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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  - Chase Ault (SDI)
  - Sunday Abraham (SSAB)
  - Jeffrey Becker (USS)

CIVS Team:
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- Armin Silaen
- Chenn Zhou

"Where Ideas Become Reality"

OUTLINE

- Introduction
- Gas-Stirred Ladle
  - CFD model
  - Parametric study
  - Heat transfer model
- EMS Ladle
  - CFD Model
- Summary
- Future Work

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

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) conditions
- Study effect of gas flow rate and plug location on mixing efficiency
  - Develop a correlation between geometrical parameters and mixing time
- Study inclusion transport and evolution
  - Develop a model of inclusion generation through chemical reaction
  - 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 OUTCOMES

- **Models:**
  - Developed gas-stirring CFD model based on Nucor ladle using Eulerian-VOF and VOF-Lagrangian approaches. VOF-Lagrangian approach found to better match with industrial measurement.
  - Developed and applied bubble breakup and coalescence model based on Laux and Johansen theory.
  - Validated model with water model, cold metal model experimental data and Nucor measurement. Average percentage of 8.71% different compared with Nucor measurement.
  - Developed heat transfer model on gas-stirring ladle. The temperature stratification is reduced with gas-stirring.
  - Developed initial EMS model based on industrial scale ladle.

PROJECT OUTCOMES

Research Findings:

- Effects of argon flow rate
  - Argon flow rate ↑, slag eyes size ↑
  - Argon flow rate ↑, wall shear stress ↑
  - Argon flow rate ↑, mixing time ↓
- Slag surface tension show little effect on eye size
- Effect of slag thickness and slag density

  - Slag thickness ↓, slag density ↑, eye size ↑
- Effects of flow rate on bubbles size, breakup and coalescence.
  - Argon flow rate ↑, breakup frequency ↑, coalescence frequency ↓
  - All bubbles will reach equilibrium diameters as time elapse

PROJECT OUTCOMES

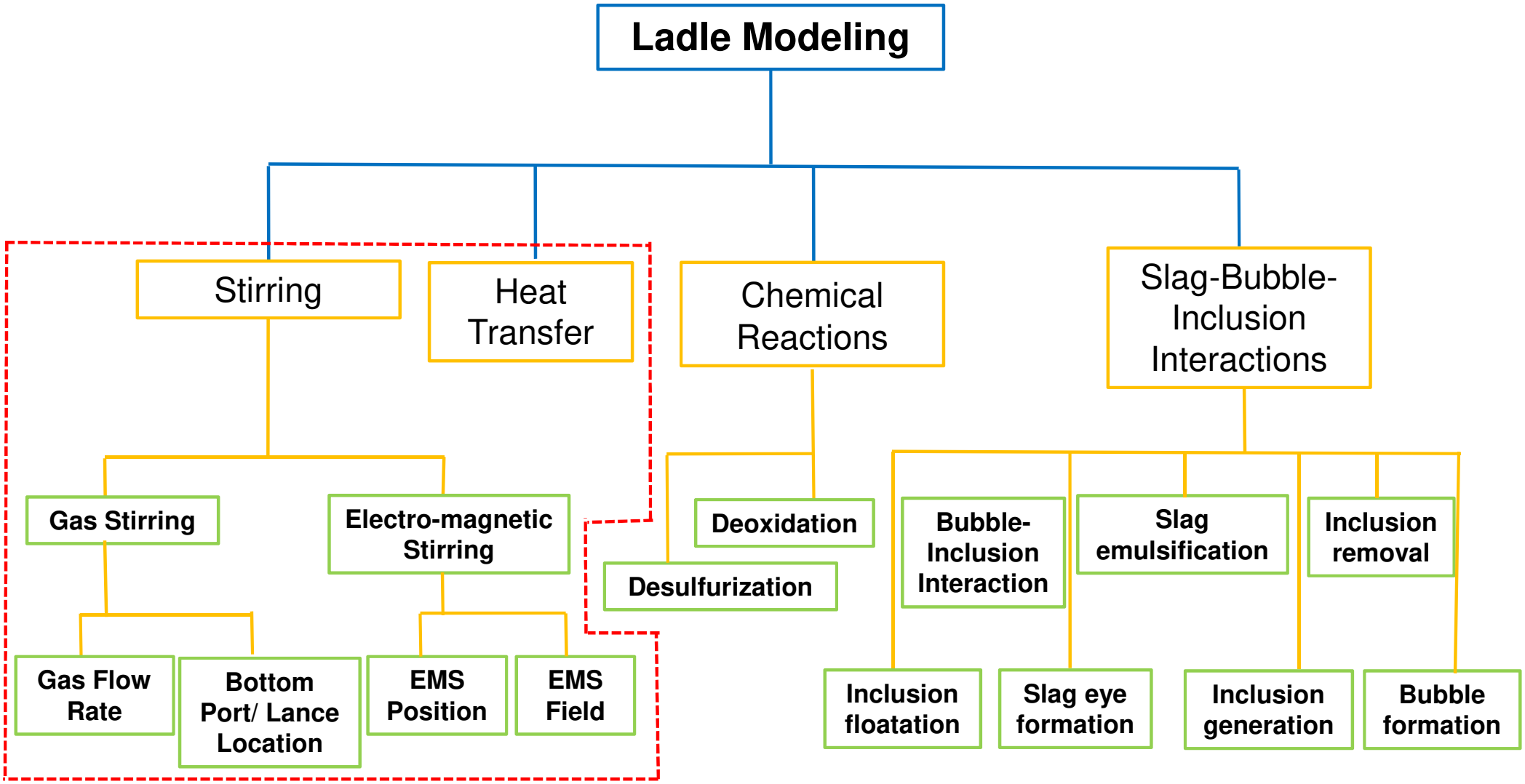
Research Findings:

- Effect of plug position
  - Plug distance ratio ↑ mixing efficiency ↑
  - Mixing efficiency is better at separation angle of 60°
- Effect of ladle aspect ratio
  - Aspect ratio ↑ mixing efficiency ↑
- Effect of EMS – large circulation throughout entire ladle
- Effect of initial wall temperature – Temperature stratification decrease faster with higher wall initial temperature

OBJECTIVES – 2nd YEAR

- Further validate the isothermal gas-stirred ladle model
- Use CFD to model a ladle for mixing process with various geometry, plug position and flow rate
- Develop heat transfer and chemical reaction model
- Develop an EMS ladle model

ROADMAP


Ladle Modeling
Stirring
Heat Transfer
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, Transient

Slag & Melt Zones

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

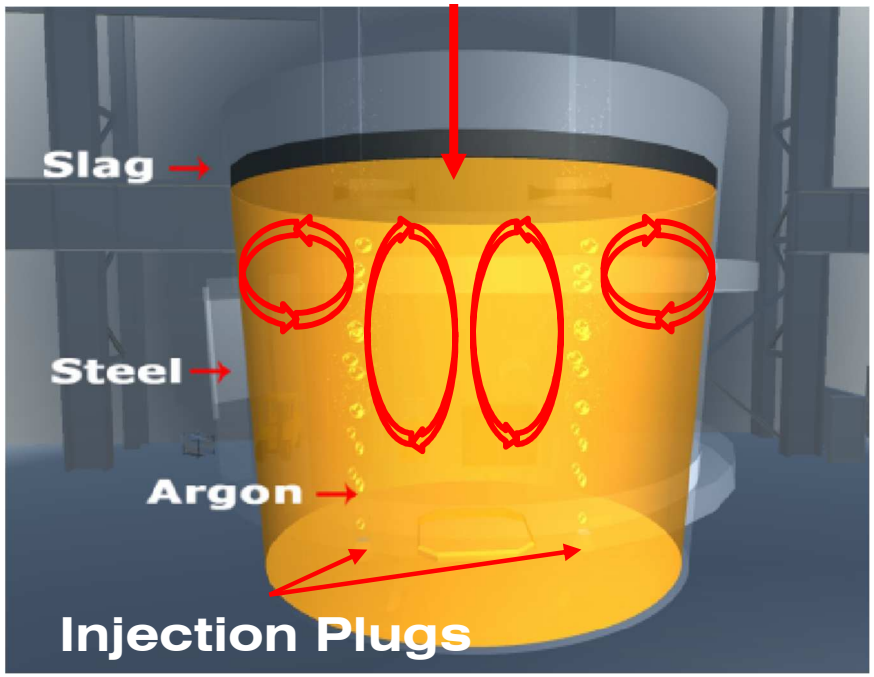
Argon Injection

- 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.

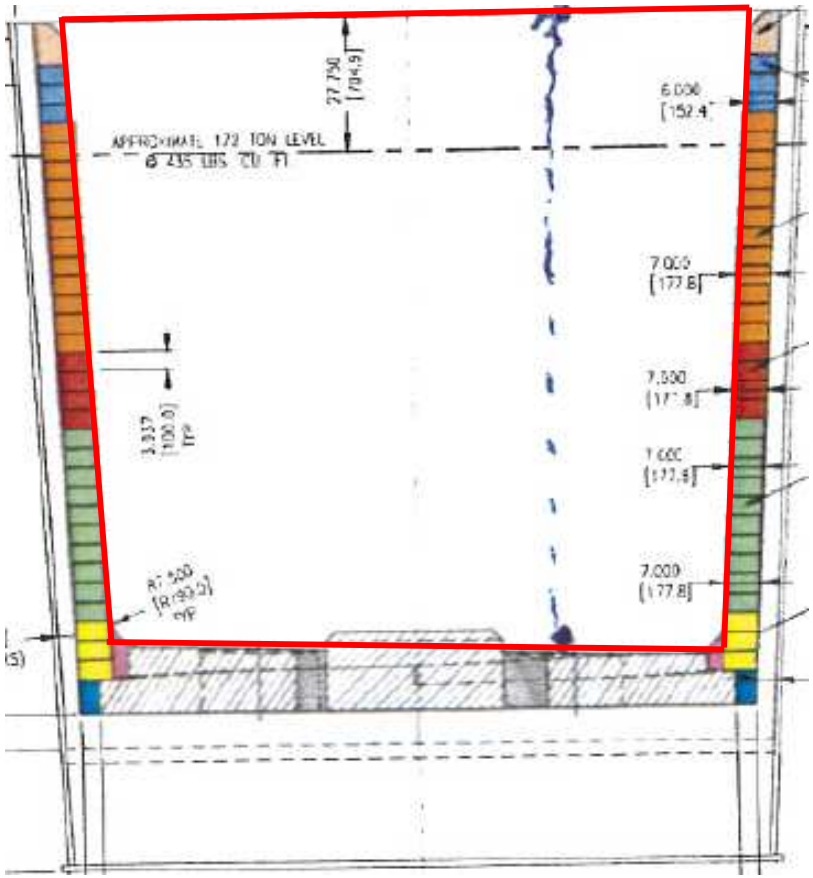
Mixing Process

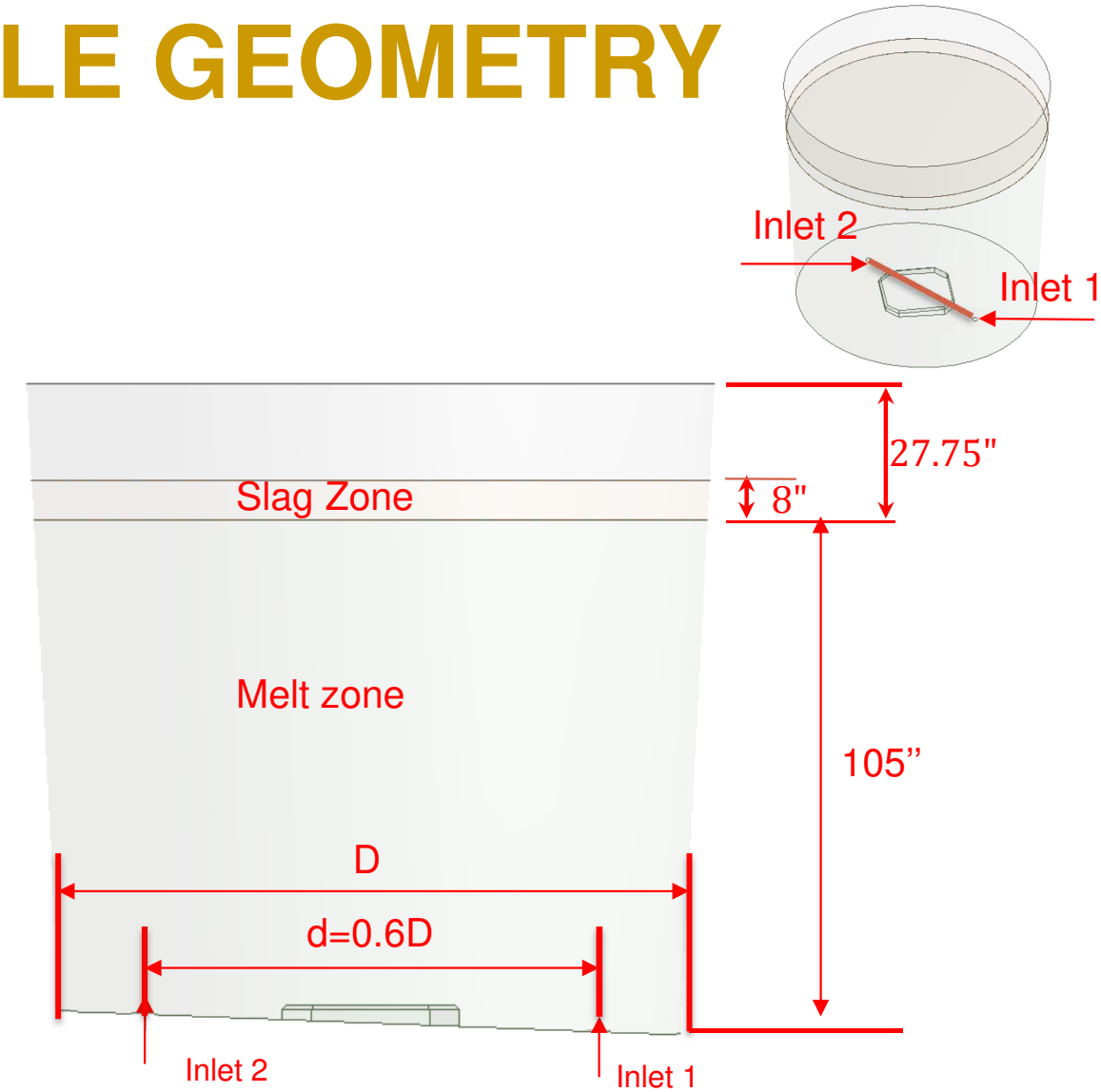
- Multiphase flow: Eulerian-VOF
- Species transport

Tracers are put into the ladle



NUCOR LADLE GEOMETRY

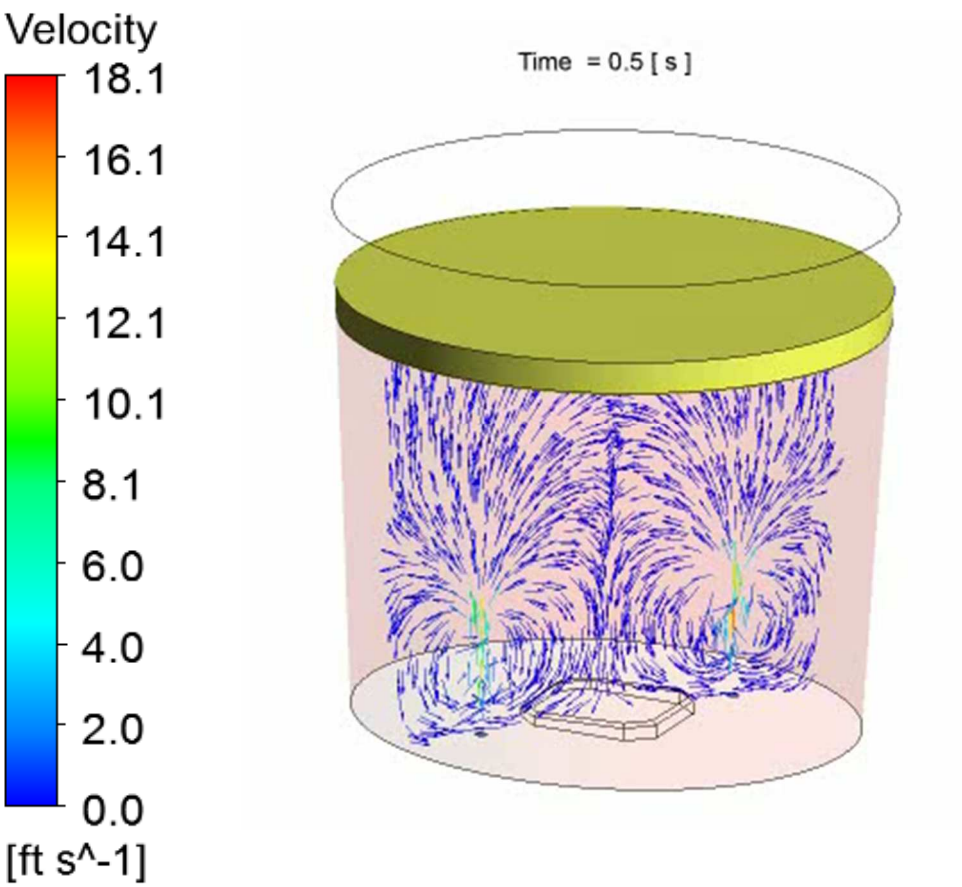




- Technical drawing from Nucor
- Computational domain

BASE CASE SIMULATION RESULTS

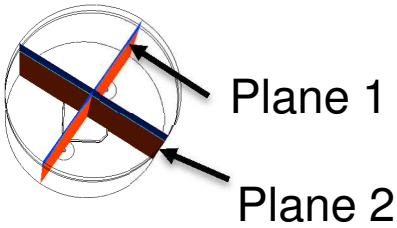
- Base Case
  - Argon flow rate: 30SCFM per injection plug
  - Melt depth: 105 inch
  - Slag depth: 8 inch

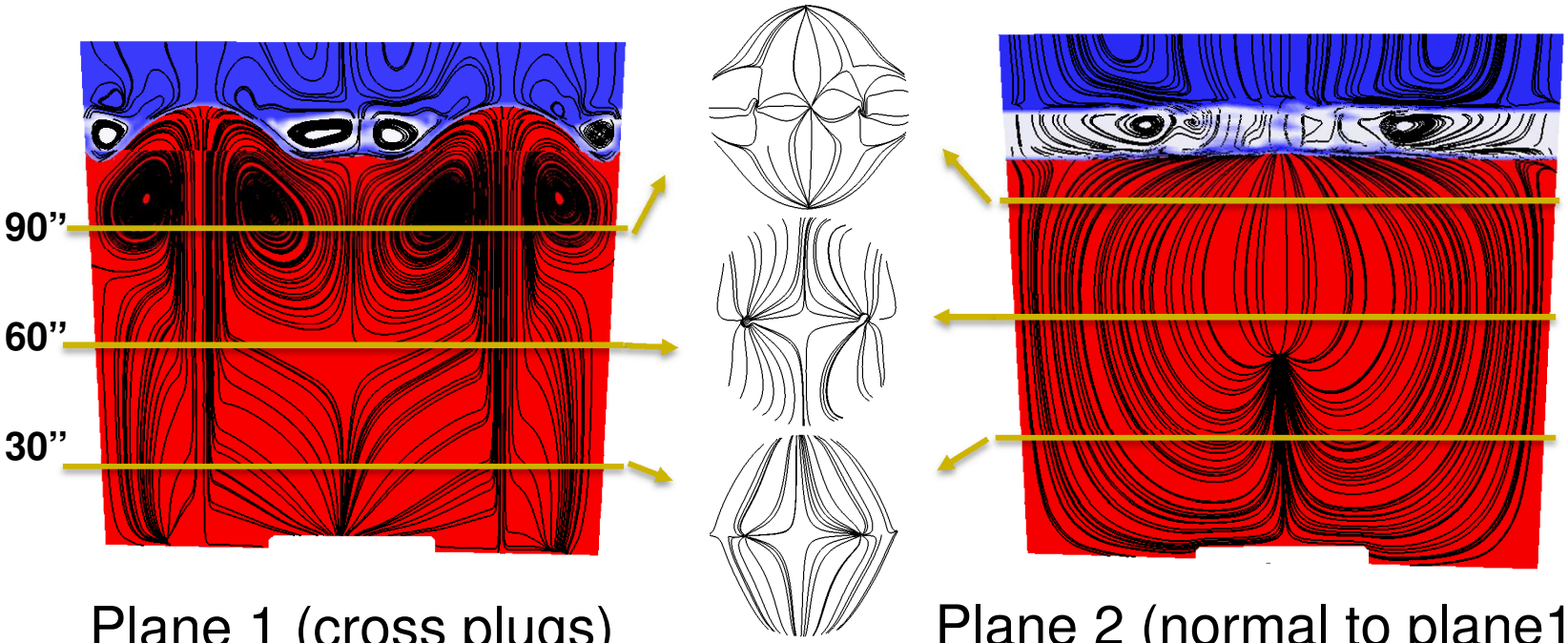


	Slag eye diameter (in)
CFD simulation	31.2
Industrial measurement	28-31 (out of 5 measurements)
% diff	~ 8.71%

FLOW STREAMLINE

- Streamline on different planes





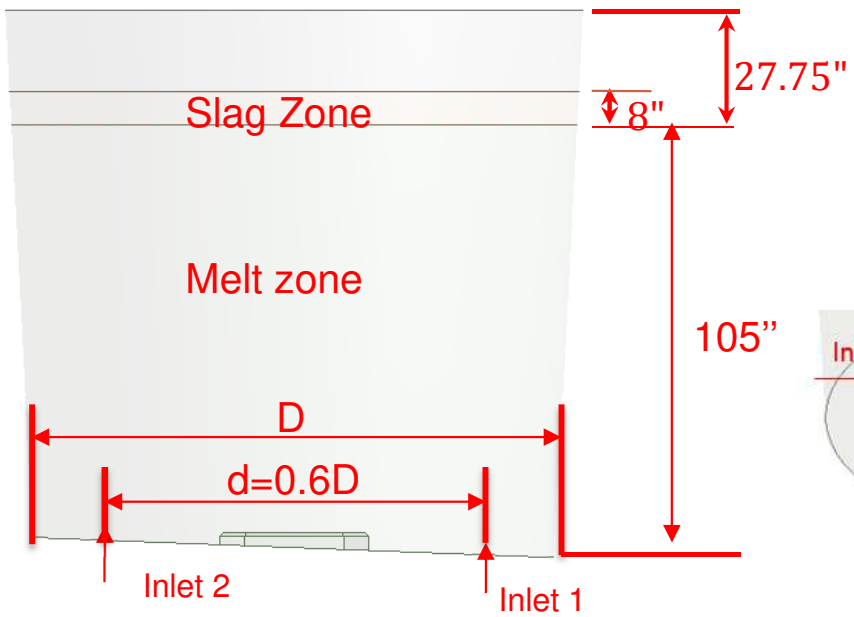
Plane 1 (cross plugs)

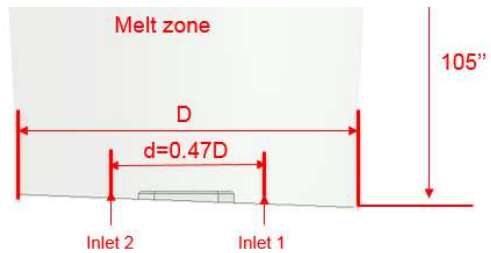
Plane 2 (normal to plane1)

- More circulations can be found at the top region of liquid

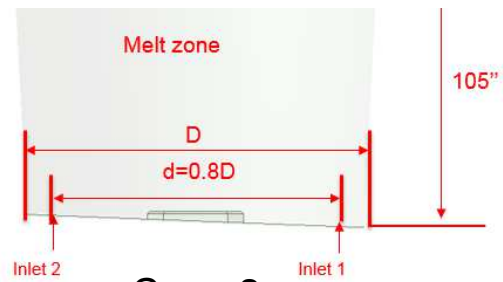
PARAMETRIC STUDY

CASE MATRIX-PLUG LOCATIONS

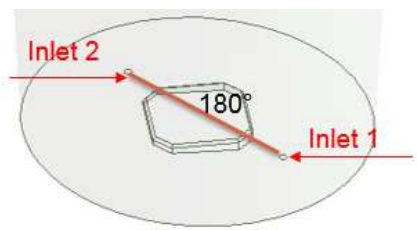




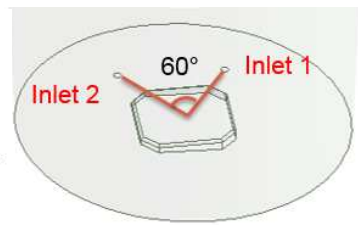
Case 2



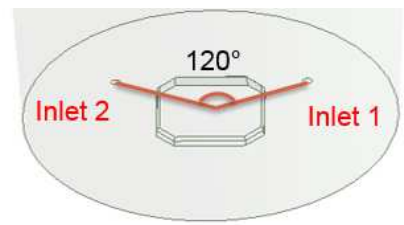
Case 3



Case 1



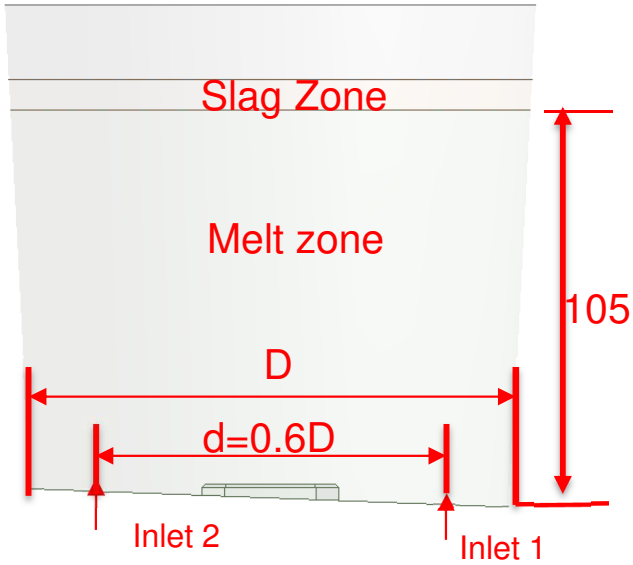
Case 4



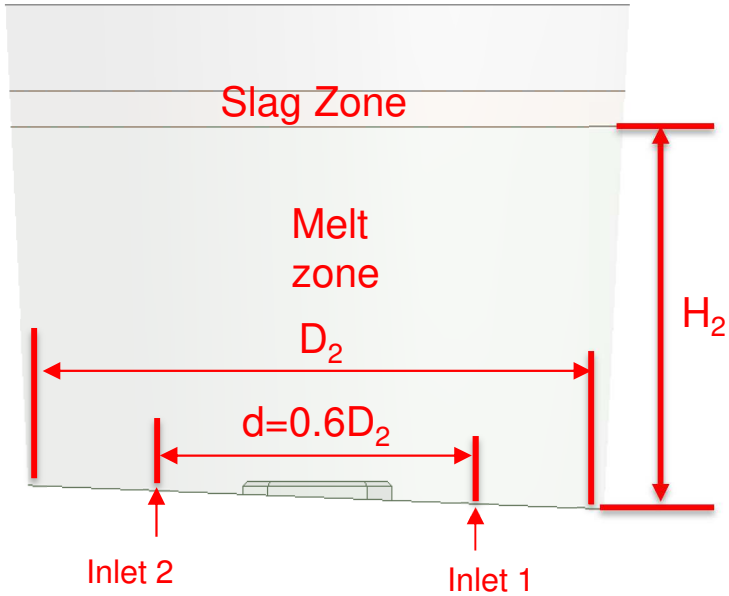
Case 5

Investigation Factor	Parametric Cases	Values
Plug distance ratio	Case 2	0.47
	Case 1 (base)	0.6
	Case 3	0.8
Plug separation angle	Case 4	60°
	Case 5	120°
	Case 1 (base)	180°

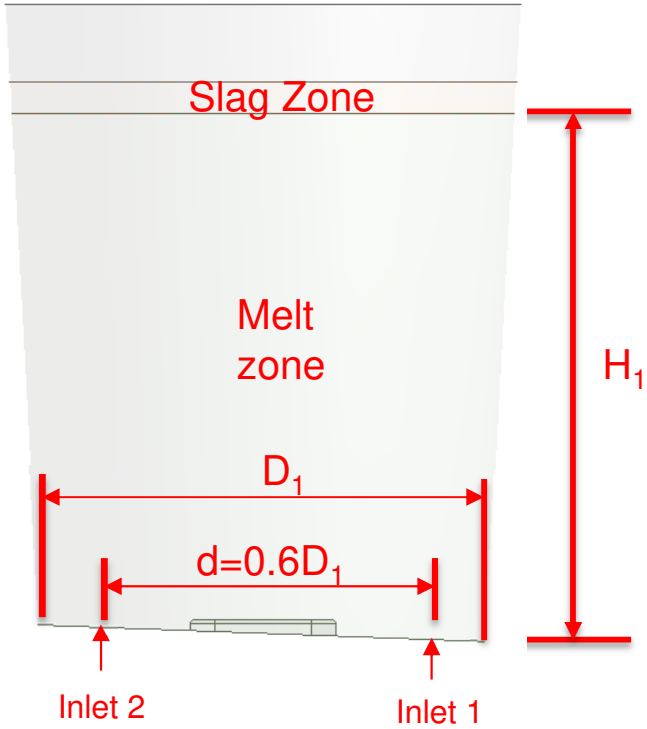
CASE MATRIX-LADLE GEOMETRY



Case 1



Case 9

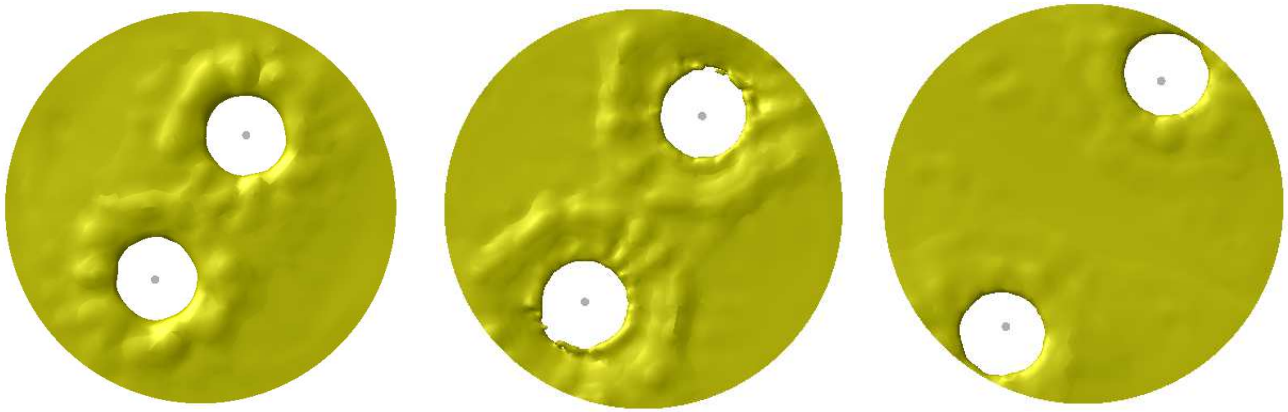


Case 10

Investigation Factor	Parametric Cases	Values
Ladle aspect ratio $\frac{H}{D}$	Case 9	0.6
	Case 1 (base)	0.8
	Case 10	1.2

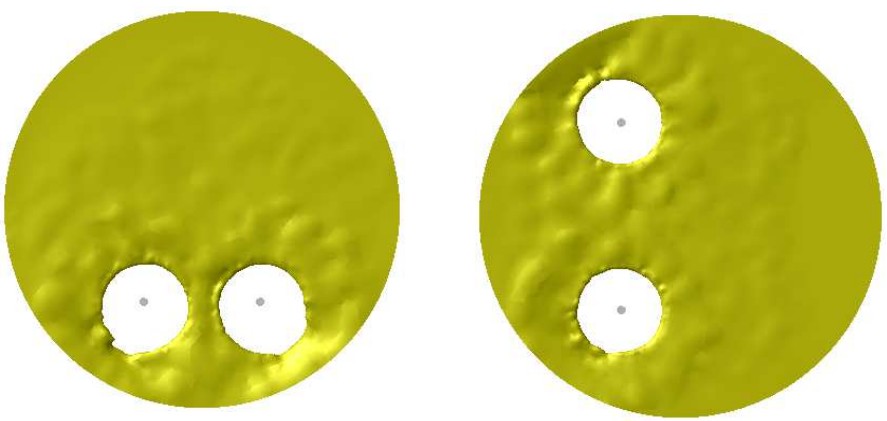
EFFECTS OF PLUG LOCATION

- Time-average results for slag eye size.
  - Case 2 (d=0.47D)
  - Case 1 (d=0.6D)
  - Case 3 (d=0.8D)



Distance ratio	Slag Eye Size (in)
0.47	28.8
0.6 (base)	31.2
0.8	29.0

  - Case 4 (60°)
  - Case 5 (120°)



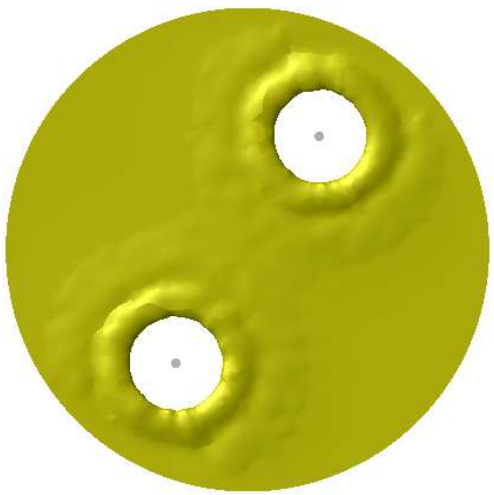
Separation angle	Slag Eye Size (in)
60°	31.5
120°	29.5
180°(base)	31.2

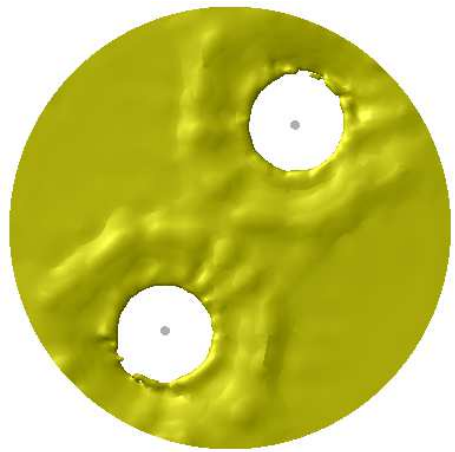
$$\text{Distance ratio} = \frac{\text{radial distance}}{\text{ladle bottom diameter}}$$

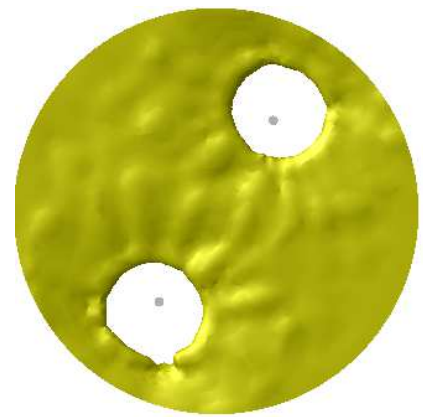
- Plug location has insignificant effect on the slag eye sizes.

EFFECTS OF LADLE ASPECT RATIO

- Time-average results for slag eye size.
  - Case 9 ($\frac{H}{D}$=0.6)
  - Case 1 ($\frac{H}{D}$=0.8)
  - Case 10 ($\frac{H}{D}$=1.2)



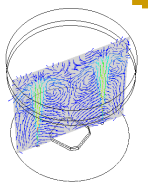




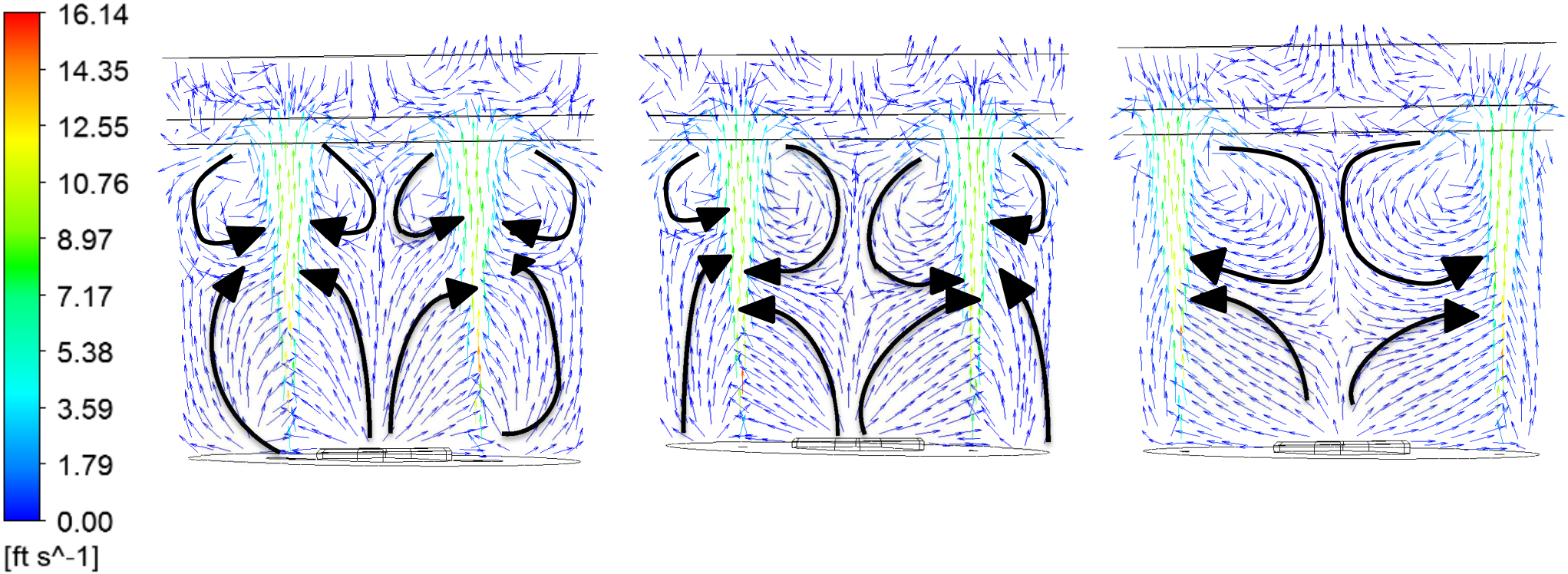
Aspect Ratio	Slag Eye Size (in)
0.6	29.0
0.8 (base)	31.2
1.2	29.5

- Ladle aspect ratio has little effect on the slag eye sizes.

EFFECTS OF PLUG DISTANCE RATIO



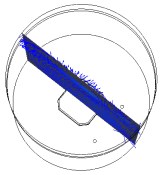
- Case 2 (d=0.47D)
- Case 1 (d=0.6D)
- Case 3 (d=0.8D)



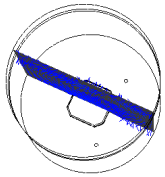
On the plane crossing the plugs:

- Argon plume changes with the distance between two plugs.

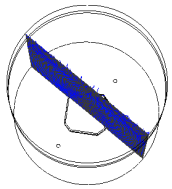
EFFECTS OF PLUG SEPARATION ANGLE



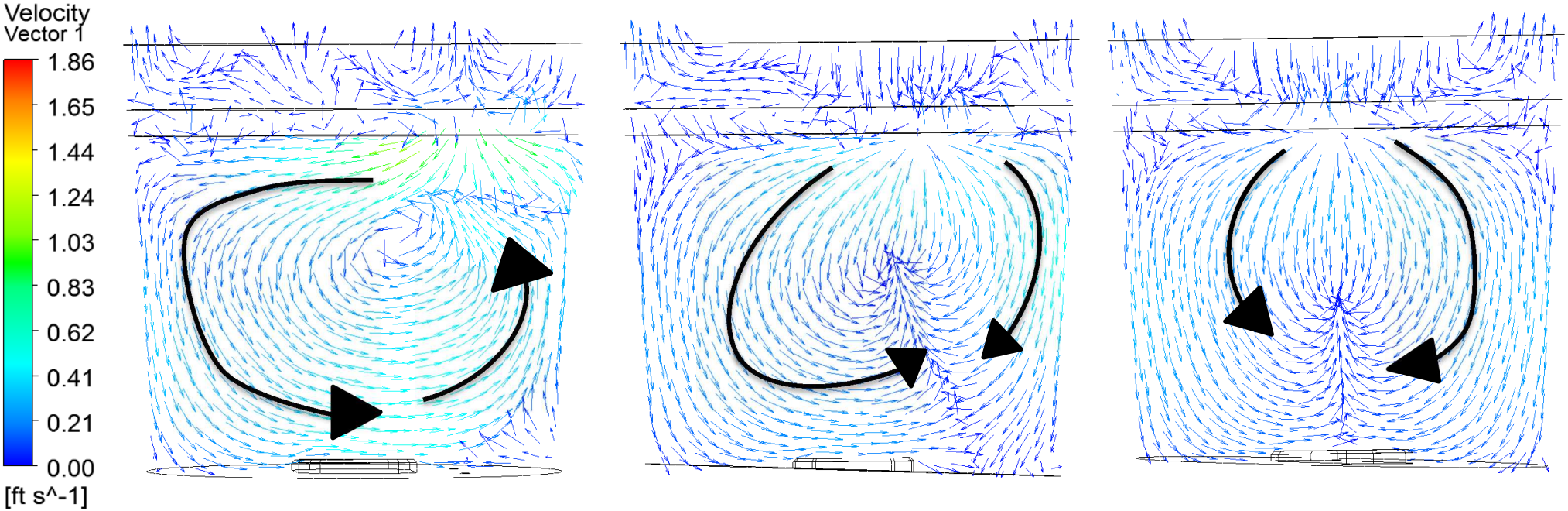
- Case 4 (60°)



- Case 5 (120°)

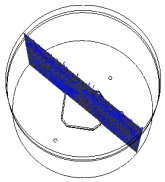


- Case 1 (180°)

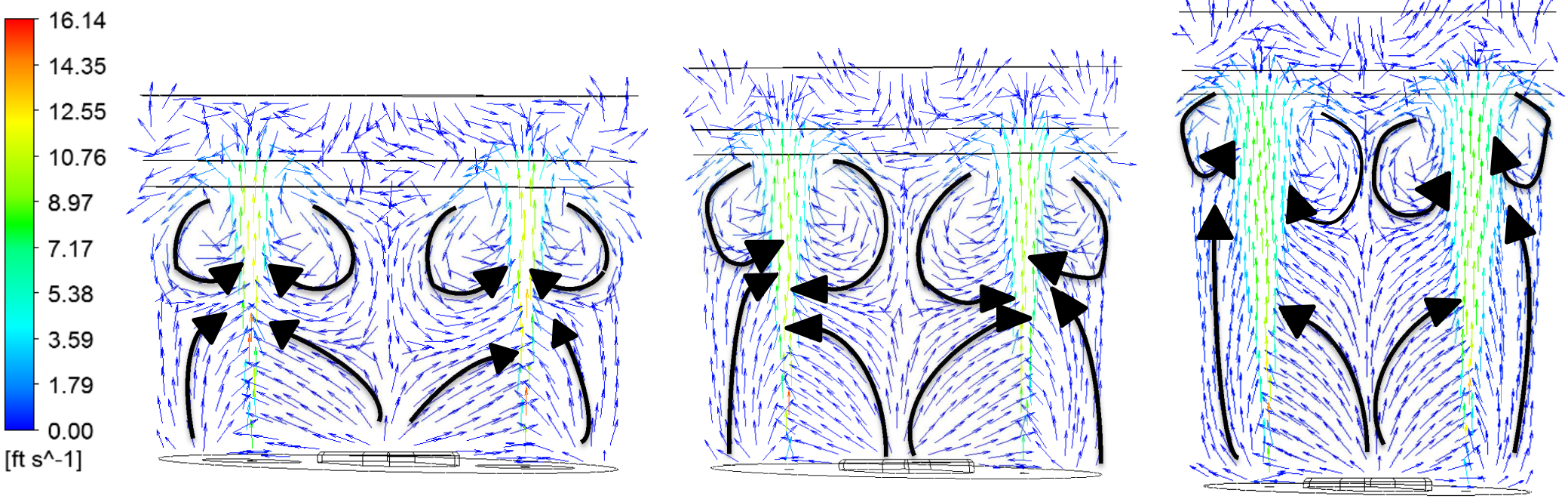


- Separation angle of 60° and 120° creates non-symmetric flow.

EFFECTS OF LADLE ASPECT RATIO

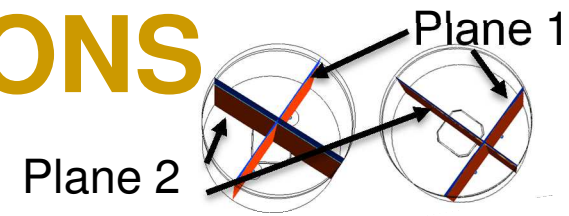


- Case 9 ($\frac{H}{D}$=0.6)
- Case 1 ($\frac{H}{D}$=0.8)
- Case 10 ($\frac{H}{D}$=1.2)



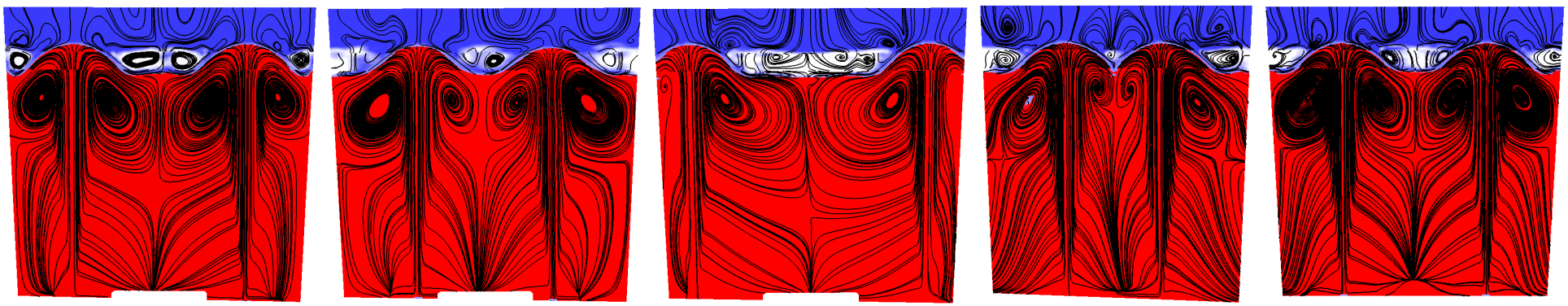
- Larger ladle aspect ratio allows the bubbles buoyant potential energy to increase.
- Larger ladle aspect ratio creates more spreadout and wider plume at the top region of ladle

EFFECT OF PLUG LOCATIONS



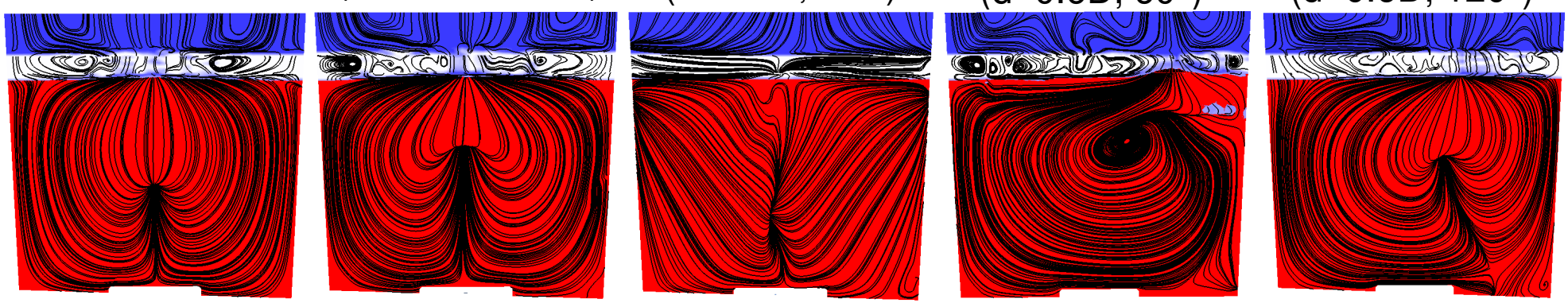
- Streamline on different planes

- Case 1 (d=0.6D, 180°)
- Case 2 (d=0.47D, 180°)
- Case 3 (d=0.8D, 180°)
- Case 4 (d=0.6D, 60°)
- Case 5 (d=0.6D , 120°)



Plane 1 (cross plugs)

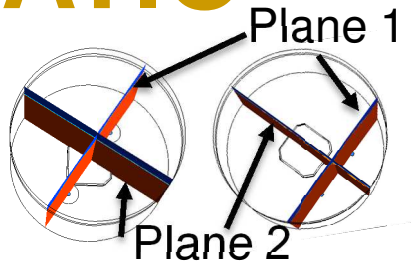
- Case 1 (d=0.6D, 180°)
- Case 2 (d=0.47D, 180°)
- Case 3 (d=0.8D,180°)
- Case 4 (d=0.6D, 60°)
- Case 5 (d=0.6D, 120°)



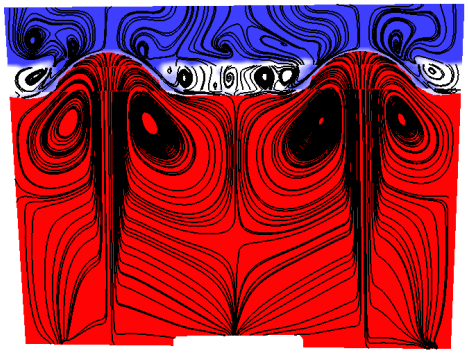
Plane 2 (normal to plane 1)

EFFECT OF LADLE ASPECT RATIO

- Streamline on different planes

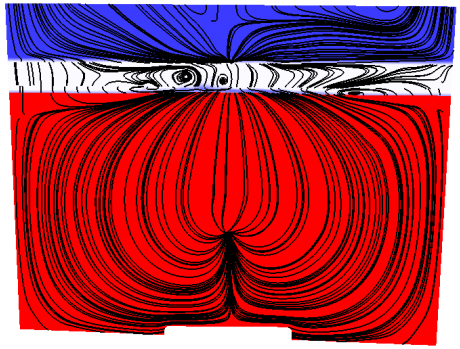


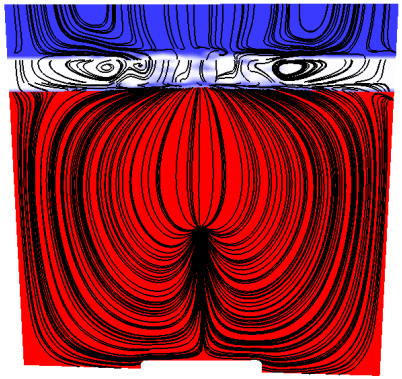
- Case 9 ($\frac{H}{D} = 0.6$)
- Case 1 ($\frac{H}{D} = 0.8$)
- Case 10 ($\frac{H}{D} = 1.2$)

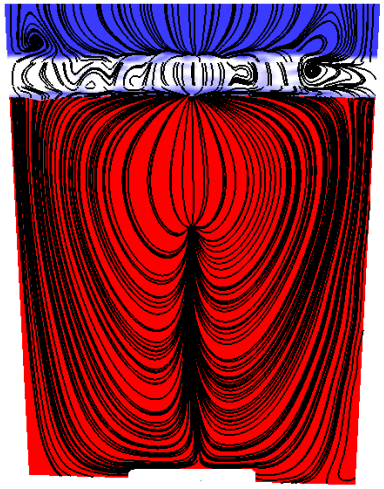


Plane 1
(cross plugs)

- Case 9 ($\frac{H}{D} = 0.6$)
- Case 1 ($\frac{H}{D} = 0.8$)
- Case 10 ($\frac{H}{D} = 1.2$)



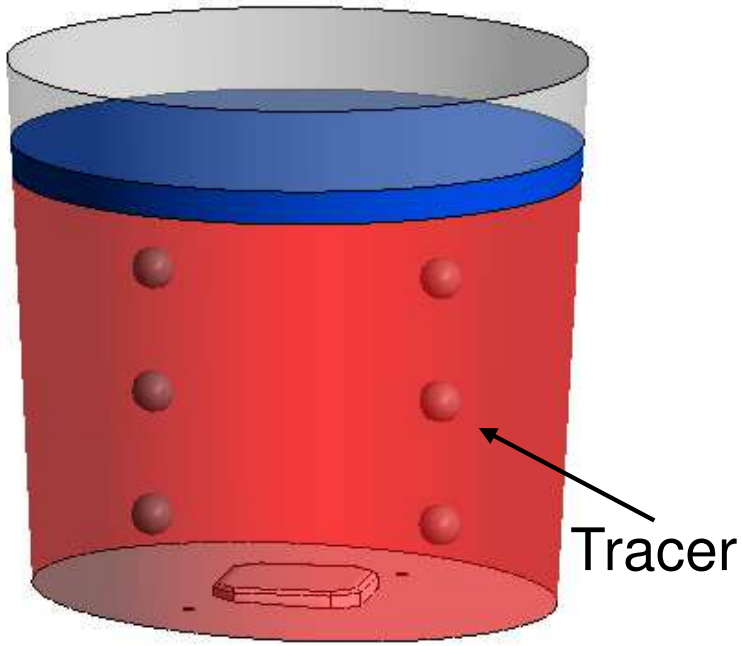




Plane 2
(normal to plane1)

MIXING PROCESS-METHODOLOGY

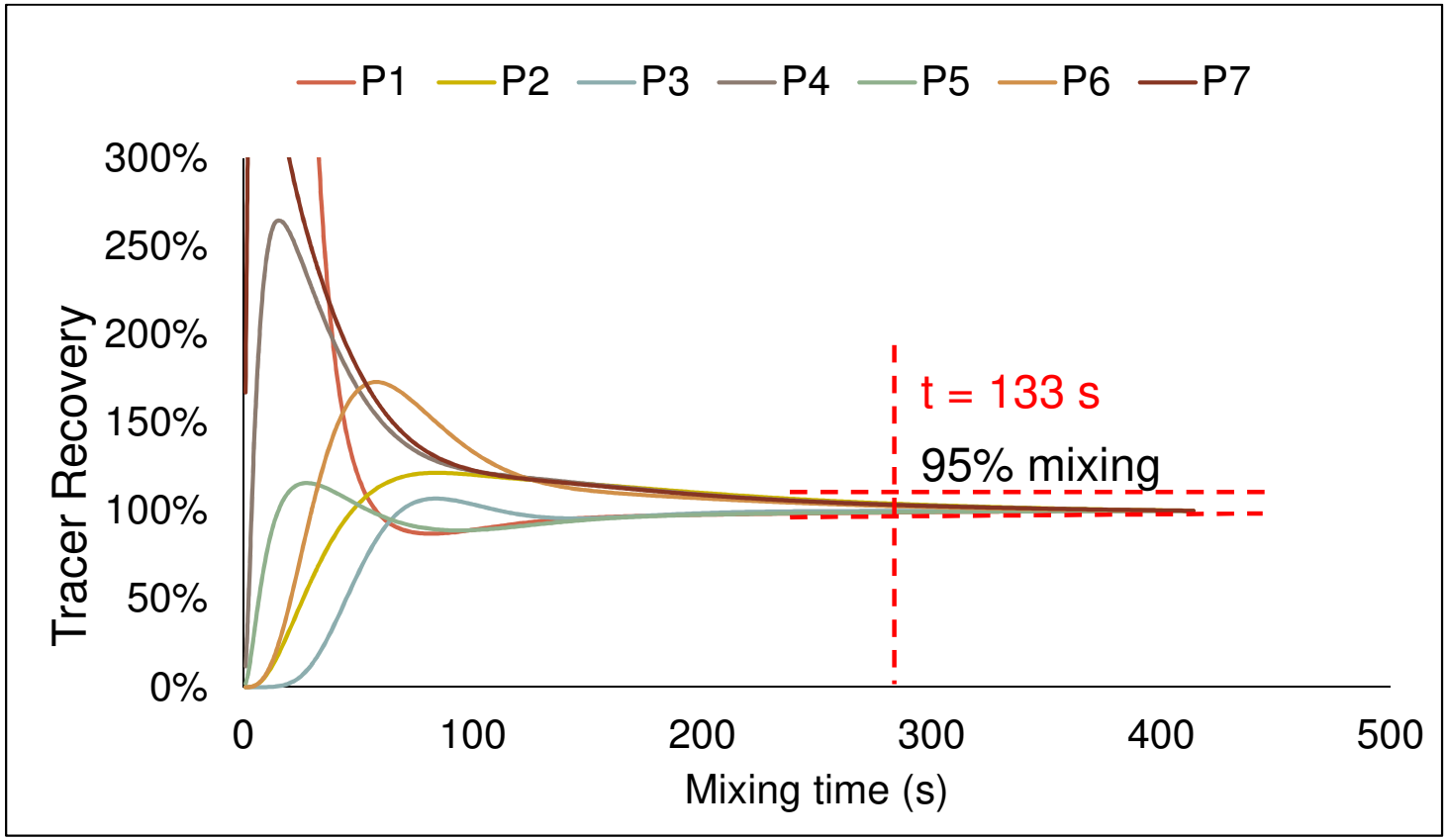
- The flow reached quasi-steady state.
- Six tracers are introduced in the ladle
- Tracer recovery was calculated.
- The mixing time is defined as the time of attaining a 95% degree of homogenization.

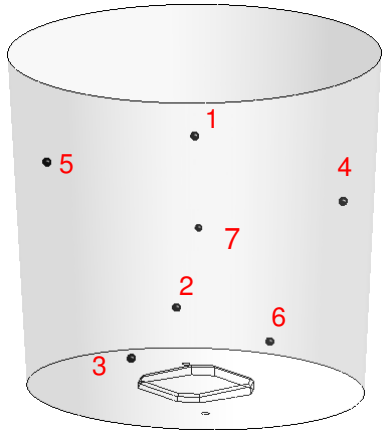


Tracer recovery(%) = Current tracer concentration / Equilibrium tracer concentration

MIXING TIME

Mixing time for base case

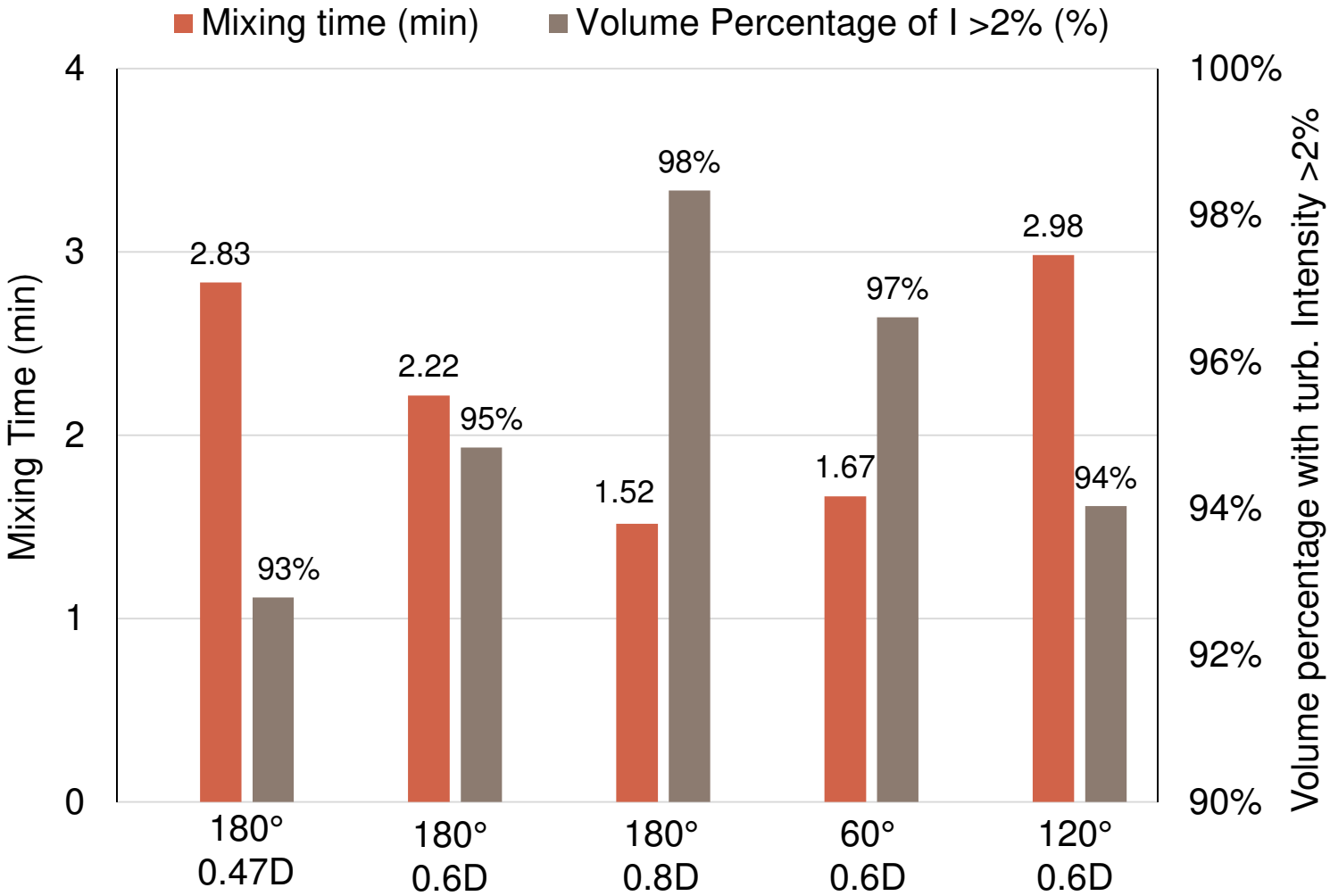




Point 1 (0, 2.8, 0)
Point 2 (-1, 1.5, 1)
Point 3 (0, 0.4, -1)
Point 4 (1, 2.2, 1)
Point 5 (-1, 2.5, -1)
Point 6 (0.5, 0.8, 0.5)
Point 7 (0, 2, 0)

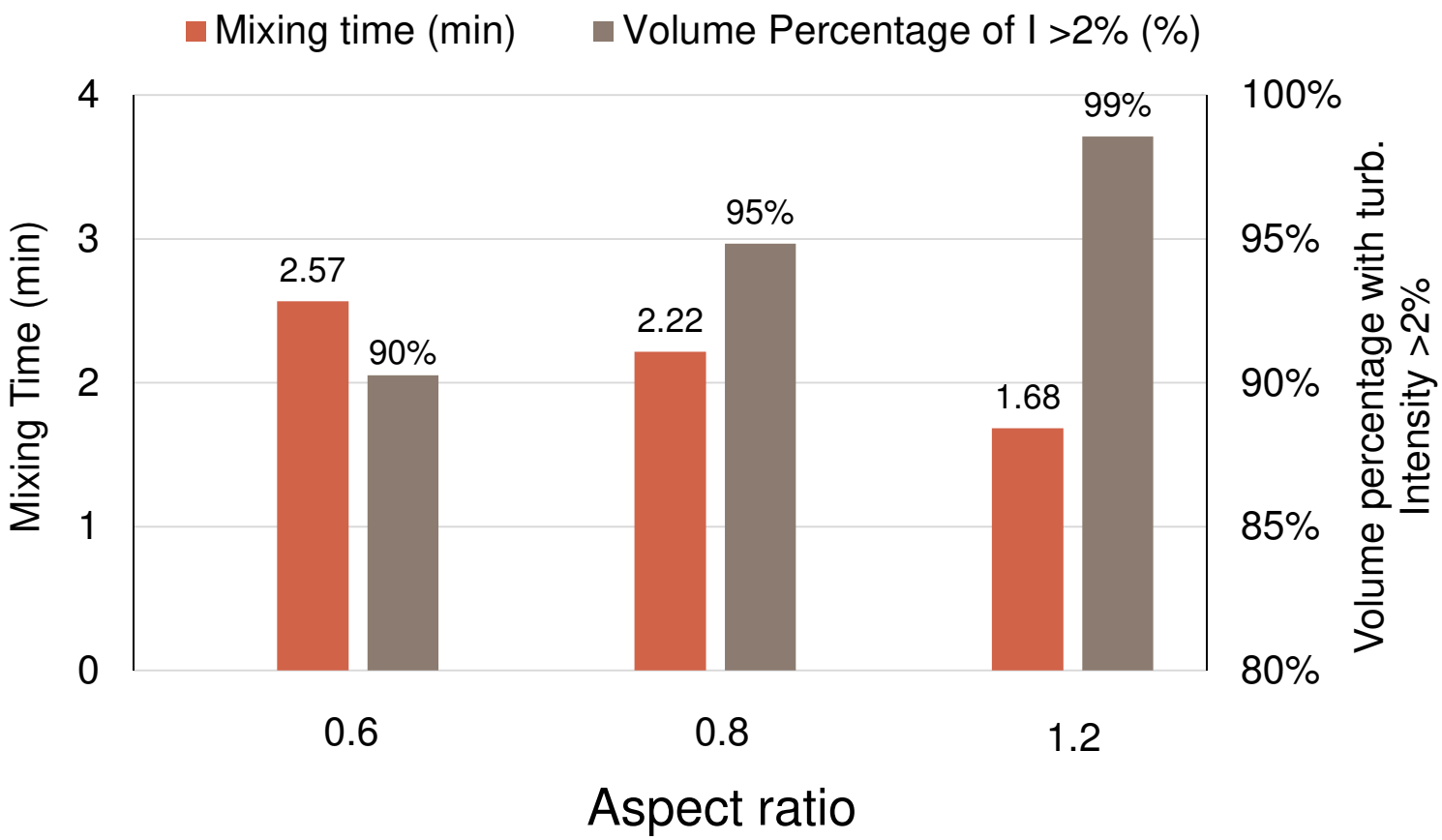
- All point locations reach 95% mixing in 133s

EFFECT OF PLUG LOCATION



- For 180° separation angle, mixing time is lowest at distance ratio of 0.8 (case 3).
- For 0.6D distance ratio, the mixing time first increases from 60° separation angle then decreases from 120°

EFFECT OF LADLE ASPECT RATIO



- Mixing time decreases with the increase of turbulence intensity.
- Taller ladle can promote the mixing process.

HEAT TRANSFER

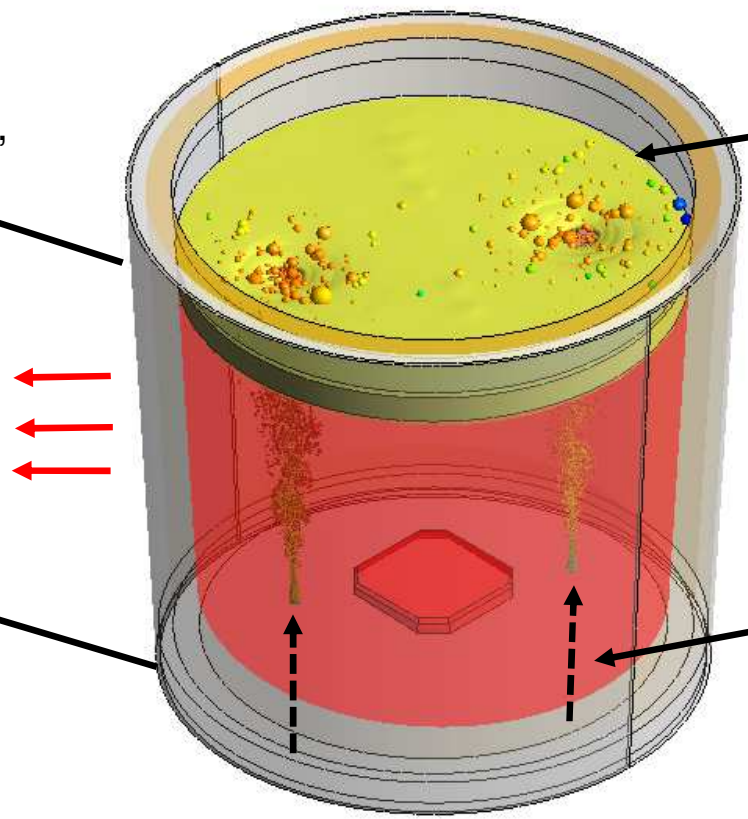
BOUNDARY CONDITIONS

Side wall

- **Exterior free convection**, $h_{side} = 7.82 \frac{W}{m^2.K}$
- **External radiation**, $\varepsilon = 0.5$

Bottom wall

- **Exterior free convection**, $h_{bottom} = 2.29 \frac{W}{m^2.K}$
- **External radiation**, $\varepsilon = 0.5$



Pressure outlet

$T_{back\ flow} = 300\ K$

Argon gas injection

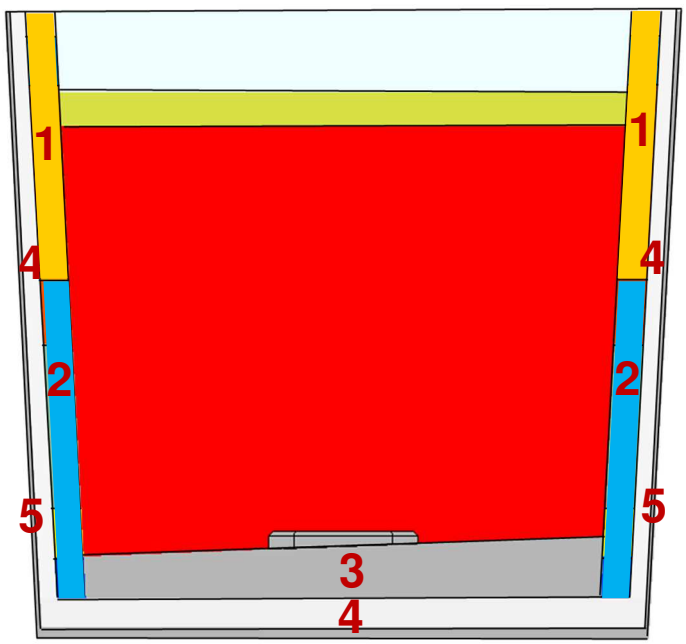
$Q = 5\ SCFM$

External heat transfer coefficient is based on correlation: $\overline{Nu} = \frac{\bar{h}_{side}L}{k} = 0.1Ra_L^{\frac{1}{3}}$ and $\overline{Nu} = \frac{\bar{h}_{bottom}L}{k} = 0.27Ra_L^{\frac{1}{4}}$

- C. Y. Warner and V. S. Arpaci. "An experimental investigation of turbulent natural convection in air at low pressure along a vertical heated flat plate." *International Journal of Heat and Mass Transfer* 11.3 (1968): 397-406.
- F. J. Bayley "An analysis of turbulent free-convection heat-transfer." *Proceedings of the Institution of Mechanical Engineers* 169.1 (1955): 361-370.
- W. H. McAdams, Heat Transmission, 3rd ed., McGraw Hill, New York, 1954, Chap. 7

MATERIAL PROPERTIES

- Solid wall properties



	Wall Material	Density (kg/m^3)	Specific Heat (J/kg-K)	Thermal Conductivity (W/m-K)
1	Upper slag refractory	3280	1099.6	6.37
2	Lower refractory	2912	1816.7	4.411
3	Bottom refractory	3088	1152	3.52
4	Backup lining	2100	1200	1.87
5	Steel	7800	470	52

- C. Tetrault et. al., “CFD Analysis of Thermal Behavior of Refarctory in Steel Ladle Cycling AISTech 2004 Proceedings - Volume I AISTech 2004 Proceedings - Volume I,” *AISTech - Iron Steel Technol. Conf. Proc.*, vol. I, pp. 1205–1214, 2004.
- J. L. Xia and T. Ahokainen, “Transient flow and heat transfer in a steelmaking ladle during the holding period,” *Metall. Mater. Trans. B*, vol. 32, no. 4, pp. 733–741, 2001.

MATERIAL PROPERTIES

- Fluid properties

Material	Density (kg/m^3)	Specific Heat (J/kg-K)	Thermal Conductivity (W/m-K)	Viscosity (kg/m-s)
Air	1.2	f(T)	f(T)	1.7894e-05
Slag	2785.96	787	0.044	0.094
Molten steel	f(T)	787	30	0.0062
Argon gas	f(T,P)	520.64	-	-

- B. Glaser and D. Sichen, “Thermal conductivity measurements of ladle slag using transient hot wire method,” *Metall. Mater. Trans. B Process Metall. Mater. Process. Sci.*, vol. 44, no. 1, pp. 1–4, 2013
- J.L. Xia and T. Ahokainen, “ Homogenization of Temperature Field in a Steelmaking Ladle with Gas Injection”, *Scandianavian J. Metall.*, vol. 32, pp. 211–217, 2003.
- C. E. Grip et. al., “Numerical Prediction and Experimental Verification of Thermal Stratification during Holding in Pilot Plant and Production Ladles,” *ISIJ Int.*, vol. 39, pp. 715–721, 1999.
- A. Jauhiainen, L. Jonsson, P. Jonsson and S. Eriksson,"The influence of stirring method on hydrogen removal during ladle treatment." *steel research international* 73.3 (2002): 82-90.

WALLS' INITIAL CONDITION

- Two initial temperature estimations (ladle's walls only):
  - **Cold ladle** (immediately after preheater): $T_{ambient}$ = 1200 K
  - **Hot ladle** (after contact with metal during processing and casting): $T_{ambient}$ = 1525 K
- Heat transfer through ladle wall is simulated using estimated inner wall forced convection with initial constant temperature.

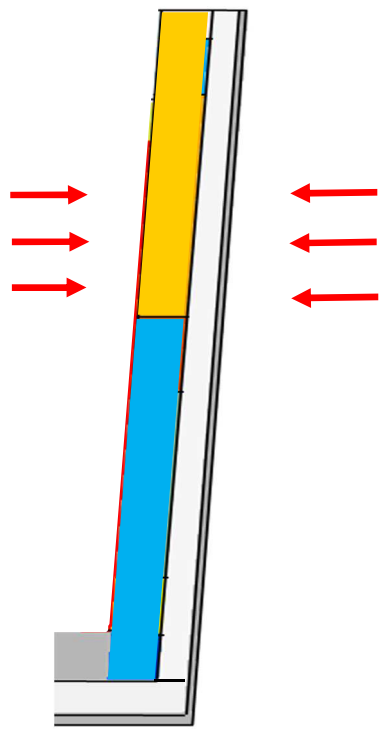
Inner wall

- **Interior forced convection**,

$$h_{side} = 3000\ \frac{W}{m^2.K}$$

$$h_{bottom} = 3000\ \frac{W}{m^2.K}$$

- $T_{ambient}$ = 1200 K / 1525 K



Bottom and side wall

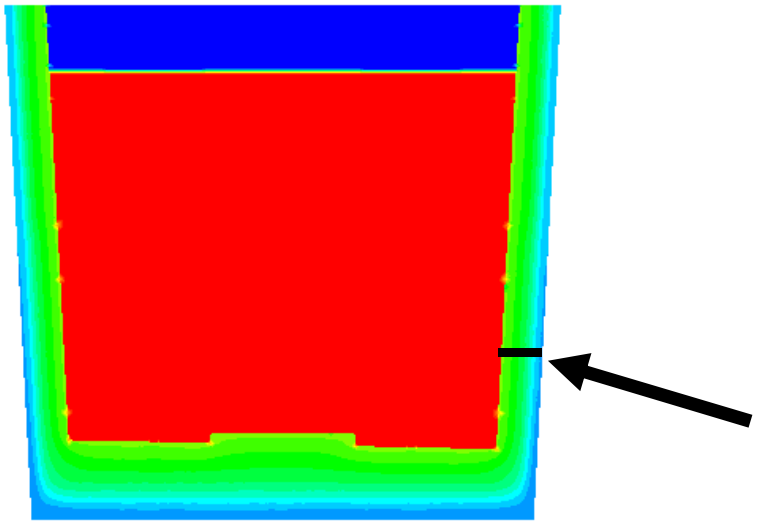
- **Exterior free convection**,

$$h_{side} = 7.82\ \frac{W}{m^2.K}$$

$$h_{bottom} = 2.29\ \frac{W}{m^2.K}$$

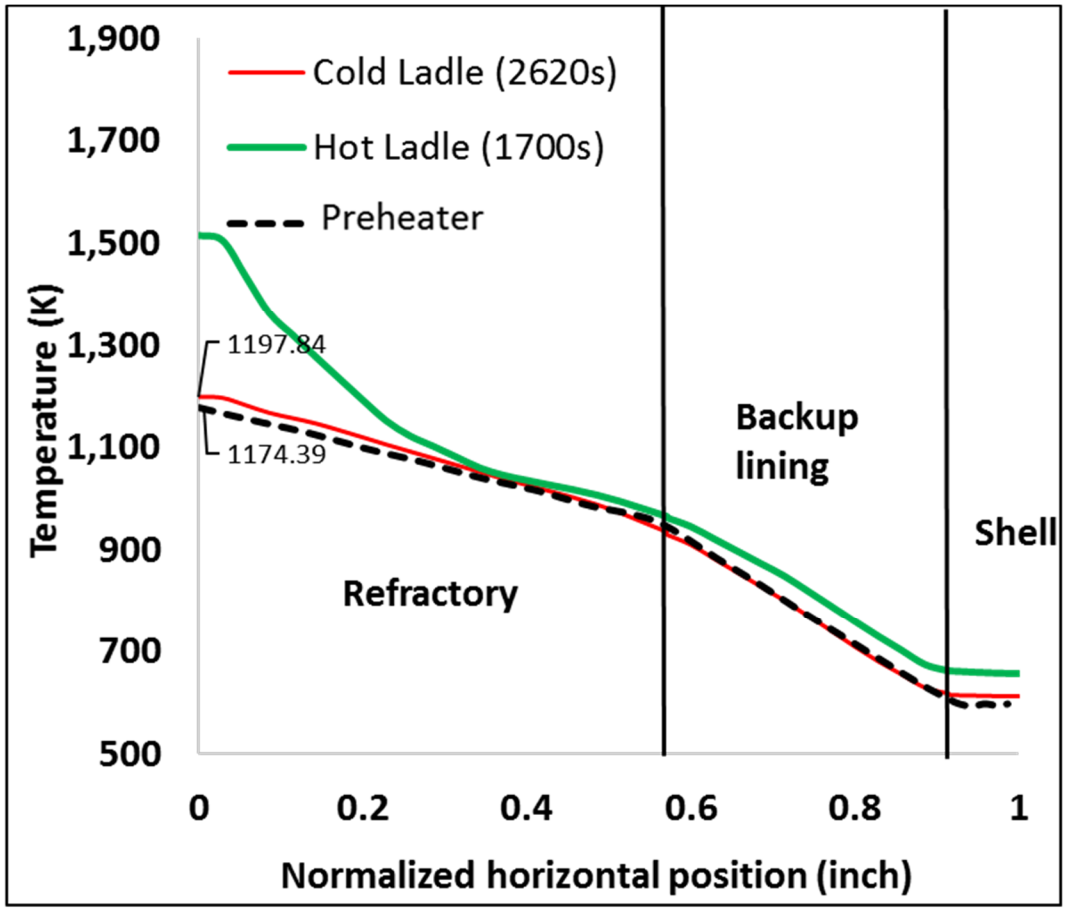
- **External radiation**, $\varepsilon = 0.5$
- $T_{ambient}$ = 300 K

INITIAL TEMPERATURE



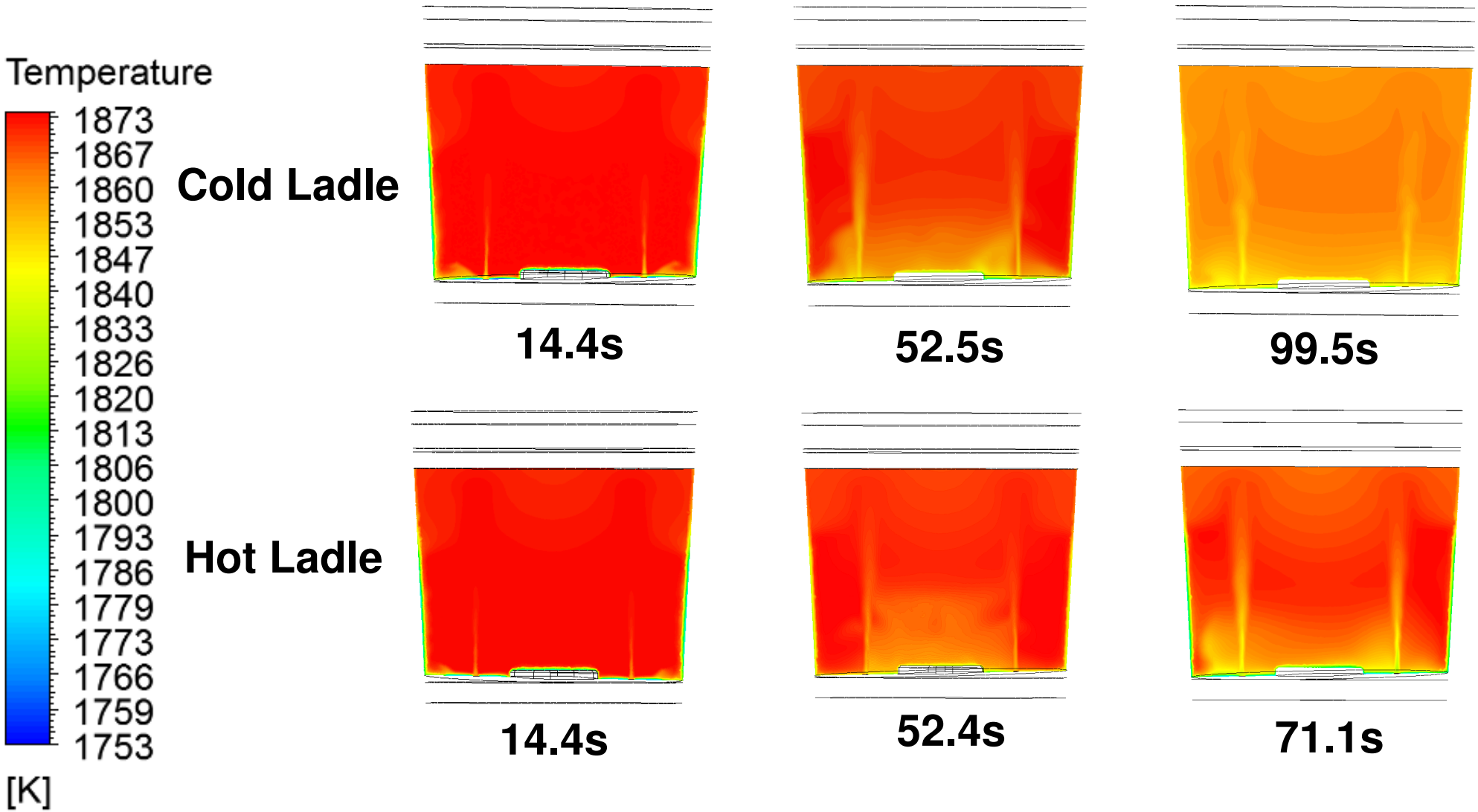
Domain	Initial temperature (K)
Air	300
Slag	1875
Molten steel	1875
Argon gas	300

Side wall temperature profile



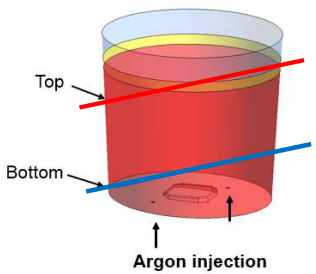
Interior temperature profile after preheater is assumed from Nucor

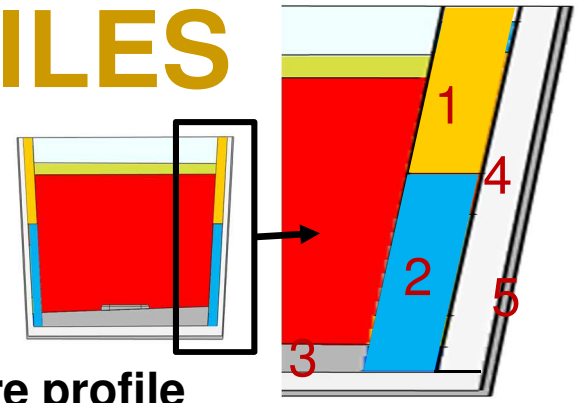
TEMPERATURE RESULTS



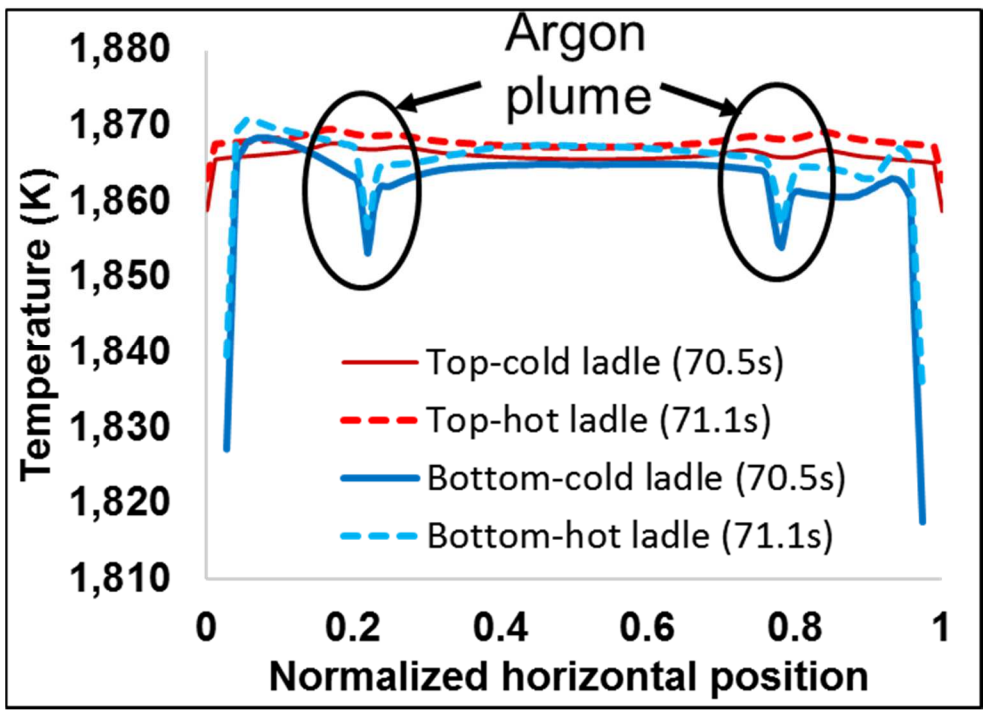
- Heat is lost through top surface and through side wall.
- Liquid steel temperature is slowly destratified due to stirring.

TEMPERATURE PROFILES

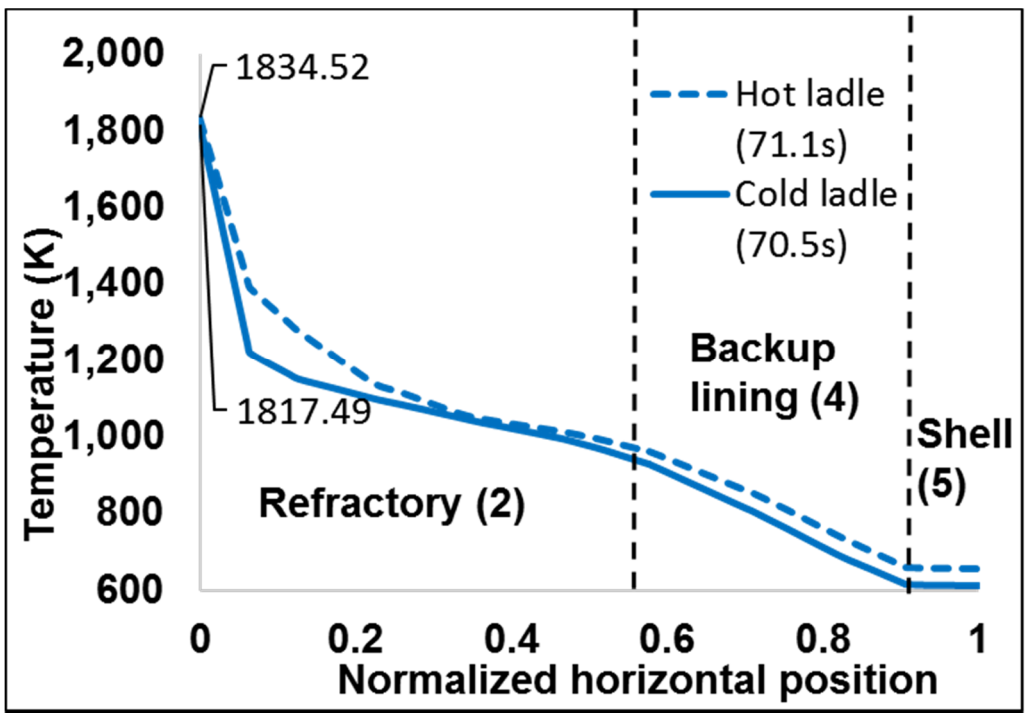




Liquid steel temperature profile



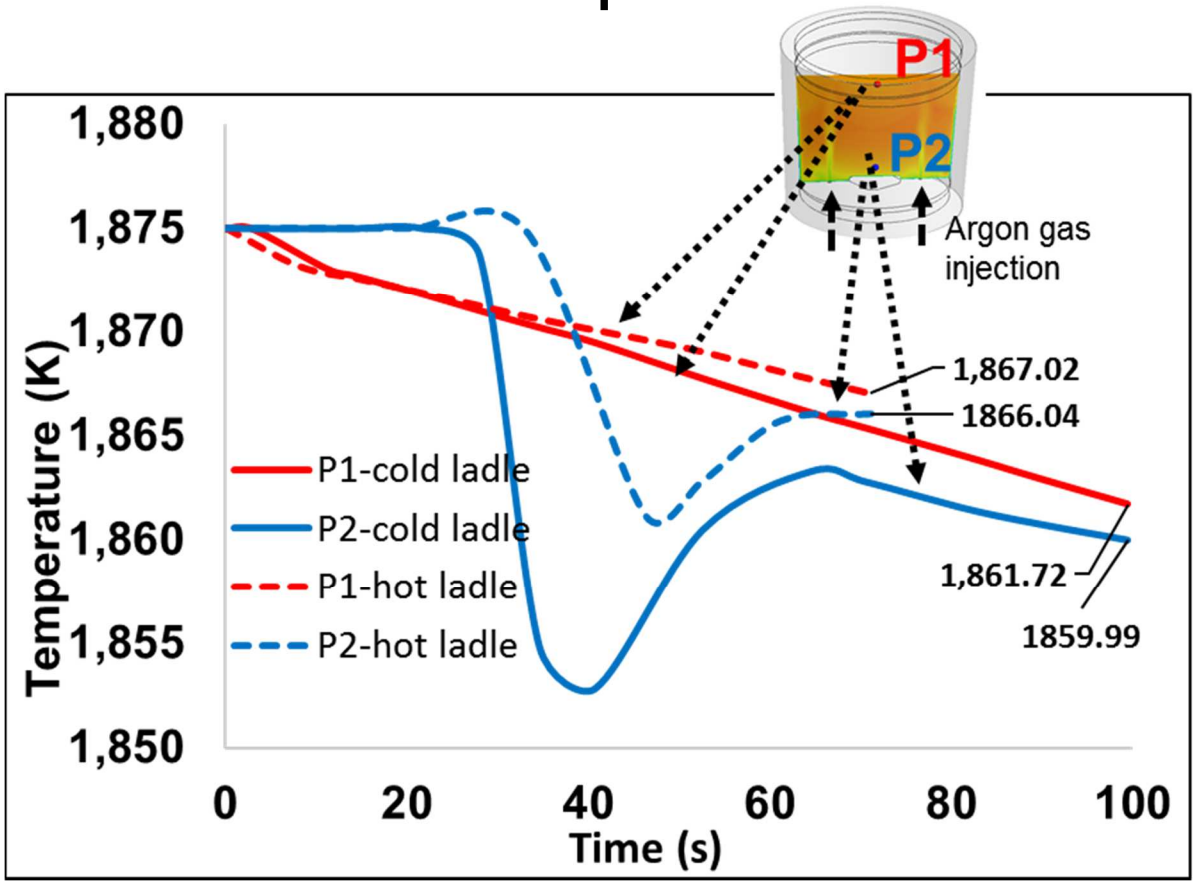
Wall temperature profile

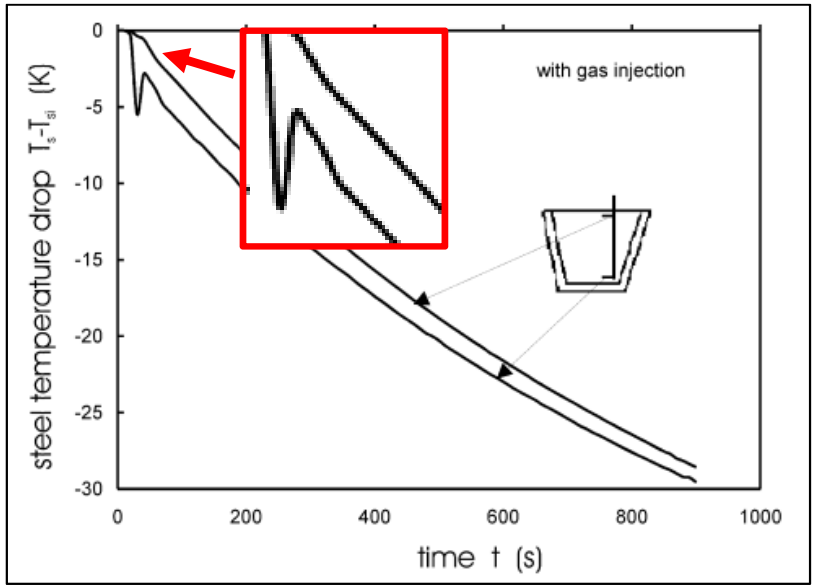


- Top surface has lower near wall temperature gradient compared to bottom region.
- Wall temperature profiles show non-linear temperature drop.

TEMPERATURE STRATIFICATION

Steel temperature measurement at two locations





J. L. Xia and T. Ahokainen (2001)

- Hot ladle de-stratified faster than cold ladle.
- Top region shows higher temperature then bottom region.
- Similar phenomena for temperature at the bottom of ladle is observed from literature.

• J. L. Xia and T. Ahokainen, "Thermal stratification in a steel ladle." Canadian metallurgical quarterly 40.4 (2001): 479-487.

SUMMARY OF GAS STIRRED LADLE

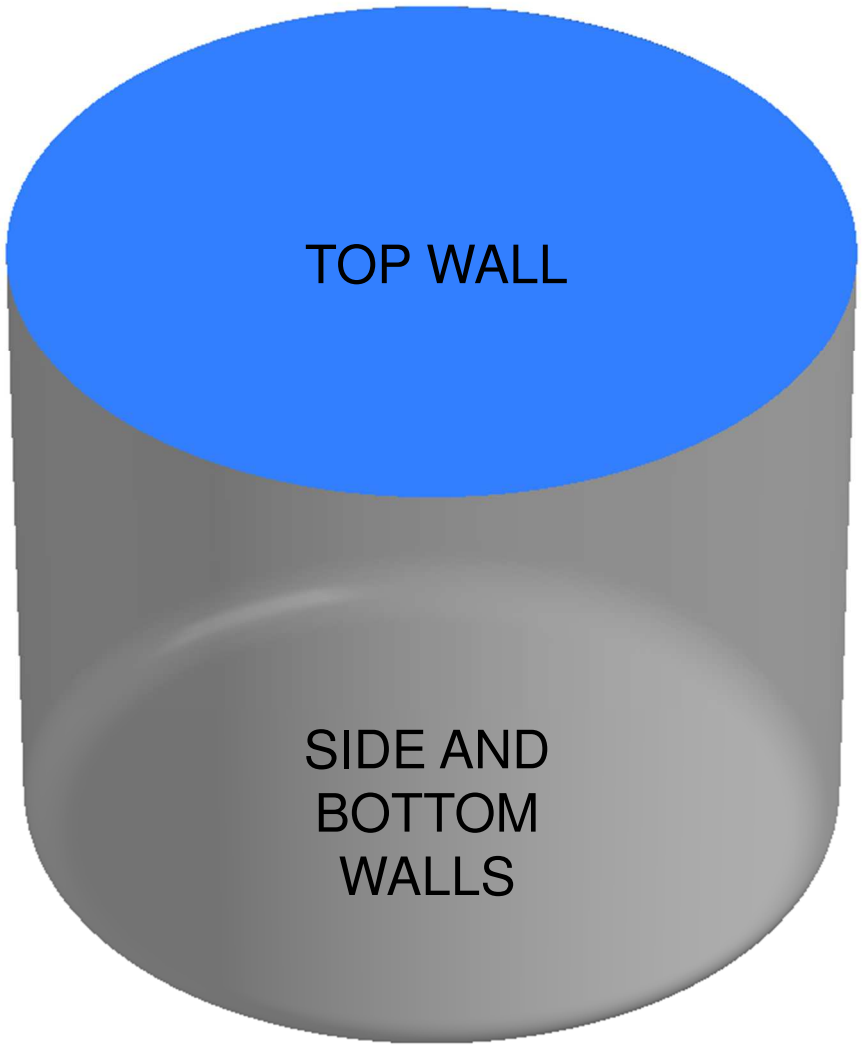
- Parametric study on changing injection plug location and aspect ratio have been performed.
- Effect of plugs radial location and their separation angle on the slag eyes and mixing time are studied.
- For current simulation, each ladle with injection distance ratio of 0.8 and separation angle of 60° show less mixing time.
- Mixing efficiency is improved with increasing ladle aspect ratio.
- Two different non-constant walls initial temperatures are estimated and used as initial wall temperature conditions for heat transfer model.
- Argon gas helps reduce temperature drop near to the wall at the upper region of ladle.
- Lower initial wall temperature shows more temperature drop (more heat loss) at the bottom region.
- Temperature stratification in the ladle is reducing with time.

EMS LADLE MODEL

INITIAL GEOMETRY & MODEL

- Nucor ladle geometry, Single phase, no gas injection
- Transient 3D simulation (0.2s/step)
- Spalart-Allmaras 1-eqn turbulence model
- Energy off
- Magnetic Induction MHD model

- Top Wall: Slip wall
- Side and Bottom Walls: no-slip
- Vessel Dimensions:
  - Diameter: ~3.3m to 3.8m
  - Height: ~3.6m



Melt Material:

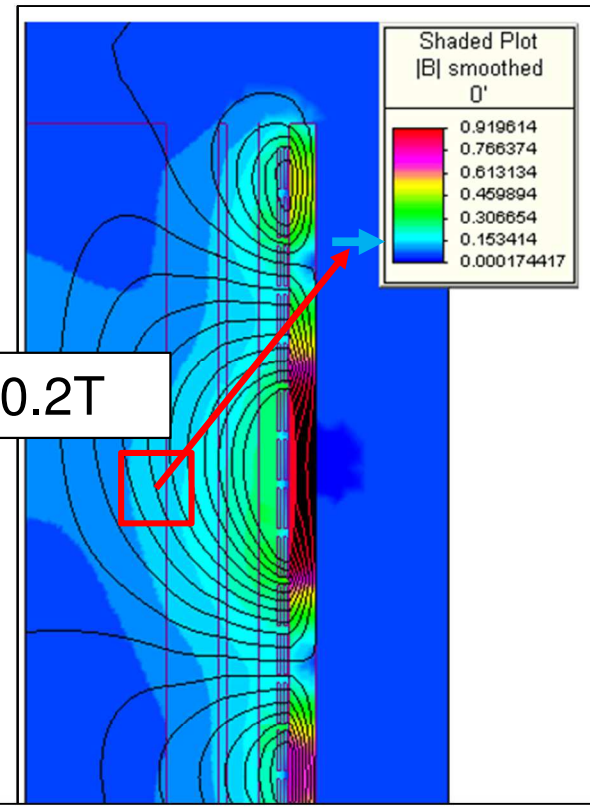
Parameter	Value
Density	7200 kg/m3
Viscosity	6.5e-3 kg/m.s
Conductivity	6.99e6 S/m
Magnetic Permeability (mu)	1.26e-4 h/m

MHD CONDITIONS

- Some magnetic field conditions approximated from provided data
  - PPT regarding ladle stirring system
- Simulation calculates Lorentz Force
- MHD Boundary Conditions:
- Top wall – Conducting
- Side/bottom walls – Thin wall, 1.5”

- AC Field:
  - Moving field (wavelength 3.6m, (0,1,0) vector (upwards)
  - Frequency 1.5 Hz
  - B0 Components:
    - (0.2, 0, 0.2) T
  - X-Z field direction chosen to create “rotating magnetic field”

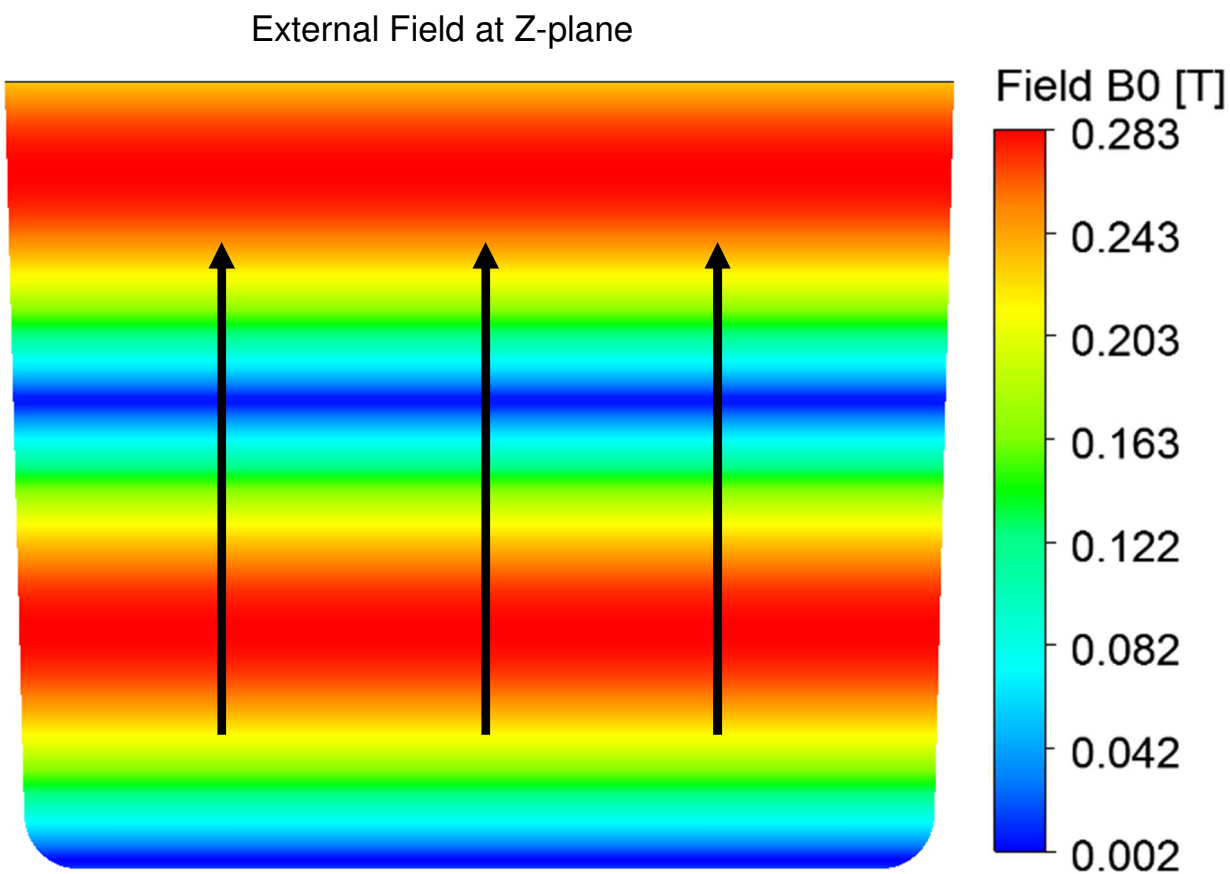
Info from PPT



Based upon the assumptions made on the thickness of the ladle SS wall at 1.5”, it appears that for an ORT 1824 the optimum stirring frequency would be in the neighborhood of 1.5Hz…..per FAL this is in the ball park of where the unit was designed to run

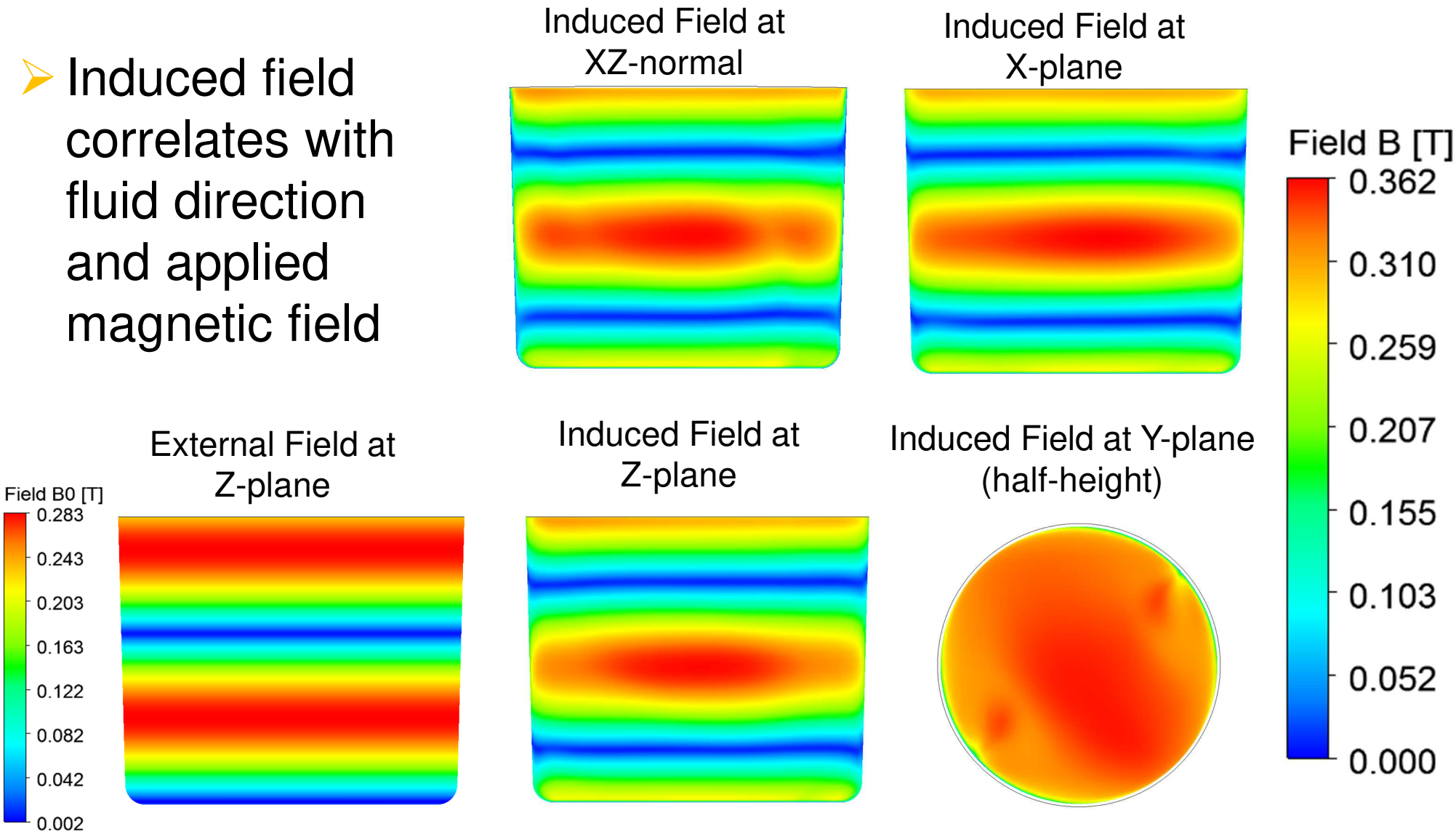
APPLIED MAGNETIC FIELD

- Field patched in using Fluent module
- Applied magnetic field only varies in the y (vertical) direction.
- Field cycles with a wavelength of 3.6m (slightly taller than the ladle)

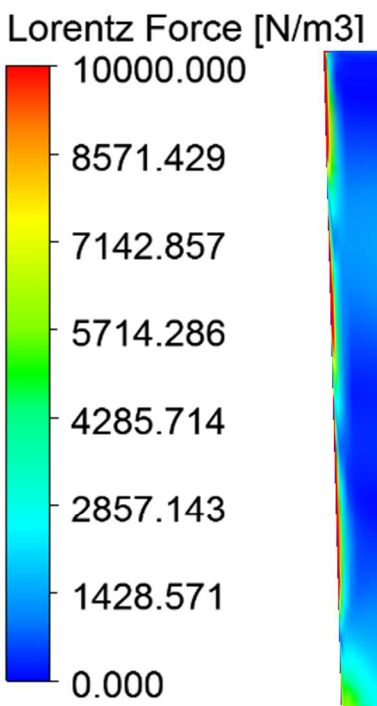


RESULTS – INDUCED MAGNETIC FIELD

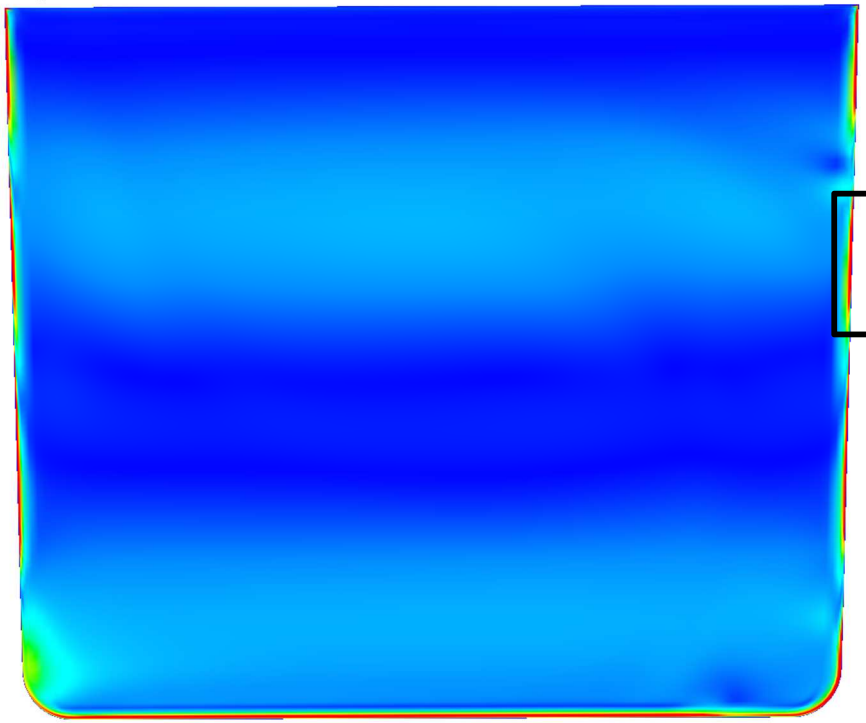
- Induced field correlates with fluid direction and applied magnetic field

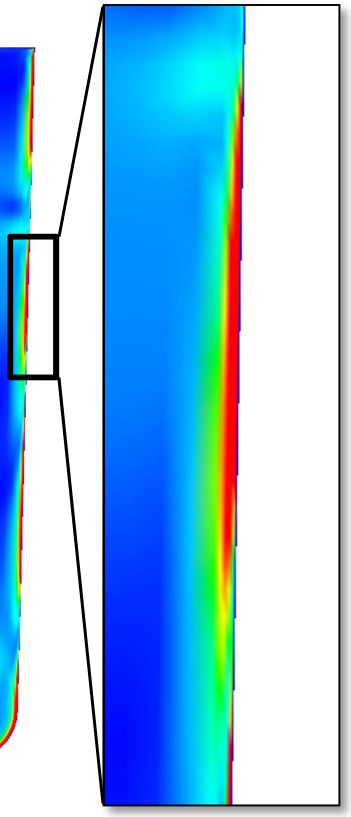


RESULTS LORENTZ FORCE

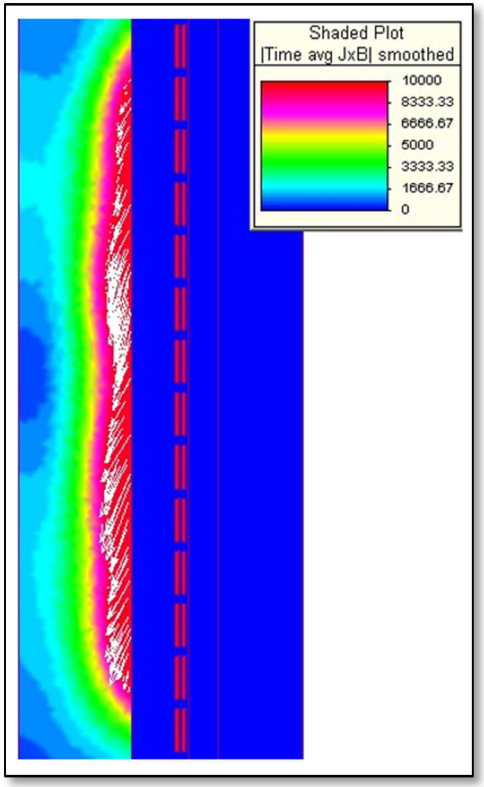


Force at XZ-normal

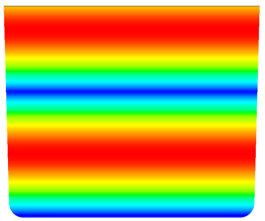




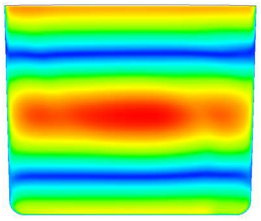
Force from PPT



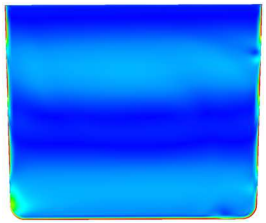
- Lorentz forces highest at near-wall regions
- Force has “banding” pattern, correlating to induced and applied B fields



Applied B0

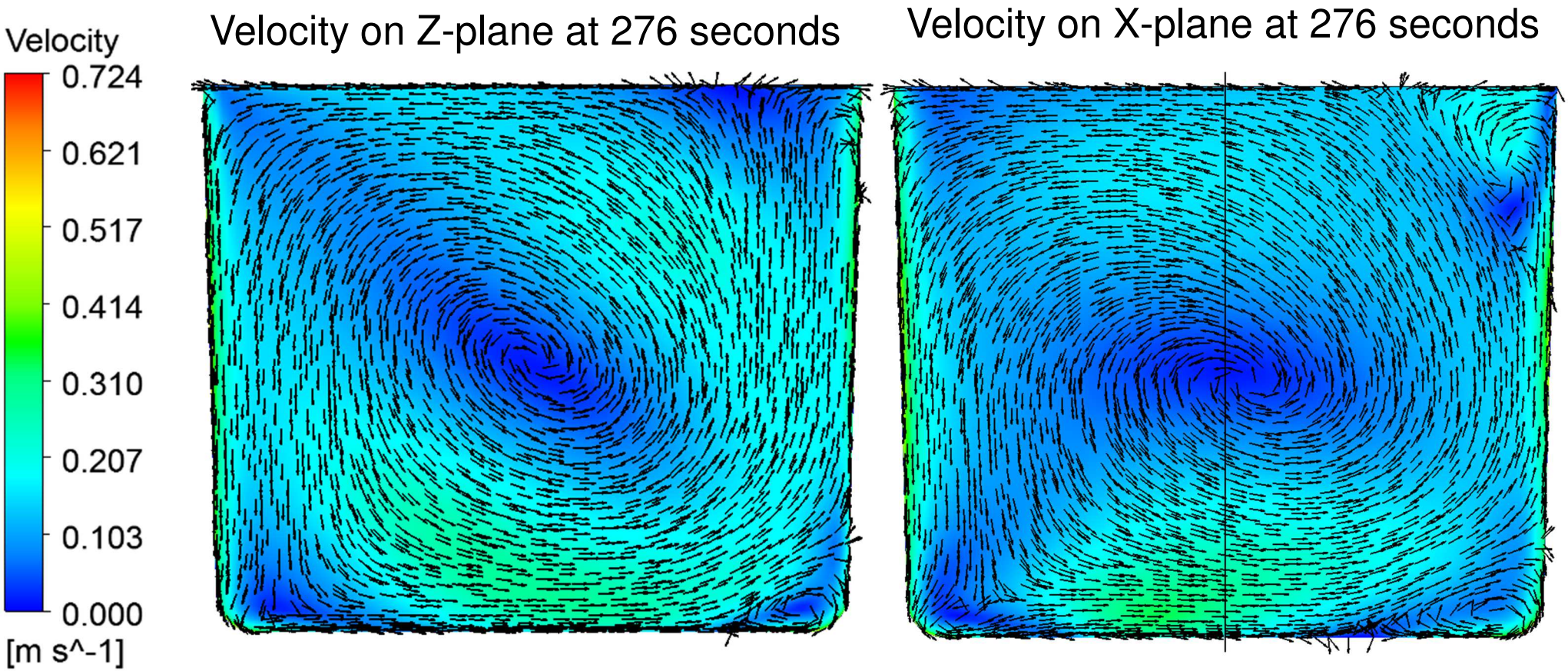


Induced B



Lorentz Force

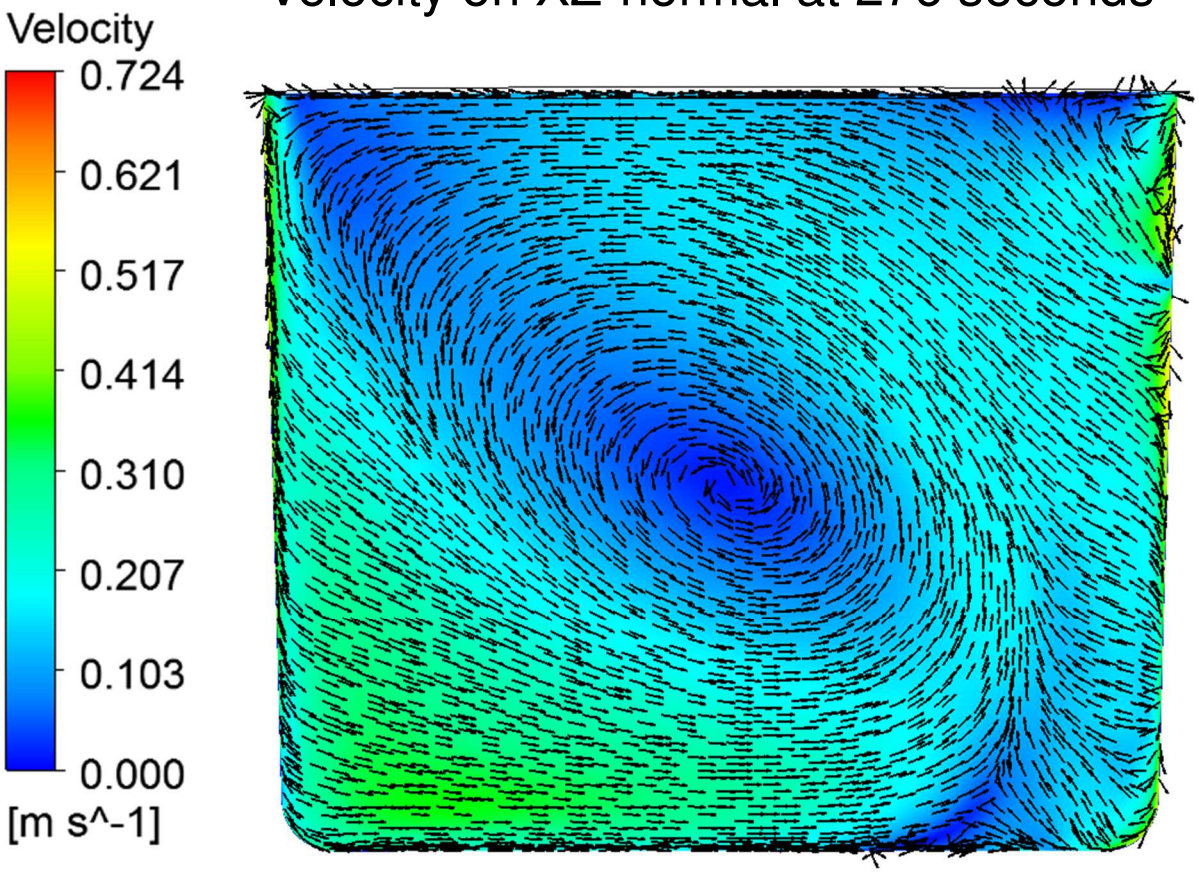
RESULTS - VELOCITY FIELD



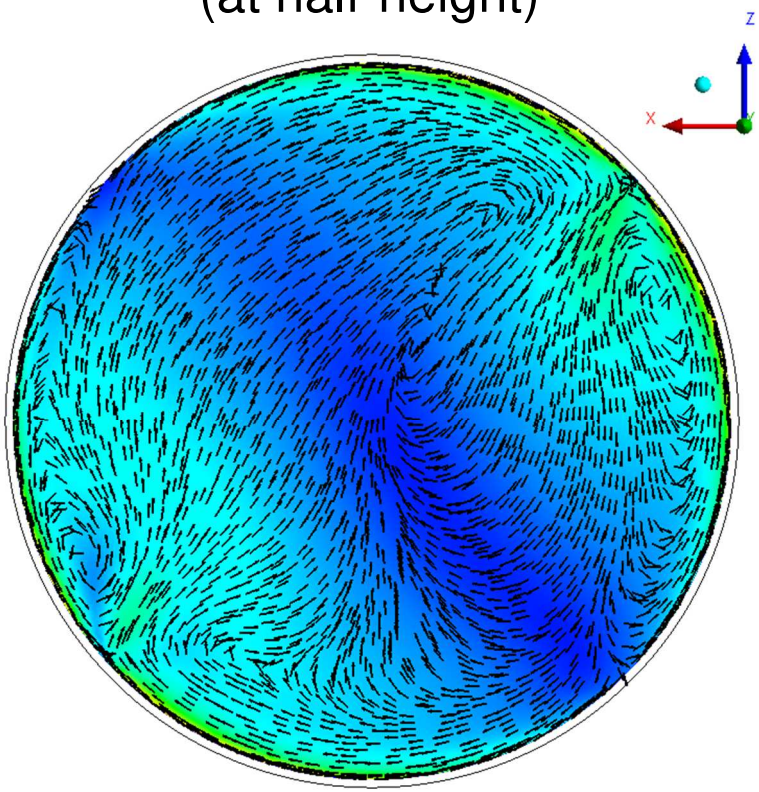
- Applied magnetic field creates ladle-wide recirculation

RESULTS - VELOCITY FIELD

Velocity on XZ-normal at 276 seconds

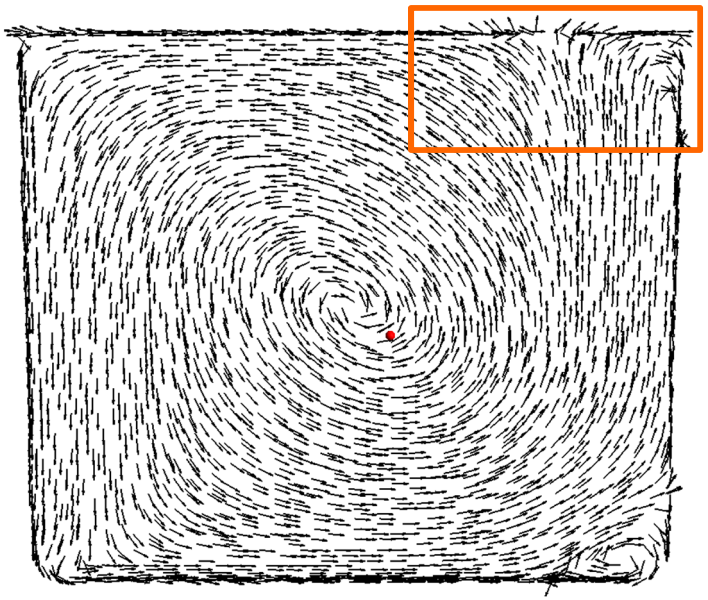


Velocity on Y-plane at 276 seconds (at half-height)



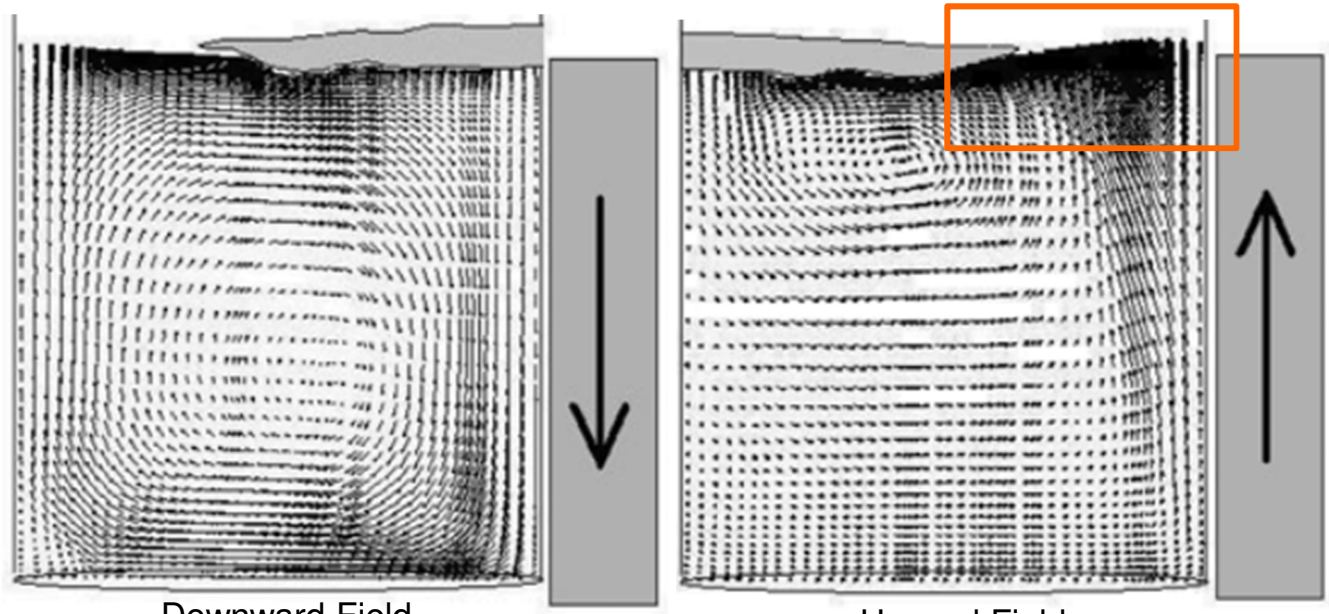
LITERATURE COMPARISON

Our Simulation



Upward Field

From literature



Downward Field

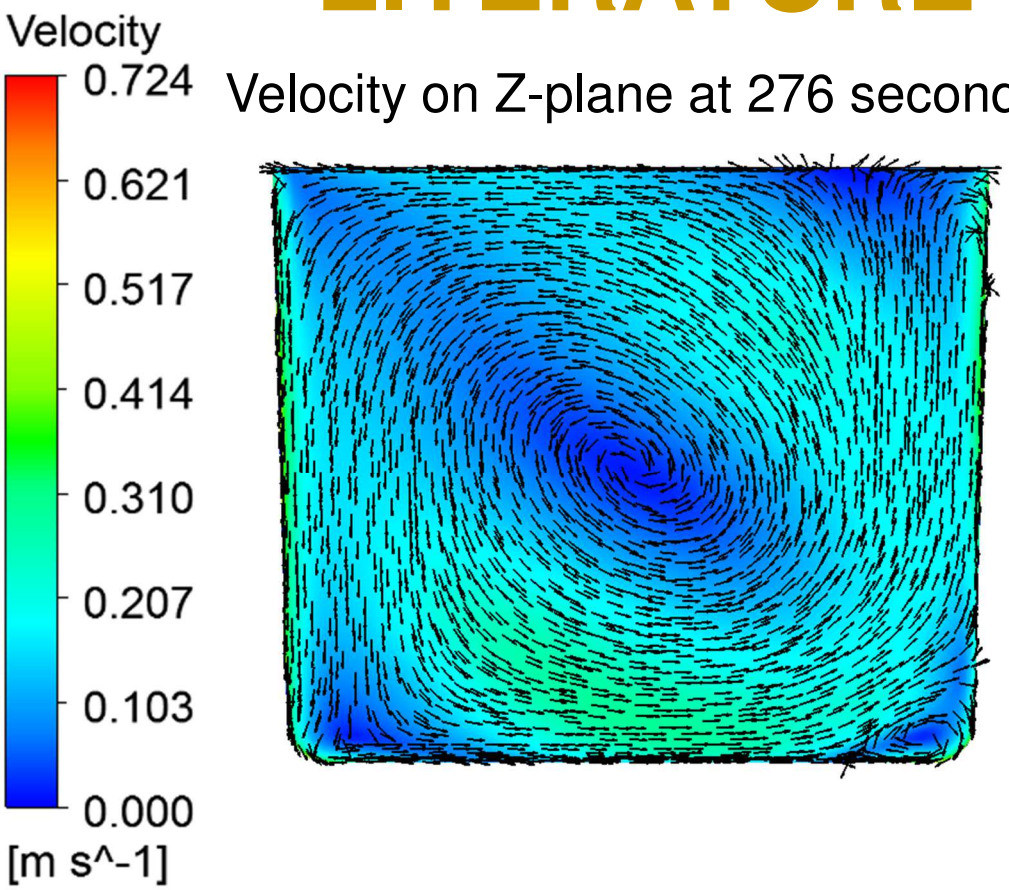
Upward Field

- Simulation shows similar trend as literature by stirring unit manufacturer
- Trend more closely matches downward field from literature, likely due to lack of free surface in our simulation
- Simulation shows upwards vectors where eye exists on literature free surface

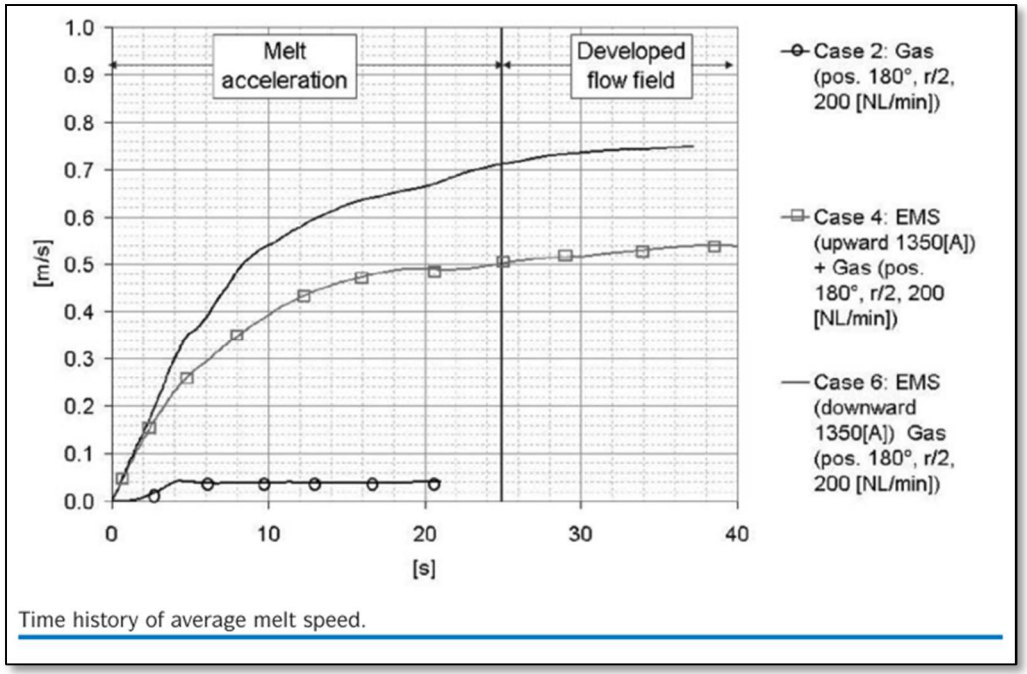
U. Sand, H. Yang, J.-E. Eriksson, and R. B. Fdhila, “Control of Gas Bubbles and Slag Layer in a Ladle Furnace by Electromagnetic Stirring,” *Iron Steel Technol.*, no. July 2009, 2009.

LITERATURE COMPARISON

Velocity on Z-plane at 276 seconds



From [1]



Time history of average melt speed.

- Magnitude of velocities correlate with time-averaged values from literature
- Simulation slower to develop, likely due to nature of patched-in field

[1] U. Sand, H. Yang, J.-E. Eriksson, and R. B. Fdhila, “Control of Gas Bubbles and Slag Layer in a Ladle Furnace by Electromagnetic Stirring,” *Iron Steel Technol.*, no. July 2009, 2009.

EMS STIRRING – FUTURE PLANS

1. **Addition of free surface**
   - Free surface introduces momentum sink as seen in literature, altering flow field greatly
   - Allows examination of potential eye formation from stirring
2. **Use of imported magnetic field**
   - Imported field based on provided information from stirring unit manufacturer or field samples
   - Current field “patched-in”, actual field will better provide more realistic flow development rate and patterns

POTENTIAL ECONOMIC BENEFITS

- Cost saving for operation process by optimizing mixing efficiency - Alloy cost saving from increased alloy recovery rate, improve inclusion removal rate and by increasing in number of heat
- Cost saving in reducing failure during casting process (nozzle clogging)
- Improve the quality of steel by improving steel cleanliness
- Energy saving for control of temperature

$$\varepsilon = 0.5$$
$$T_{steel} = 1753\ K$$
$$T_{air} = 500\ K$$
$$A = 9.6\ m^2$$

- $Q = \varepsilon\sigma\left(T_{steel}^4 - T_{air}^4\right) = 175\,\frac{kW}{m^2}$
- Total heat loss/year = Q*A*45mins holding time/day*360 days/year = $454\mathrm{MWh}$
- Cost of energy loss = 454 MWh * 0.0836 USD/kWh ≈ 40000 USD per heat

F.J. Ahualli, J.G. Sagasti, S. Meyer and F. Memoli, "Physical Ladle Tracking", AISTech 2014 Proceedings,vol. 2, pp. 1567–1576, Warrendale, PA.;2014.

CONCLUSION

- Parametric study on changing injection plug location and ladle aspect ratio have been performed.
- For current simulation, each ladle with injection distance ratio of 0.8 and separation angle of 60° show less mixing time.
- Mixing efficiency is improved with increasing ladle aspect ratio.
- Heat transfer model for gas-stirred ladle has been developed with two different estimate non-constant walls initial temperatures profile.
- Lower initial wall temperature shows more temperature drop (more heat loss) at the bottom region.
- Temperature stratification in the ladle is reducing with time.
- Temperature stratification for hot ladle is smaller compared with cold ladle
- Electromagnetic stirring creates recirculation region across entire ladle, avoiding isolated regions seen in gas-stirring method.

FUTURE WORK – YEAR 3

- Validate the models by plant data.
- Develop and modify DPM-VOF coupled model
  - Desulfurization and deoxidation
  - Numerical model for inclusion generation due to chemical reaction
  - Slag/inclusion interaction model
- Further improved EMS ladle model
  - Incorporated industrial magnetic field
  - Validation with industrial data

Thank You
Questions and Comments

MATERIAL PROPERTIES

- Fluid properties

Material	Density (kg/m^3)	Viscosity (kg/m-s)
Slag	2785.96	0.094
Molten steel	7000	0.0062
Argon gas	f(p)	8.535×10^{-5}

- Surface tension

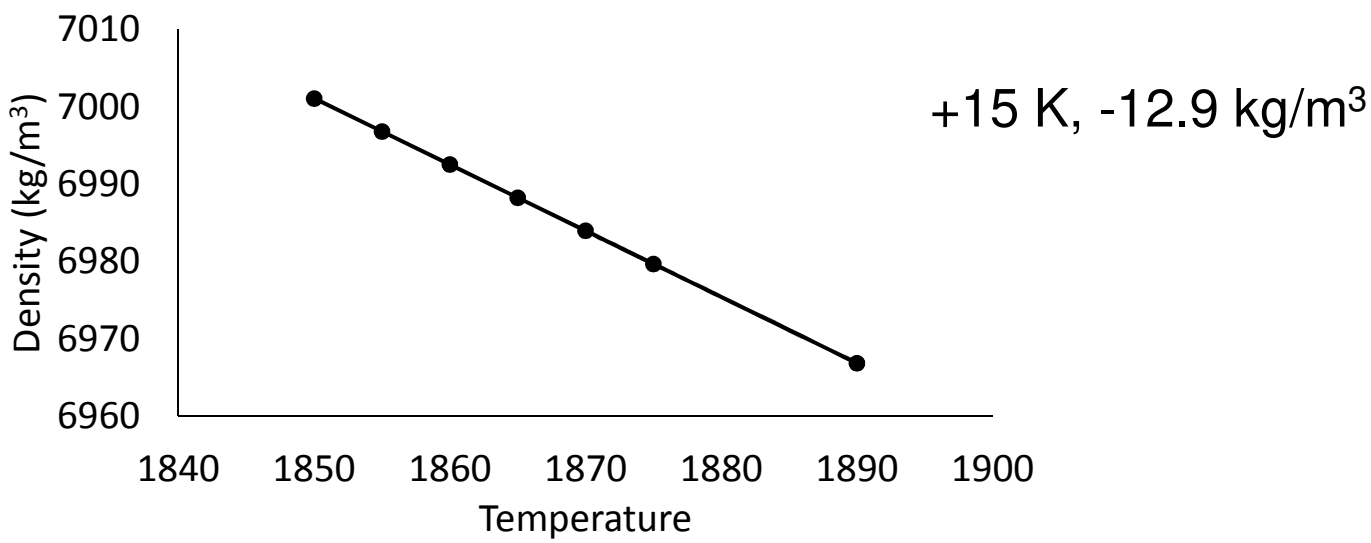
	Surface tension coefficient (N/m)
Melt/Argon	1.823
Melt/Slag	1.15
Slag/Argon	0.58

Heping Liu, Zhenya Qi and Mianguang Xu, "Numerical Simulation of Fluid Flow and Interfacial Behavior in Three-phase Argon-Stirred Ladles with One Plug and Dual Plugs", *Steel research int*, 82(2011), No. 4.

DENSITY

Sources	Density (kg/m^3)	
	Slag	Steel
Current model/ Grip et. al (1999)	2785.96	f(t)

$$\rho = 8586 - 0.8567T$$



C. E. Grip et. al., "Numerical Prediction and Experimental Verification of Thermal Stratification during Holding in Pilot Plant and Production Ladles," *ISIJ Int.*, vol. 39, pp. 715–721, 1999.

SPECIFIC HEAT CAPACITY

Sources	Specific Heat (J/kg-K)	
	Slag	Steel
Austin et. al. (1992)	-	627
Grip et. al. (1999)	-	789
Xia and Ahokainen (2003)	-	787
Tetrault et. al. (2004)	900	910
Ganguly and Chakraborty (2004)	-	787
Jauhiainen (2002)	779.79* (T=1873K)	770 (T=1873K)

Partial molar models

$$C_{p,slag} = (\%CaO)C_{p,CaO} + (\%Al_2O_3)C_{p,Al_2O_3} + (\%MgO)C_{p,MgO} + (\%SiO_2)C_{p,SiO_2}$$

$$C_{p,CaO}, C_{p,Al_2O_3,}, C_{p,MgO}, C_{p,SiO_2} = f(T_s)$$

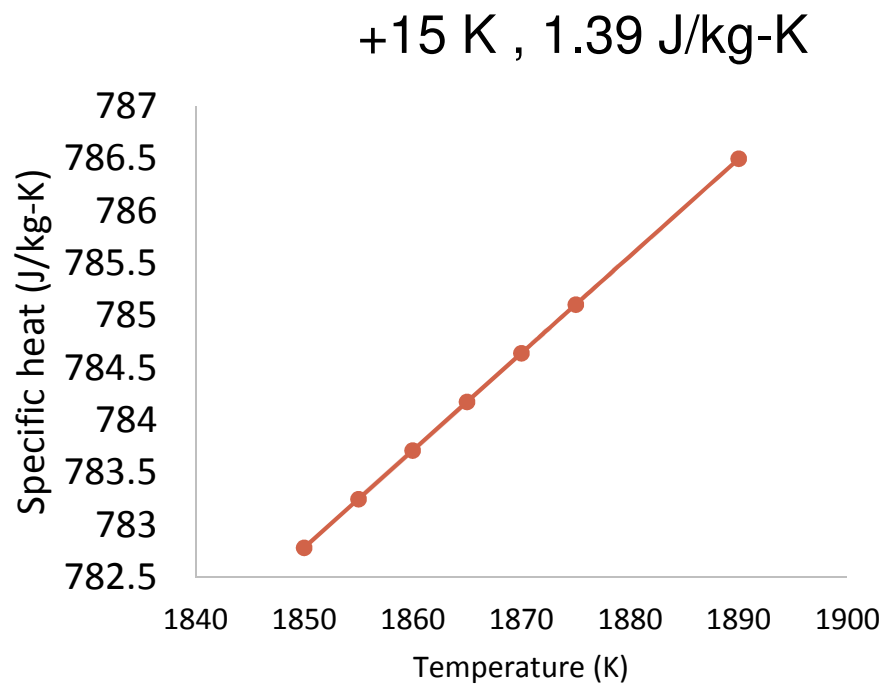
$$C_{p,Fe} = 452.963 + 176.704 * 10^{-3}\mathrm{T} - \frac{482.082 * 10^5}{T^2}$$

*$24\%\ Al_2O_3, 49\%\ CaO, 9\%\ MgO, 17.25\%\ SiO_2$

SPECIFIC HEAT CAPACITY

- Specific heat capacity of slag

Heat	Specific Heat (J/kg-K) @T=1875K
Current model	787
Heat 1	784.92
Heat 2	757.1592
Heat 3	738.68
Heat 4	740
Heat 5	735.372



Jauhiainen (2002)

Partial molar models

$$C_{p,slag} = (\%CaO)C_{p,CaO} + (\%Al_2O_3)C_{p,Al_2O_3} + (\%MgO)C_{p,MgO} + (\%SiO_2)C_{p,SiO_2}$$

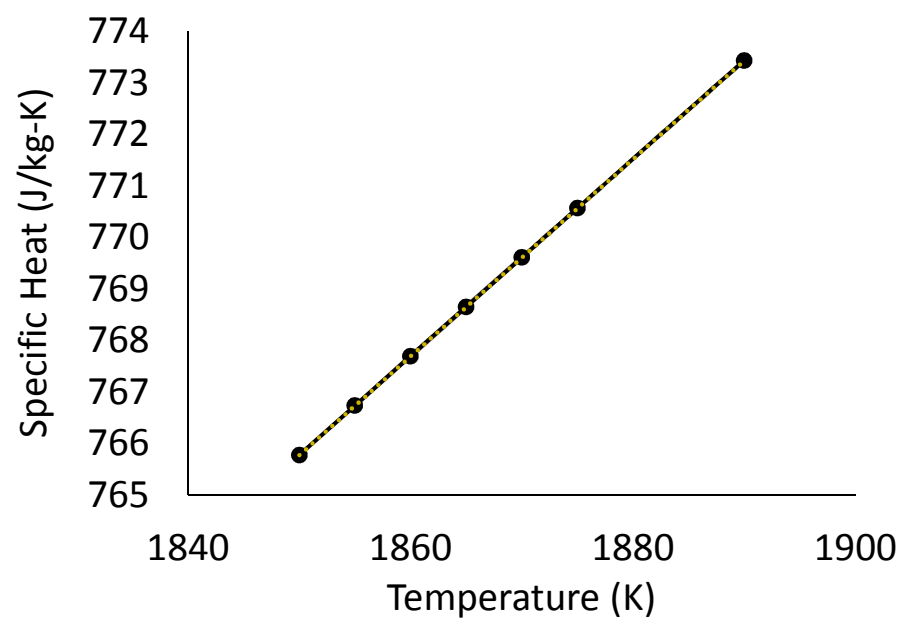
$$C_{p,CaO}, C_{p,Al_2O_3,}, C_{p,MgO}, C_{p,SiO_2} = f(T_s)$$

SPECIFIC HEAT CAPACITY

- Specific heat capacity of steel

Sources	Specific Heat (J/kg-K)
	Steel
Current model	787
Austin et. al. (1992)	627
Grip et. al. (1999)	789
Xia and Ahokainen (2003)	787
Tetrault et. al. (2004)	910
Ganguly and Chakraborty (2004)	787
Jauhiainen (2002)	*770 (T=1873K)

+15°, 2.87J/kg-K



$$^{*}C_{p,Fe} = 452.963 + 176.704 * 10^{-3}\mathrm{T} - \frac{482.082*10^{5}}{T^{2}}$$

THERMAL CONDUCTIVITY

Sources		Thermal Conductivity (W/m-K)		
		Slag		Steel
Current model		0.044		30
Xia and Ahokainen (2003)		-		30
Tetrault et. al. (2004)		14		16.5
Mills (2011)(1)		0.1113 ($\mu_{\text{slag}} = 0.094$)		-
Glaser and Sichen (2013) Slag Composition (%CaO/%MgO/%Al_2O_3/%SiO_2)	39/9/34/18	0.044 (T=1823K)		-
	43/9/43/5	T=1823K	0.095	-
		T=1873K	0.050	-
		T=1923K	0.025	-

(1) Based on relation with viscosity

$$\ln k = -2.178 + 0.282 \ln \mu_{slag}$$

NATURAL CONVECTION HTC

Side Wall

$$\overline{Nu} = \frac{\bar{h}L}{k} = 0.1Ra_L^{\frac{1}{3}} \qquad 10^9 < Ra < 10^{13}$$

$$Ra_L = Gr_L\, Pr = \frac{g\beta(T_s - T_\infty)L_c^3}{\upsilon^2} Pr$$

Gr = Grashof number
Pr = Prandlt number
β = Volumetric thermal expansion coefficient

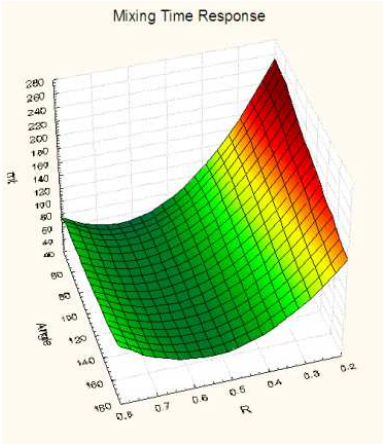
Bottom Wall

$$\overline{Nu} = \frac{\bar{h}L}{k} = 0.27Ra_L^{\frac{1}{4}}$$

C. Y. Warner and V. S. Arpaci. "An experimental investigation of turbulent natural convection in air at low pressure along a vertical heated flat plate." *International Journal of Heat and Mass Transfer* 11.3 (1968): 397-406.
F. J. Bayley "An analysis of turbulent free-convection heat-transfer." *Proceedings of the Institution of Mechanical Engineers* 169.1 (1955): 361-370.
W. H. McAdams, Heat Transmission, 3rd ed., McGraw Hill, New York, 1954, Chap. 7

LITERATURE SEARCH

Sources	Slag thickness (inches)	Plug radial position	Plug separation angle	Flow rate	Trend	Optimum
W. Lou and M. Zhu (2013)	No	0.3R	45°,90°,135°, 180°	7.1 SCFM	@135°, t_{mixing} ↓ from (0.3R – 0.7R) and ↑ (0.7R – 0.8R) @0.5R, t_{mixing} ↓ from (45° - 90°) and then ↑ (90° - 180°)	@0.5R, 90°
H. Liu et. al. (2010)	3.15	0.6875 R	90°, 180°	3.5CFM 7.1CFM 10.6CFM		@3.5CFM, 180° @7.1CFM, 180° @10.6CFM, 90°
Cloete (2008)	7.87	0.217 to 0.7R	40 to 180		t_{mixing} ↓ from (0.2R – 0.6R) and ↑ (0.6R – 0.8R)	

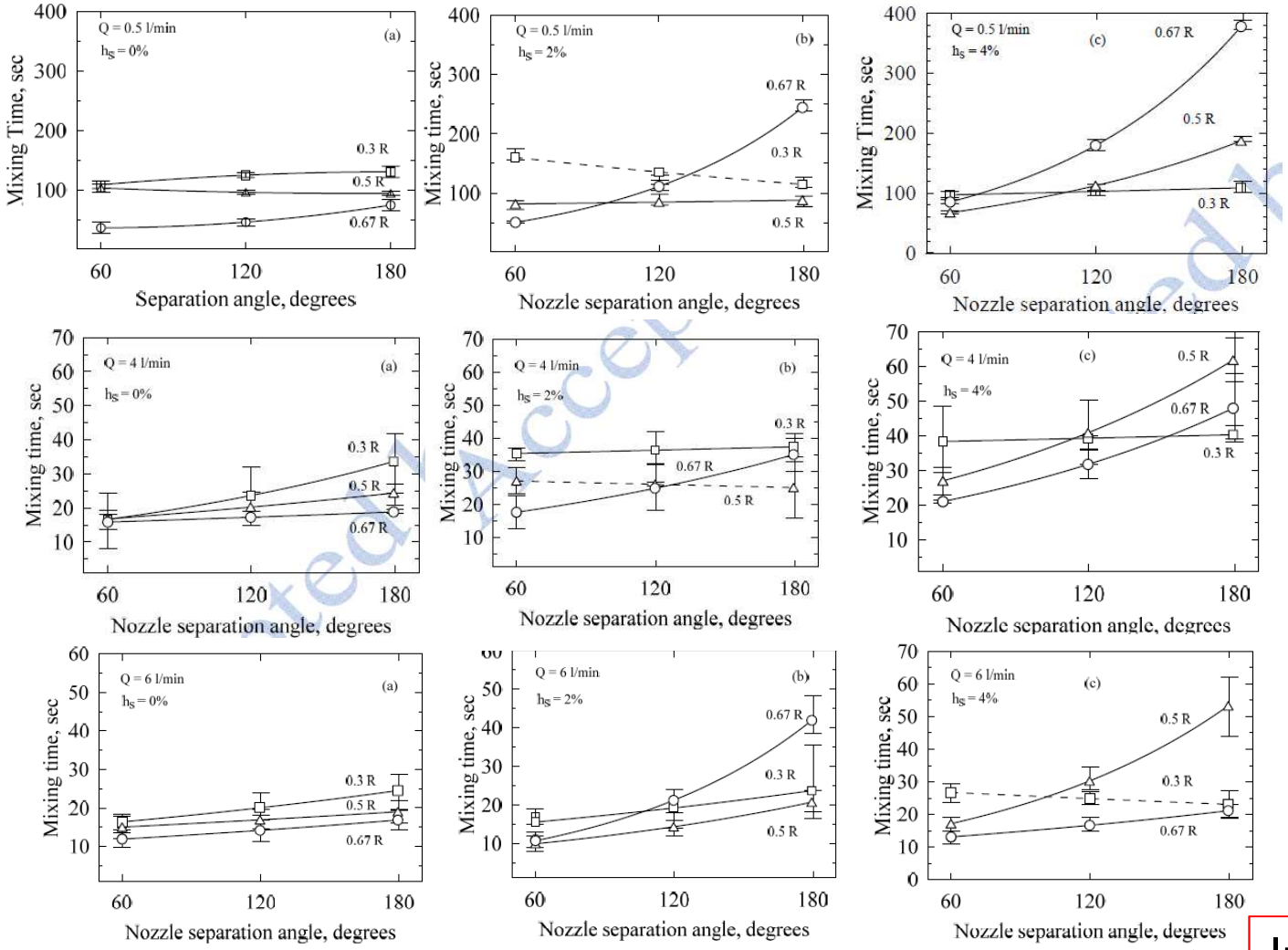


LITERATURE SEARCH

	Gomez et. al.	Conejo et. al.	NUCOR (base)
Top liquid	Motor oil	Hexane	Slag
Bath liquid	Water	Water	Molten steel
Density ratio	0.89	0.64	0.4
Ladle aspect ratio	1.32	0.8	0.8
Slag and melt height ratio	0-4%	2.6-5.1%	7.6%
Plug distance ratio	0.3, 0.5, 0.67	0.5, 0.67	0.6

Gomez et. al., “ Effect of separation angle and nozzle radial position on mixing time in ladles with two nozzles”, Journal of applied fluid mechanics(accepted before proof)
A. N. Conejo, et al., "Effects of Top Layer, Nozzle Arrangement, and Gas Flow Rate on Mixing Time in Agitated Ladles by Bottom Gas Injection." *Metallurgical and Materials Transactions B* 44.4 (2013): 914-923.

Gomez et. al.



Increase in flow rate

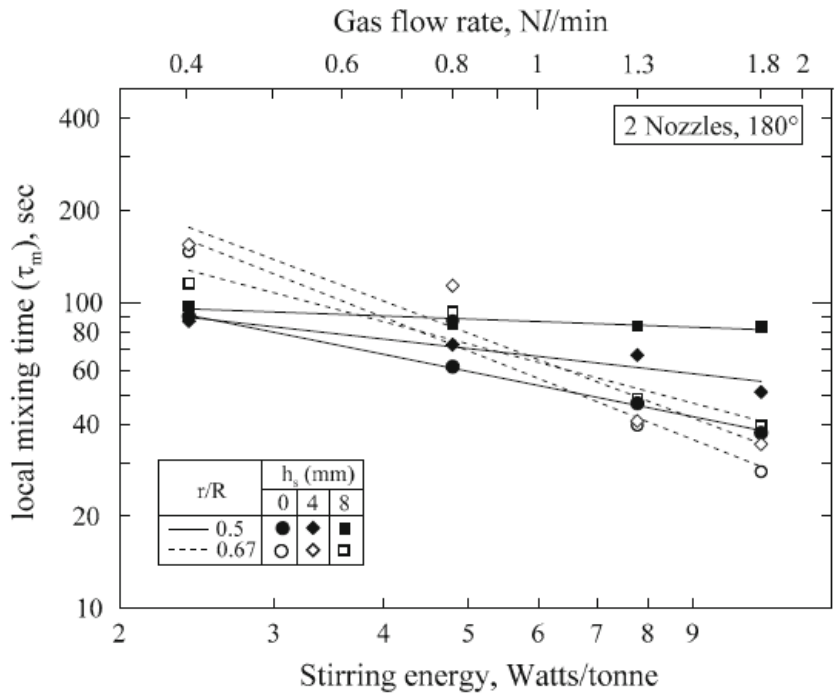
- Mixing time decrease with increase flow rate (overall)
- At low flow rate, which slag thickness greater than 2%, higher distance ratio has shows longest mixing time
- At highest flow rate, thickest slag layer, highest distance ratio shows shortest mixing time

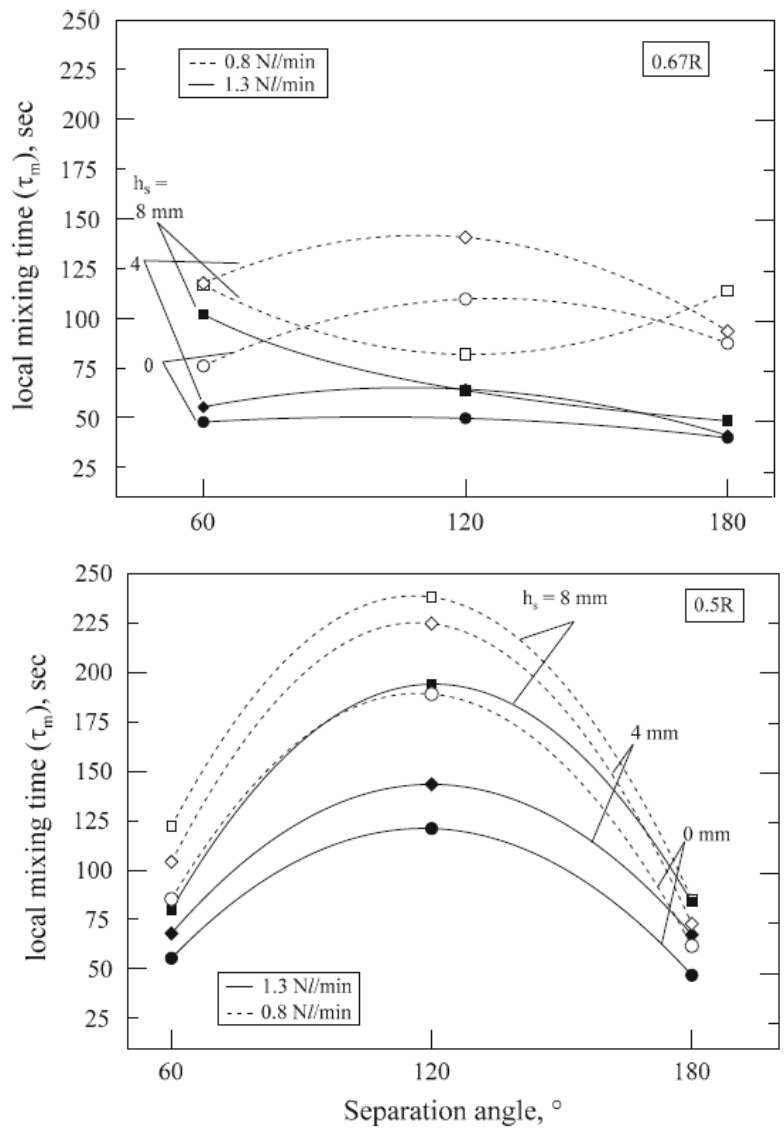
Increase in slag thickness

- Decrease in separation angle reduce mixing time (in overall)
- Separation angle has little effect when distance ratio between plugs is small
- With higher distance ratio, impact of separation angles and slag thickness on mixing time is larger
- Thicker the slag thickness, mixing time is sensitive to separation angle (180 degree has longest mixing time)
- Higher distance ratio has shorter mixing time at thinner slag)
- A 2% thickness of slag at highest flow rate, 0.5R shows least mixing time

LITERATURE SEARCH

A. N. Conejo, et al. (2013)





LITERATURE SEARCH

Turkoglu et al (1991).

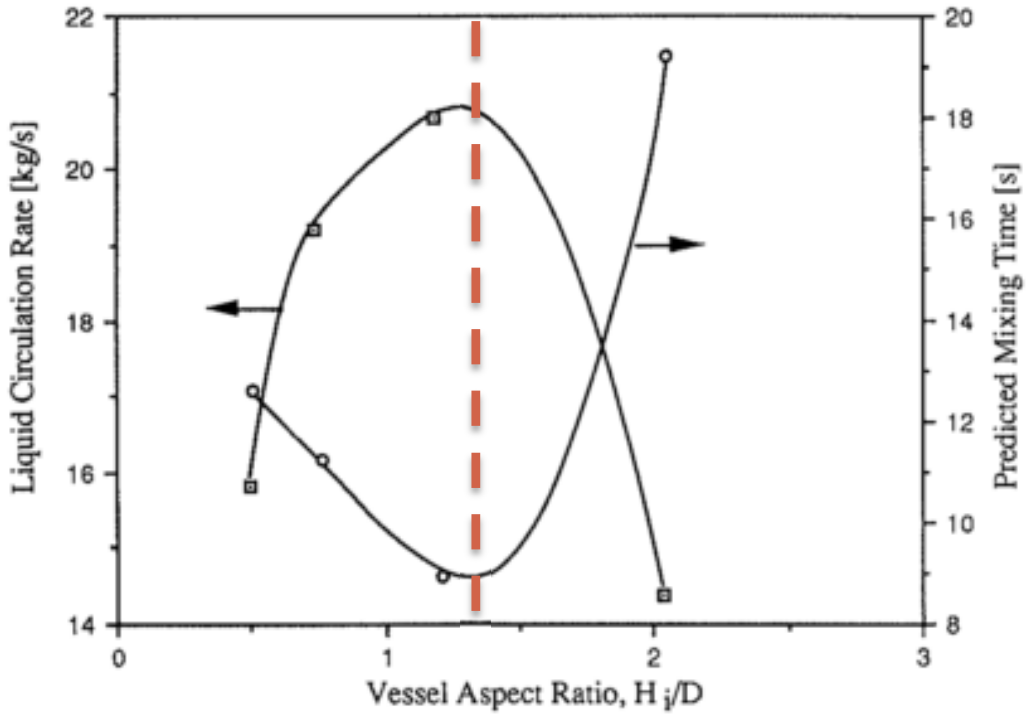
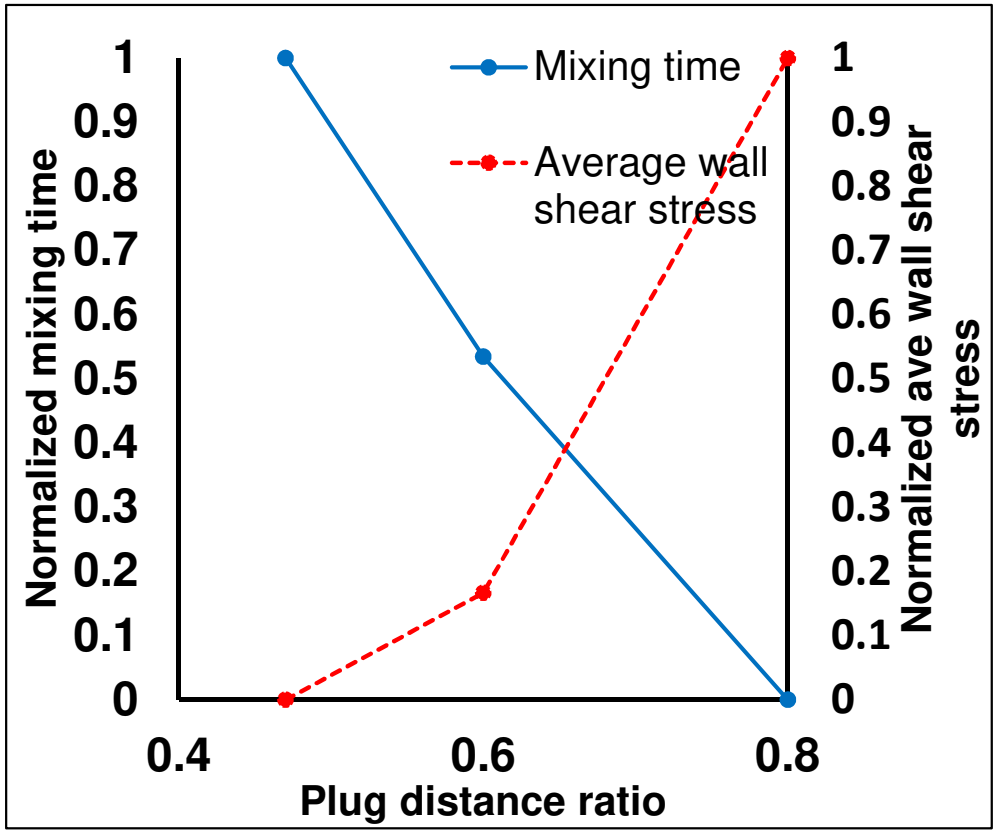
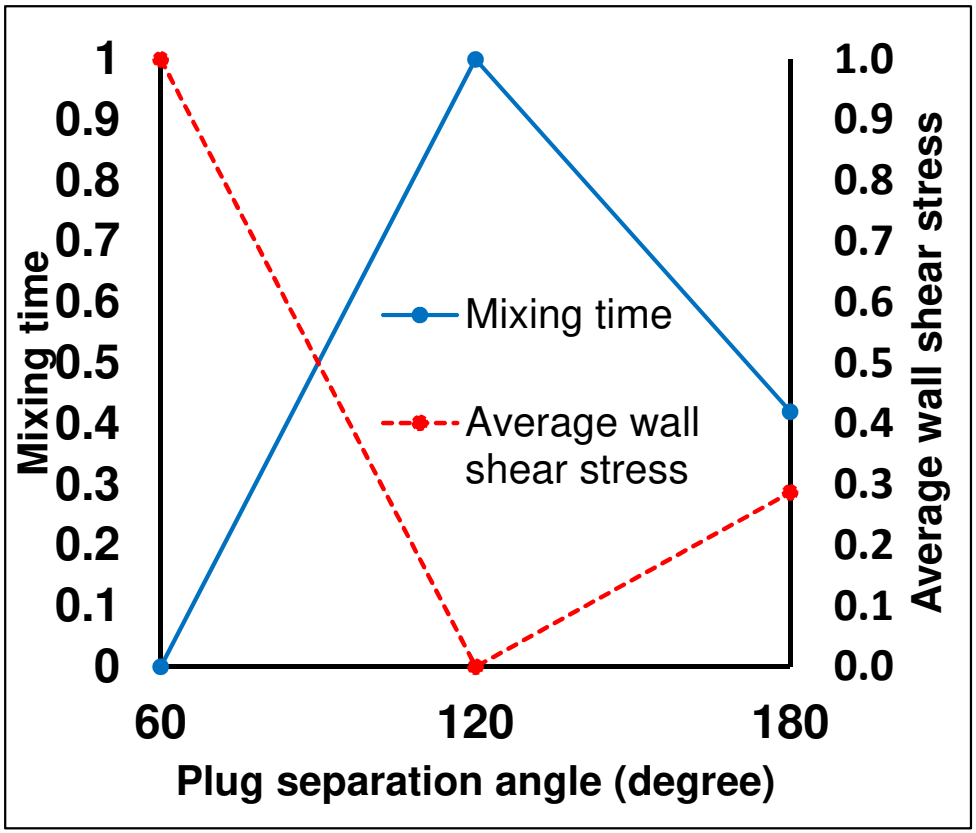


Fig. 4. Variation of the liquid circulation rate and the predicted mixing time with the vessel aspect ratio.

- Mixing time changes with the ladle aspect ratio.

WALL SHEAR STRESS

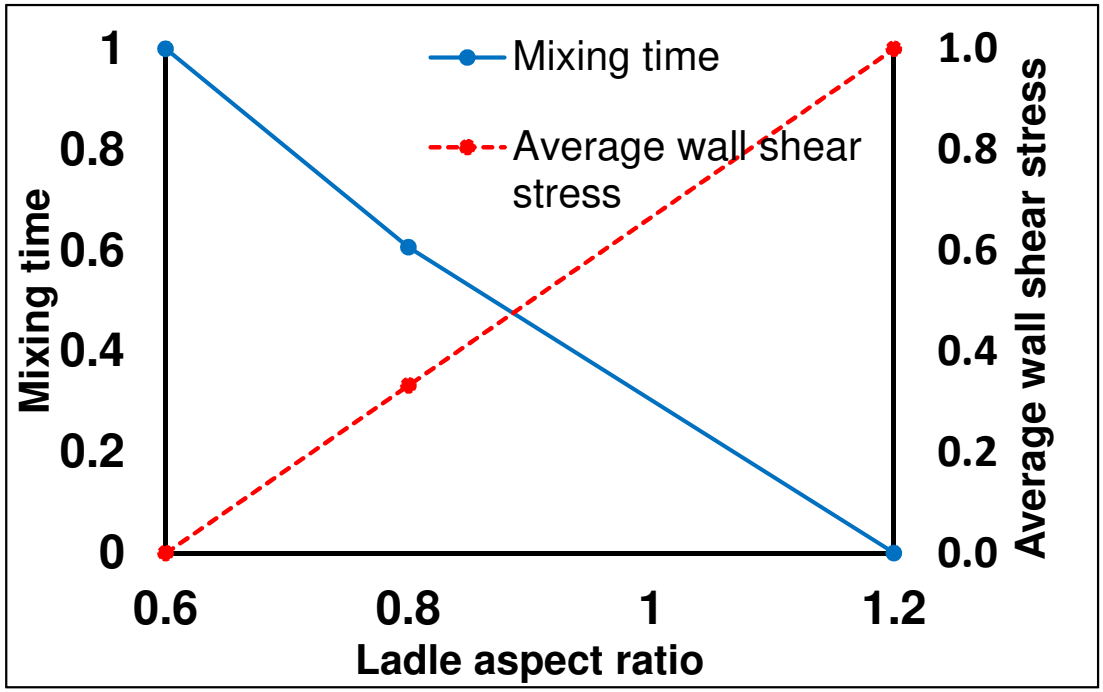




- Plug distance ratio 0.47D - 0.6D,
  - mixing time reduced by 22%
  - average wall shear stress increased by 96%
- Plug distance ratio 0.6D - 0.8D,
  - mixing time reduced by 32%
  - average wall shear stress increased by 245%

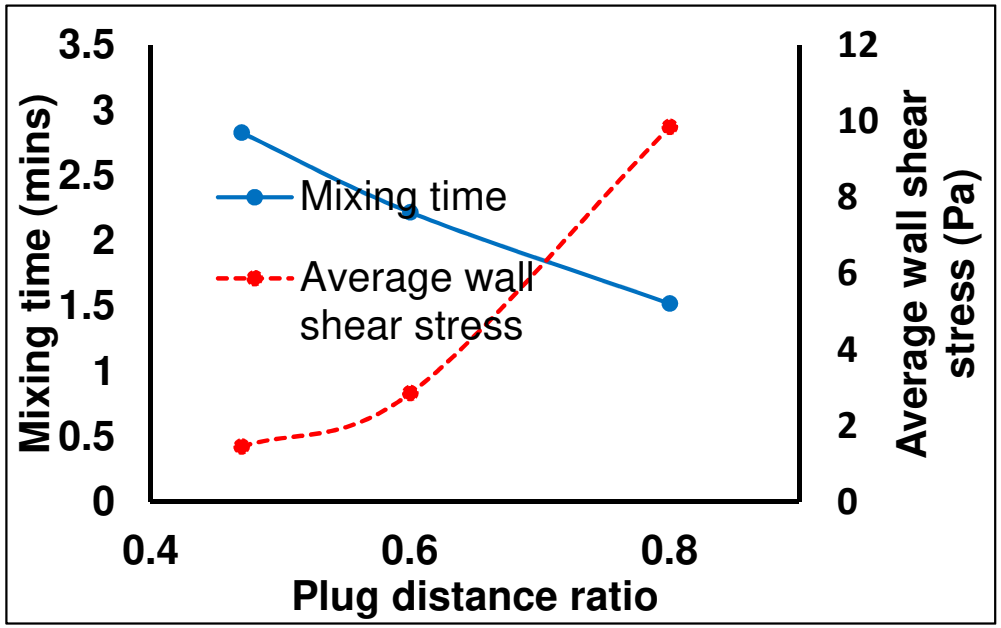
- Plug separation angle 60º – 120º,
  - mixing time reduced by 78%
  - average wall shear stress increased by 12%
- Plug distance ratio 0.6D - 0.8D,
  - mixing time reduced by 26%
  - average wall shear stress increased by 4%

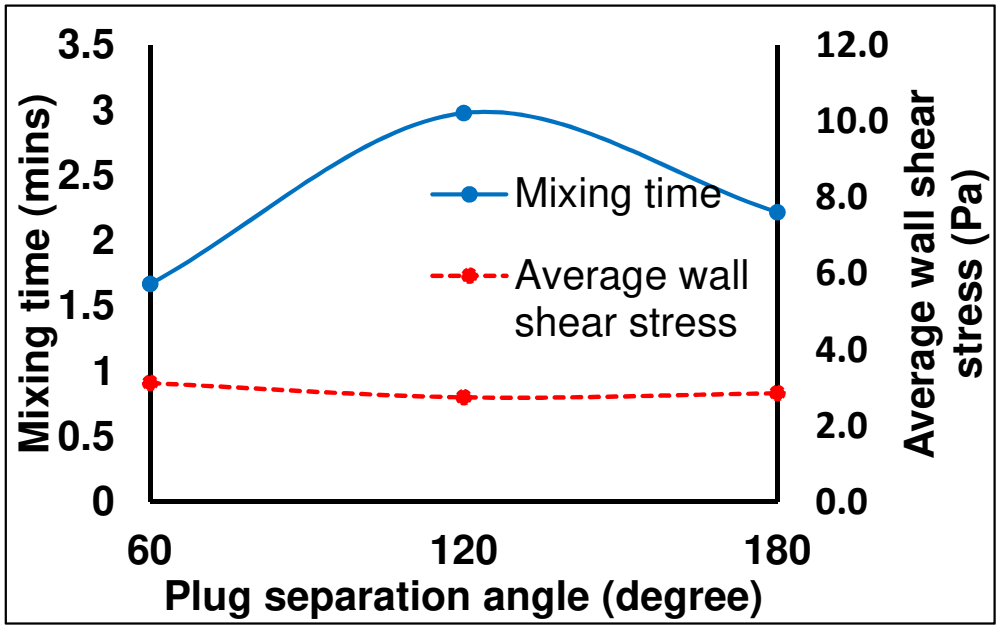
WALL SHEAR STRESS



- Ladle aspect ratio 0.6 – 0.8,
  - mixing time reduced by 14%
  - average wall shear stress increased by 245%
- Ladle aspect ratio 0.8 – 1.2,
  - mixing time reduced by 21%
  - average wall shear stress increased by 137%

WALL SHEAR STRESS





- Plug distance ratio 0.47D - 0.6D,
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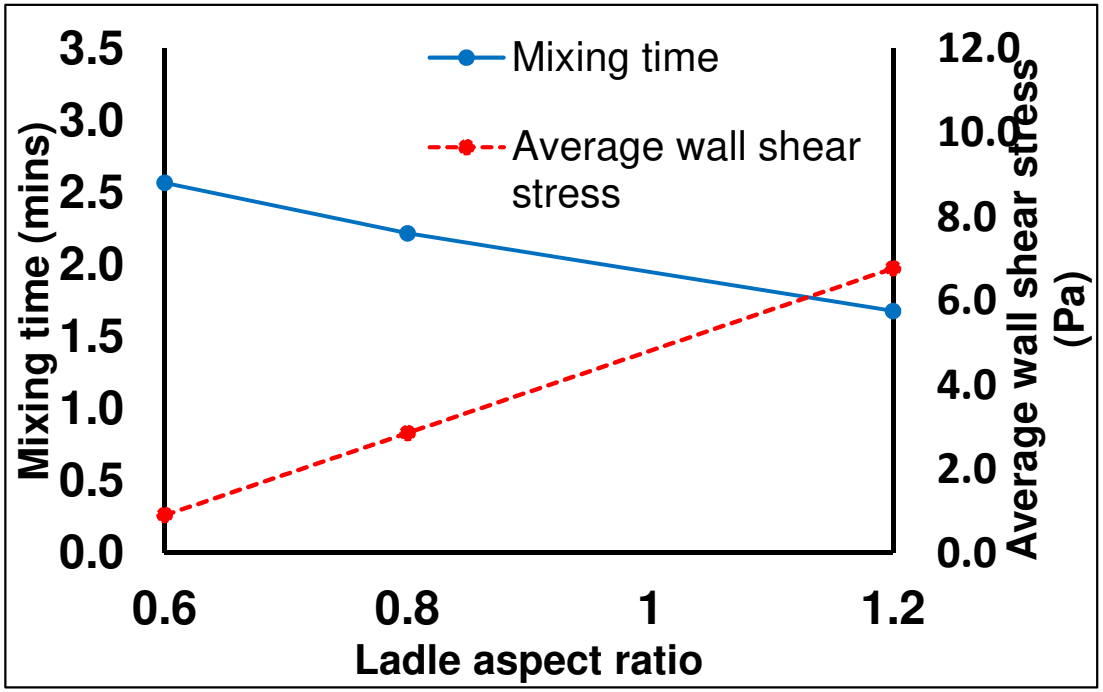
  - average wall shear stress increased by 96%
- Plug distance ratio 0.6D - 0.8D,
  - mixing time reduced by 32%
  - average wall shear stress increased by 245%

- Plug separation angle 60º – 120º,
  - mixing time reduced by 78%
  - average wall shear stress increased by 12%
- Plug separation angle 120º - 180º,
  - mixing time reduced by 26%
  - average wall shear stress increased by 4%

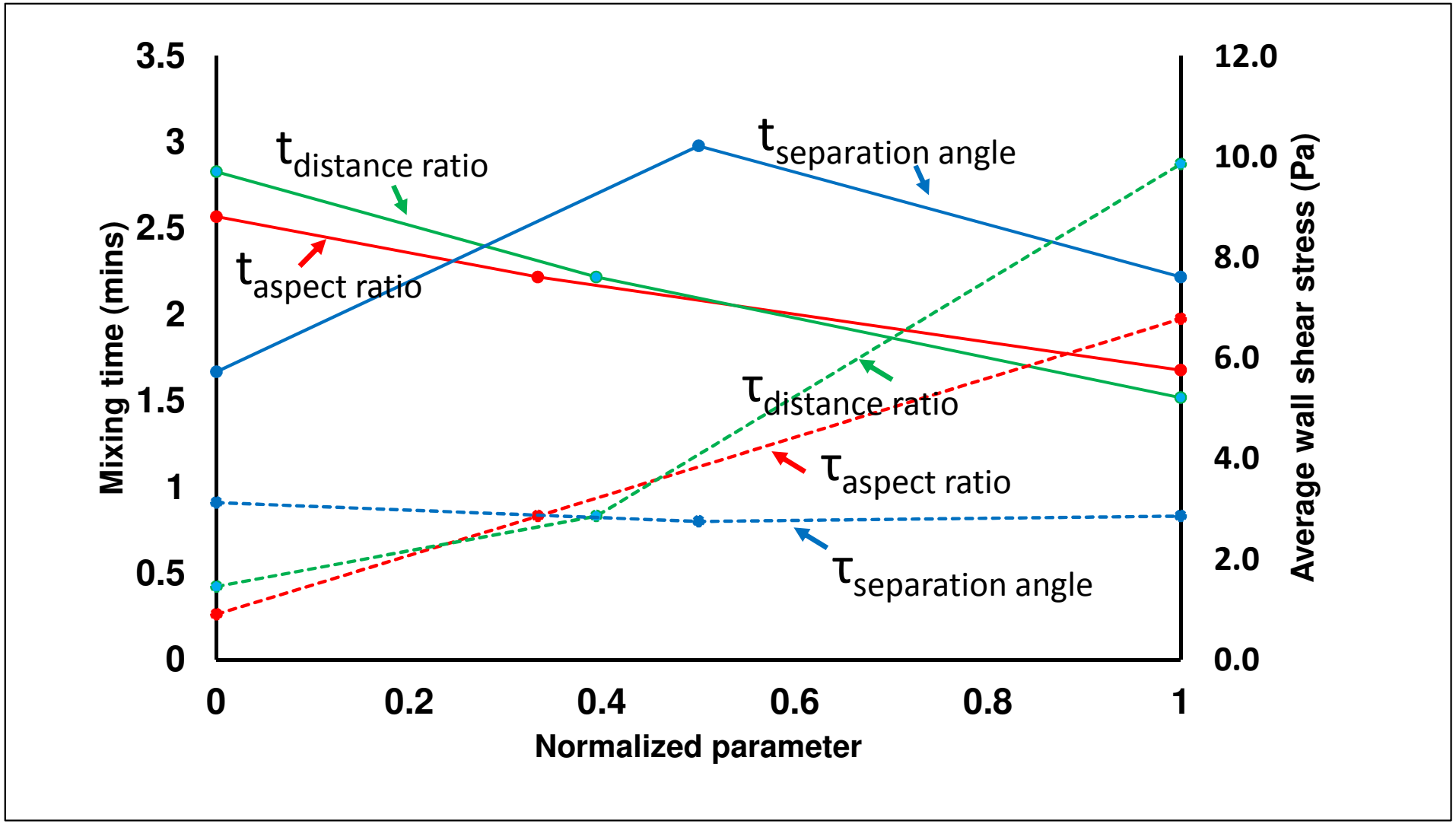
WALL SHEAR STRESS



- Ladle aspect ratio 0.6 – 0.8,
  - mixing time reduced by 14%
  - average wall shear stress increased by 245%
- Ladle aspect ratio 0.8 – 1.2,
  - mixing time reduced by 21%
  - average wall shear stress increased by 137%

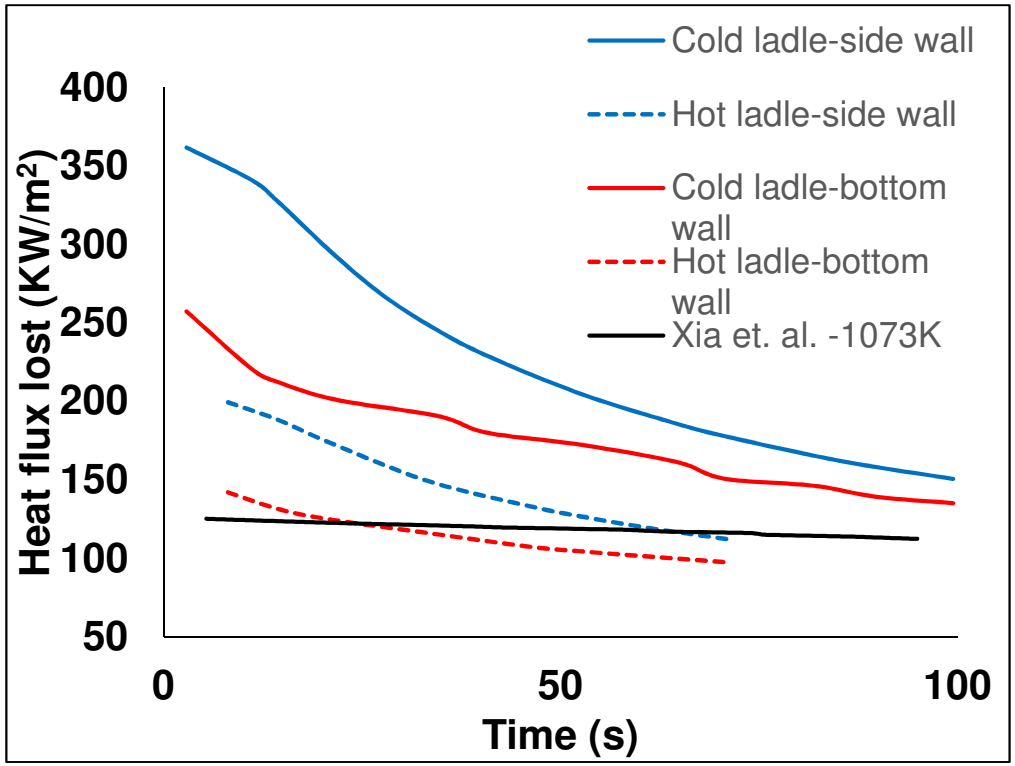
70

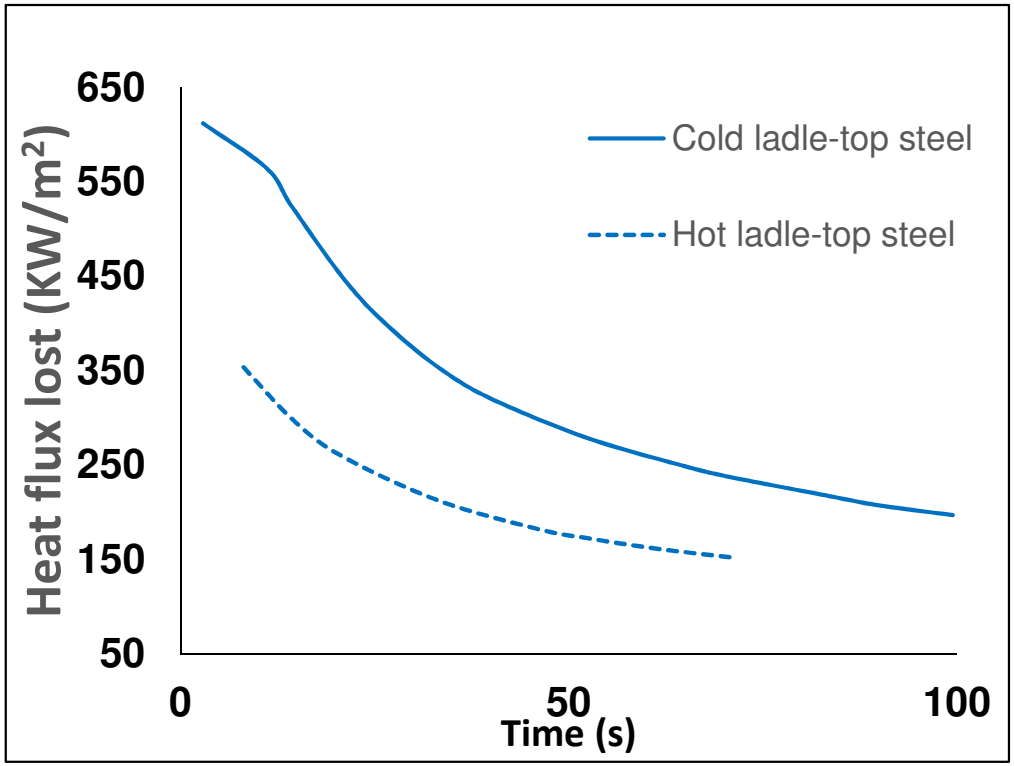
WALL SHEAR STRESS



71

HEAT LOSS





Xia et. al. used constant temperature of 1073K as initial wall temperature whereas the simulation used nonlinear temperature profile (average of 918K and 960K) as initial wall temperature.