION & SIMULATION

PURDUE UNIVERSITY NORTHWEST

COMPUTATIONAL STUDIES AND OPTIMIZATION OF INCLUSION REMOVAL IN A STEEL LADLE

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February 15, 2017

"Where Ideas Become Reality"

CONCLUSION

- Further validation on experimental work from literature is done and good agreement is observed between the experimental results and simulation results.
- Parametric study on gas-stirred ladle is done.
- Higher argon flow rate leads bigger slag eye and higher spout height
- Slag eye is bigger when top layer is thinner and when top layer liquid density is larger.
- Initial stage of EMS ladle model is developed and compared with experimental result
- Global recirculation on EMS ladle enhance flow mixture

FUTURE WORK

- Develop and modify DPM-VOF coupled model
  - Desulfurization and deoxidation
  - Species concentration in steel bath
  - Numerical model for bubble formation and interaction
- Validate the models by plant data.
- Further develop EMS ladle model
  - Develop magnetic field.
  - Develop forces exerting on melt.

Thank You
Question?

TIMELINE FOR YEAR 2

Tasks:
1.Model validation: a. slag thickness b. viscosity c. literature d. plant data 2. Literature research 3. Add temperature and reactions 4.EMS model 5. Parametric study

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Task 1												
Task 2												
Task 3												
Task 4												
Task 5												