CENTER FOR INNOVATION THROUGH VISUALIZATION & SIMULATION

PURDUE UNIVERSITY NORTHWEST

STEEL MANUFACTURING SIMULATION & VISUALIZATION CONSORTIUM

steelconsortium@pnw.edu
steelconsortium.org

COMPUTATIONAL STUDIES AND OPTIMIZATION OF INCLUSION REMOVAL IN A STEEL LADLE

PTC Members:

- **Helmut Oltmann (NUCOR)**
- Anna Voss (NUCOR)
- April Pitts (NUCOR)
- Hoyong Hwang (ArcelorMittal)
- Rui Liu (ArcelorMittal)
- Sunday Abraham (SSAB)
- Chase Ault (SDI)
- Paul Wu (AK Steel)

CIVS Team:

- **Mingyi Liang (M.S. student)**
- Huinan Shao (M.S. student)
- Yifan Wang (M.S. student)
- Guangwu Tang (Ph.D. student)
- Armin Silaen
- Chenn Zhou

Presentation at CIVS on November 16, 2016

"Where Ideas Become Reality"

BACKGROUND

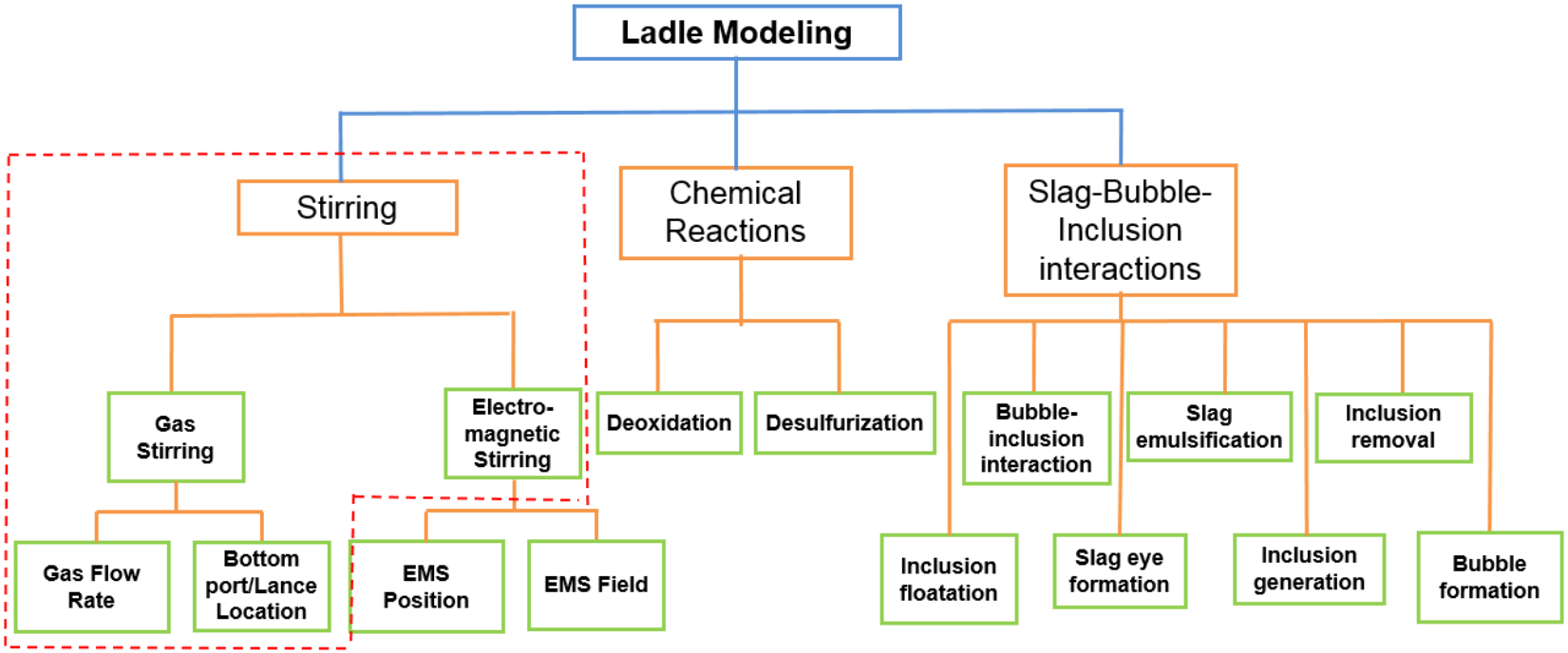
- **Current Issues**
  - Complex transport phenomena with multiple process variables
  - Difficulty in understanding the dynamic evolution of inclusions
- **Potential Impacts**
  - Process design of optimized flow condition and physical properties
  - Steel cleanliness improvement and final defects reduction

OBJECTIVES

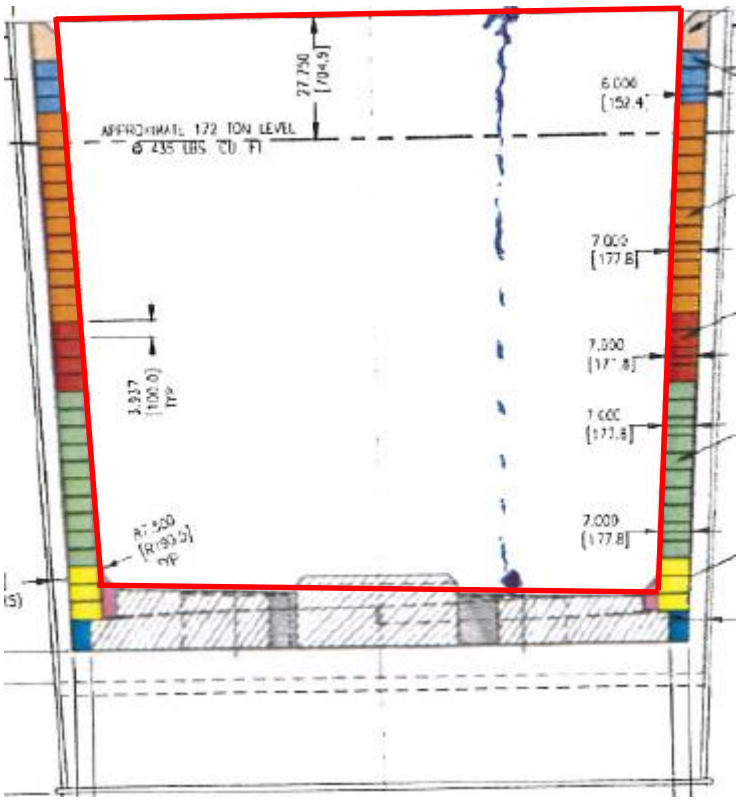
- **Long term (5 years):**
  - Develop a comprehensive multiphase model of a steel ladle for process design
  - Study inclusion transport and evolution while considering:
    - Effect of gas stirring conditions
    - Correlation between fluid flow and slag physical properties
- **Short term (1st year):**
  - Model a ladle for mixing process based on the geometry and boundary condition provided by NUCOR
  - Provide a detailed flow pattern for investigation of dead zone at current alloying position
  - Develop a correlation between geometrical parameters and mixing time

EXPECTED OUTCOMES - YEAR 1

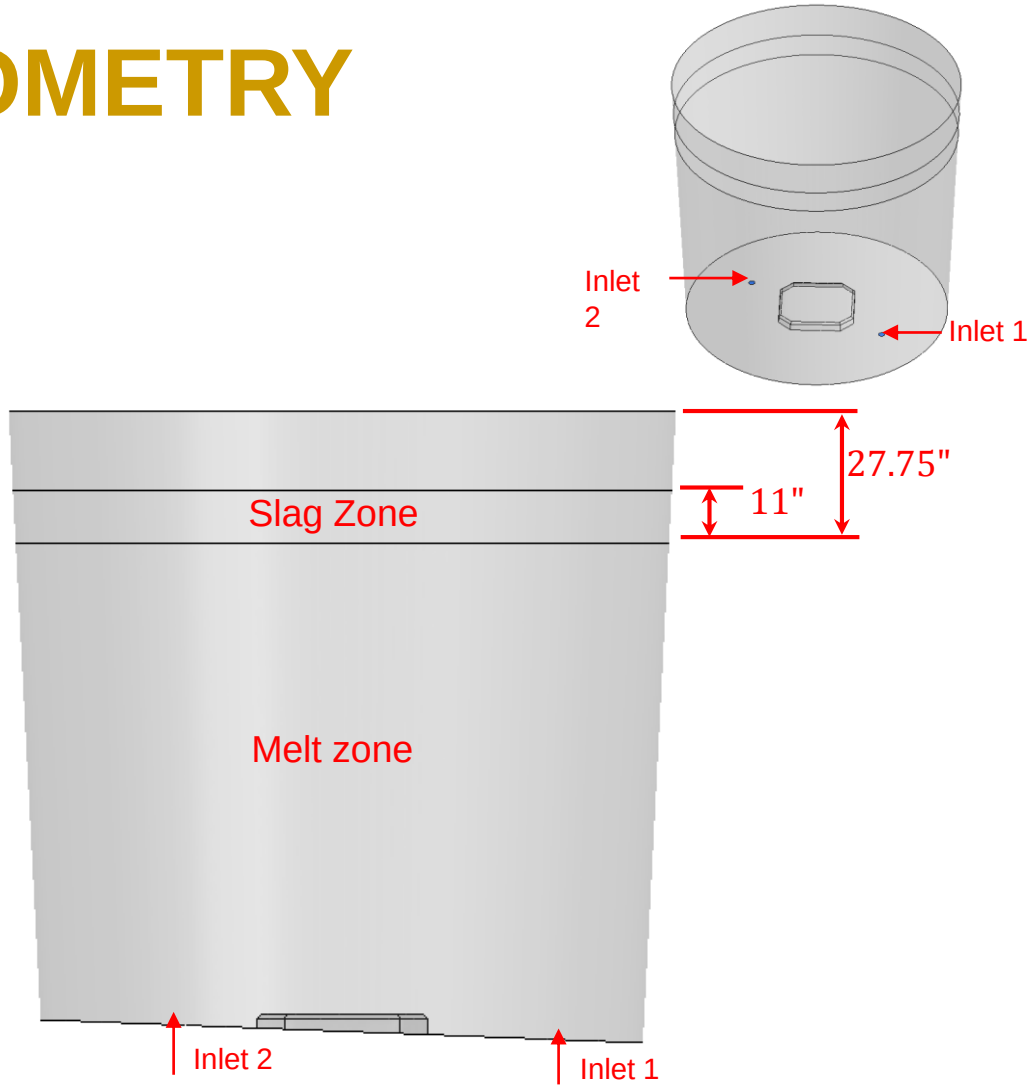
- Develop baseline cases for CFD Model - Completed
- Identification of dead zones - Completed
- Calculate mixing time - Completed
- Develop EMS ladle model – Ongoing



GEOMETRY



- Technical drawing provided by NUCOR



- Computational domain

CFD MODELS AND METHODOLOGY

Slag & Melt Zones

- 3-D; Transient; Iso-thermal
- Multiphase flow: Eulerian-VOF
- Turbulent model: Realizable k-epsilon
- Include gravity, buoyancy and drag force.

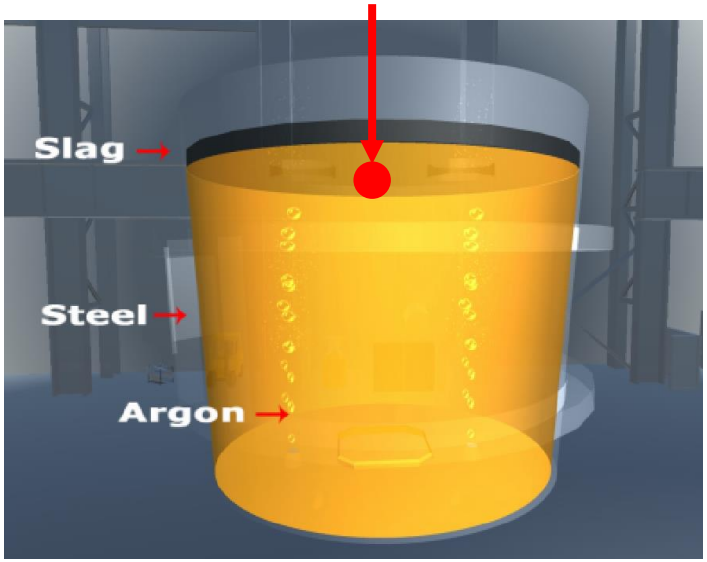
Argon Injection

- 3-D; Transient; Iso-thermal
- 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

- 3-D; Transient; Iso-thermal
- Multiphase flow: Eulerian-VOF
- Species transport

Tracer is put into the ladle



Note: Eulerian-VOF model is also used to track bubbles.

BASELINE CASE CALIBRATION

BOUNDARY & INITIAL CONDITIONS

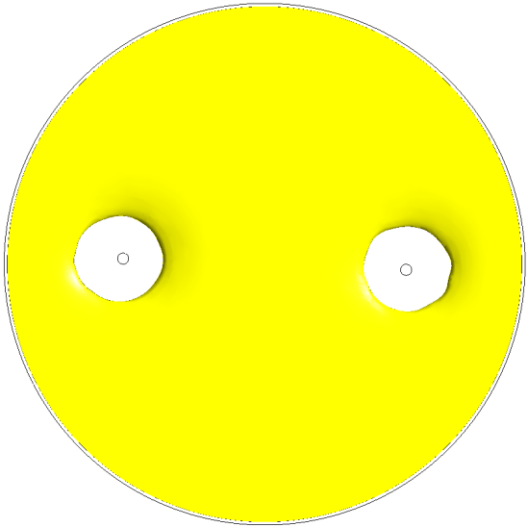
Name		Case 1	Case 2
Bubble tracking method		**DPM**	**Eulerian-VOF**
Boundary Condition	Argon flow rate per inlet	30 cfm	30 cfm
	Outlet	1 atm	1 atm
	Wall	no-slip	no-slip
Initial Condition	Bubble diameter	2 in (Aoki et al., 2004)	
	Slag depth	11 in	11 in
	Melt depth	105 in	105 in

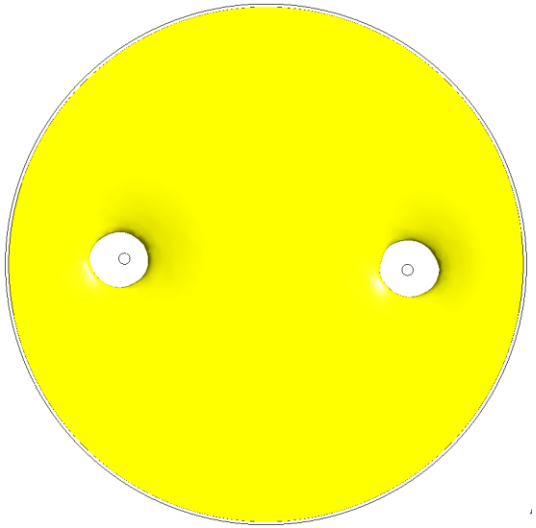
* Note: Initial bubble diameter is 2in, based on $d_{bubble} = 0.35\left({}^{Q^2}/_{g}\right)^{0.2}$, where Q is the volume flow rate of argon gas. (Aoki et al., 2004)

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

COMPARISON BETWEEN DPM-VOF AND EULERIAN-VOF MODEL

- Time-average results from 9s to 20s used to determined slag eye size.
  - Case 1 (DPM-VOF)
  - Case 2 (Eulerian-VOF)



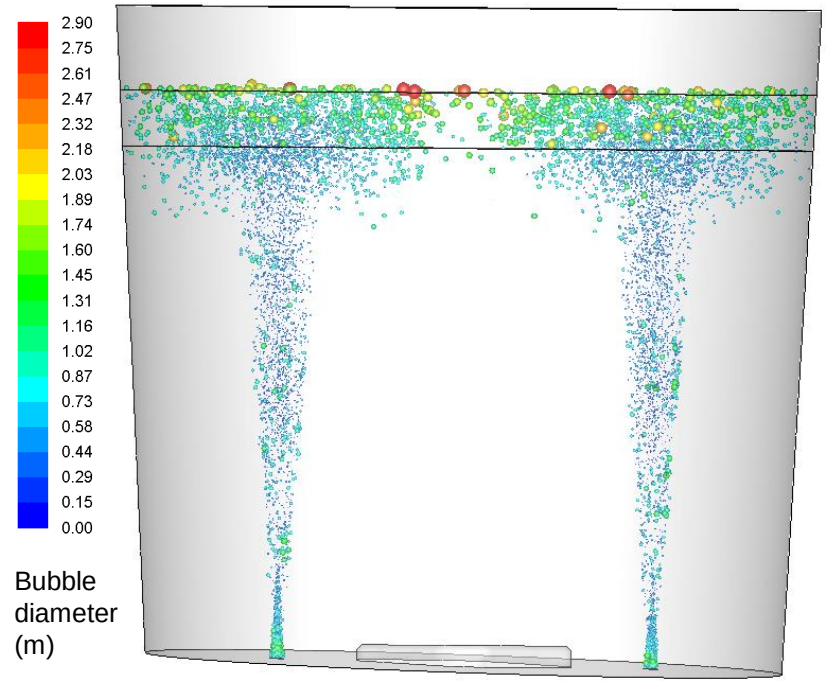


	Argon gas volume flow rate (cfm)	Slag eye size (in)		
		CFD	Plant data	Difference
Case 1	30	**24.5**	**28.8**	**14.9%**
Case 2	30	**20.7**	**28.8**	**22.5 %**

- DPM-VOF model had bigger slag eyes, because of the wider spread of bubble plume.
- DPM-VOF model can predict the slag eye size more precisely.

COALESCENCE AND BREAKUP MODEL THEORY

- Laux and Johansen coalescence and break up model
  - Coalescence and breakup for air bubble injected into water.
  - $d_b < d_{eq}$, coalescence > breakup, $\tau_{rel} = \tau_B$.
  - $d_b > d_{eq}$, coalescence < breakup, $\tau_{rel} = \tau_C$.
  - $d = \frac{\left(d_b + \frac{d_{eq}}{\tau_{rel}}\right)}{(1+\frac{t}{\tau_{rel}})}$ (Pan, 2014)



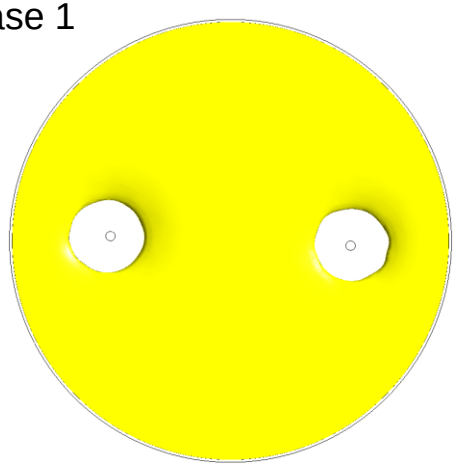
- H. Laux and S. T. Johansen, “A CFD analysis of the air entrainment rate due to a plunging steel jet combining mathematical models for dispersed and separated multiphase flows,” Fluid Flow Phenomena in Metals Processing, Trondheim, 1999.
- Q. Pan, "Modelling of Turbulent Flows with Strong Dispersed Phase-Continuous Fluid Interactions," NTNU, Trondheim, 2014.

BOUNDARY & INITIAL CONDITIONS

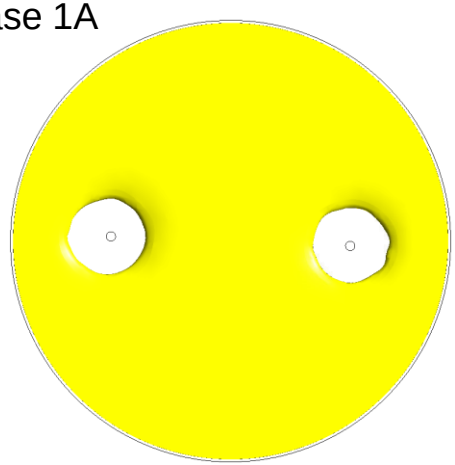
Name		Case 1	Case 1A	Case 1B (Base case)
Bubble tracking		DPM	DPM	DPM
Momentum equation discretization method		**First order**	**First order**	**Second Order**
Coalescence and breakup model		**No**	**Yes**	**Yes**
Boundary	Argon volume flow rate per inlet	30 cfm	30 cfm	30 cfm
	Outlet	1 atm	1 atm	1 atm
	Wall	no-slip	no-slip	no-slip
Initial	Slag depth	11 in	11 in	11 in
	Melt depth	105 in	105 in	105 in

EFFECT OF COALESCENCE AND BREAKUP MODEL AND MOMENTUM EQUATION

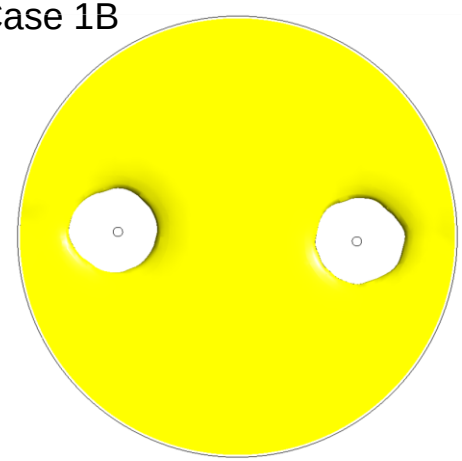
- Time-average results from 9s to 20s used to determined slag eye size.
- Case 1



- Case 1A



- Case 1B



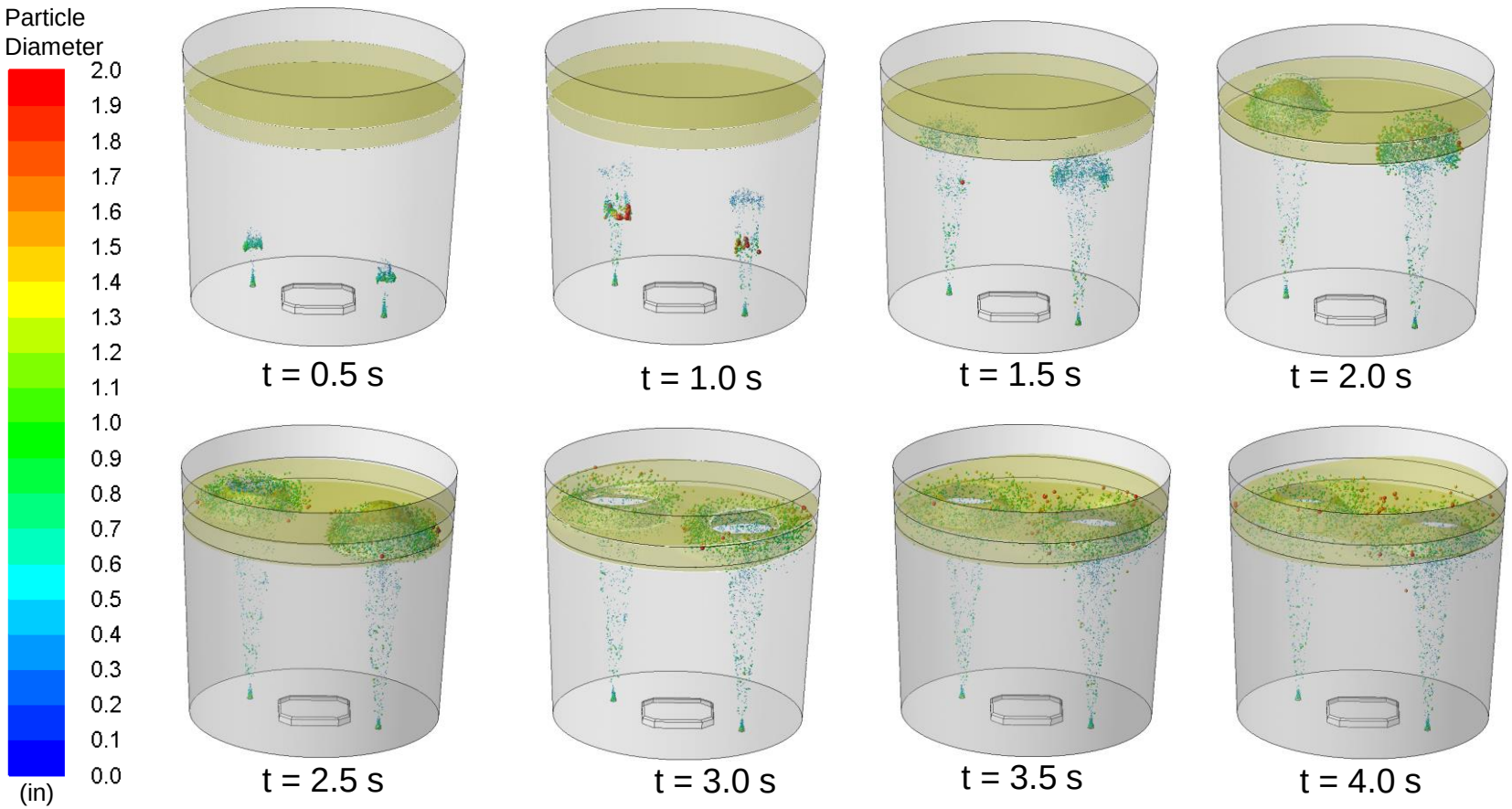
	Coalescence and breakup model of argon bubbles	Discretization of momentum equation	Slag eye size (in)		
			CFD	Plant data	Difference
Case 1	**No**	**First order**	24.5	28.8	**14.9 %**
Case 1A	**Yes**	**First order**	25.0	28.8	**10.67 %**
Case 1B	**Yes**	**Second order**	31.0	28.8	**7.64 %**

- A combination of coalescence and breakup model and second-order discretization of momentum equation was able to give a more accurate simulation, making the difference within 10 %.
- **Case 1B would be used as the Base case.**

BASELINE SIMULATION

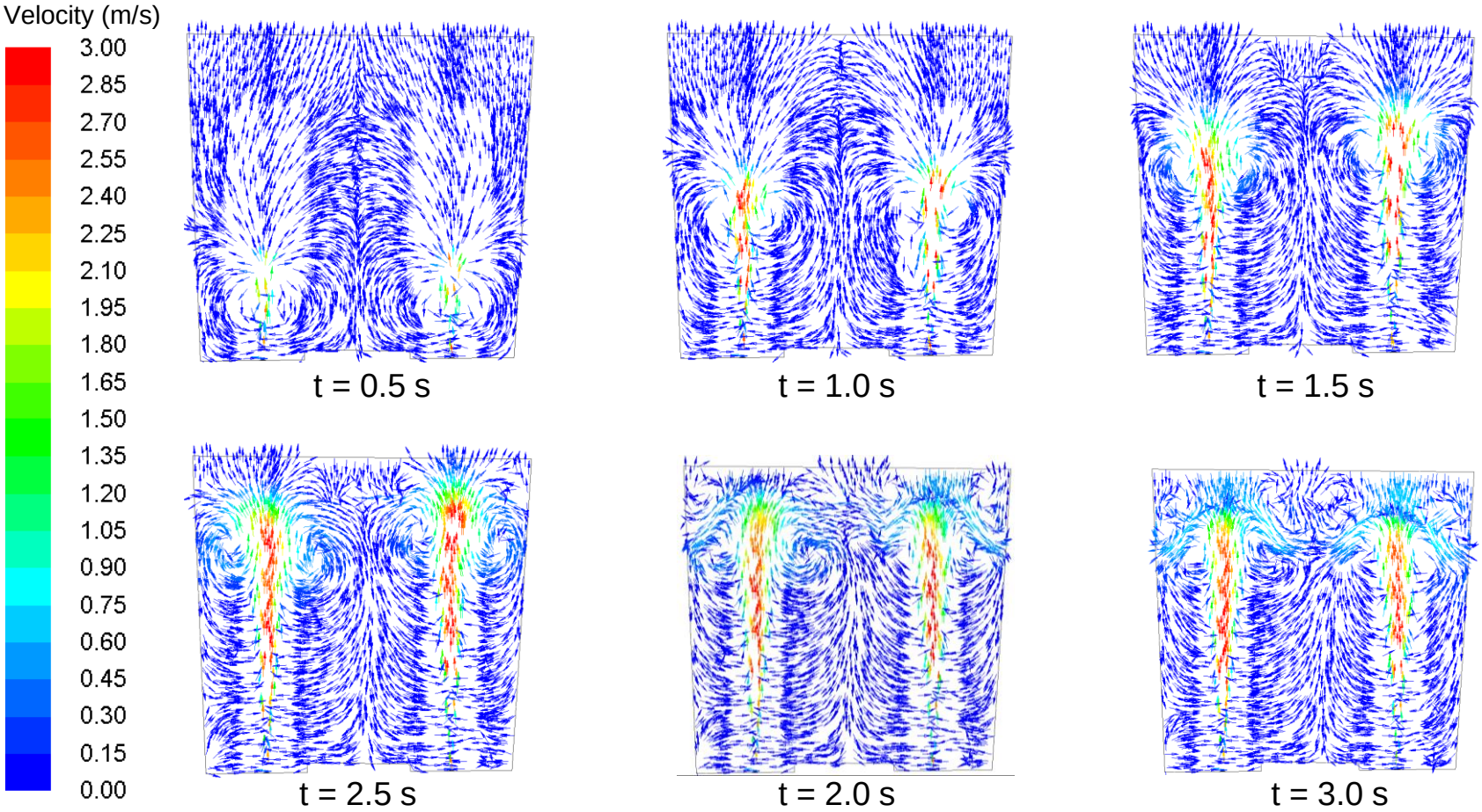
Name		Case 1B (Base case)
Bubble tracking		**DPM**
Momentum equation discretization method		**Second Order**
Coalescence and breakup model		**Yes**
Boundary	Argon volume flow rate per inlet	30 cfm
	Outlet	1 atm
	Wall	no-slip
Initial	Slag depth	11 in
	Melt depth	105 in

RESULTS – BUBBLE PLUME



- It took approximately 2.0 seconds for a bubble to reach the free surface.
- Slag eyes were opened at approximately 2.3 seconds.
- Coalescence and breakup happened as the bubbles were rising.

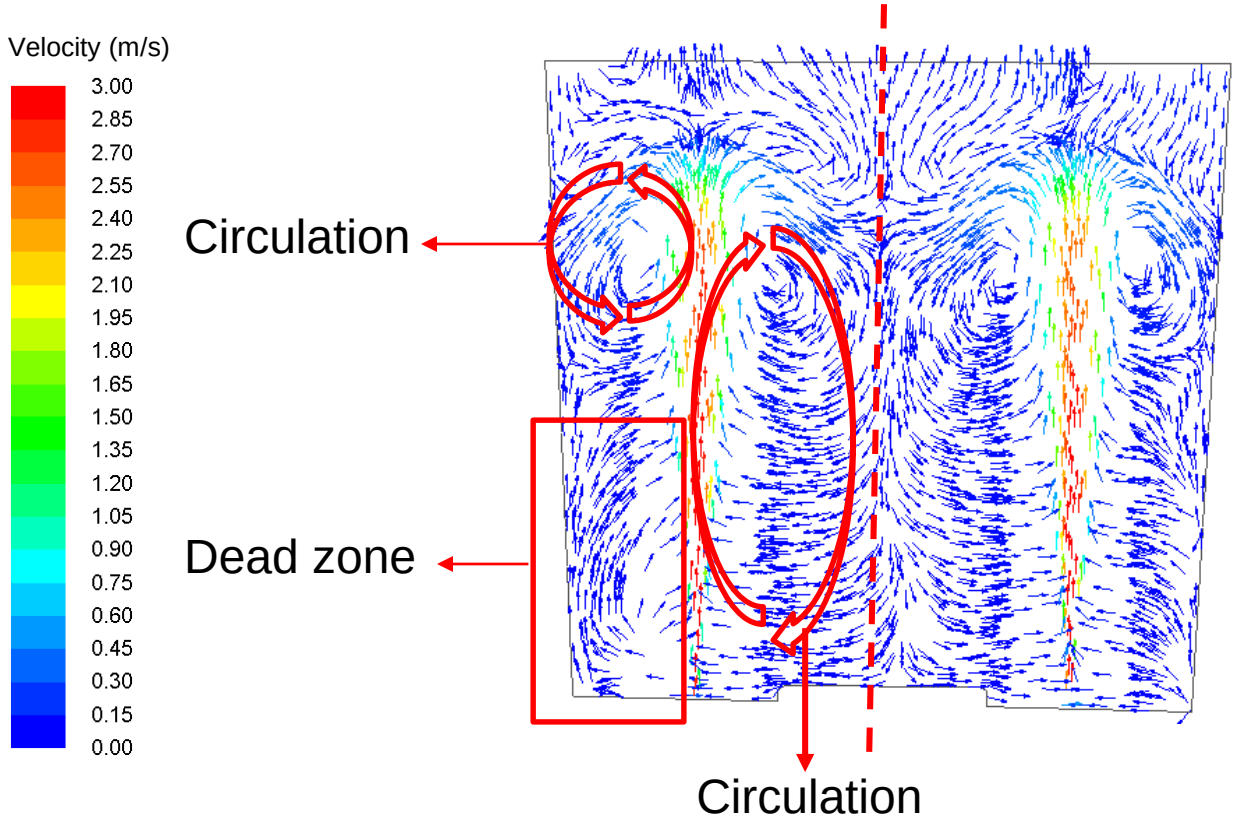
RESULTS – VELOCITY VECTOR



- With the argon gas injected, some circulations formed inside the ladle.

DEAD ZONE IDENTIFICATION

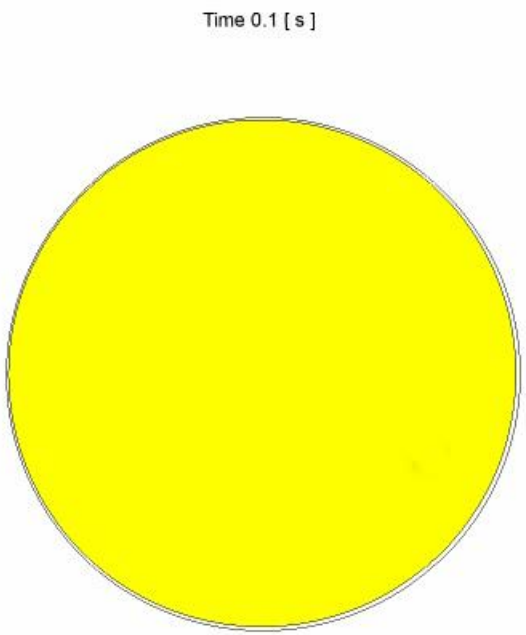
- Velocity vector after Case 1B reached quasi-steady state:



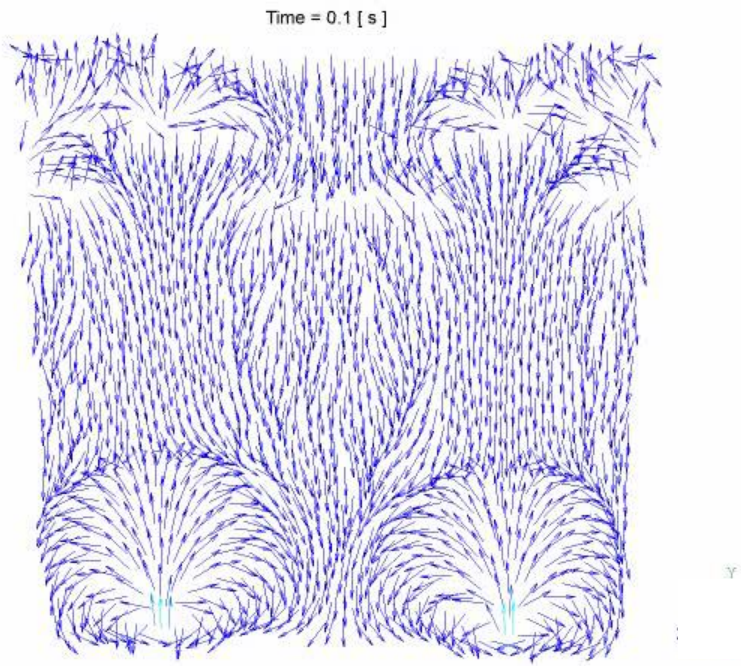
- Dead zone was located at the corner of the ladle bottom.

BASE CASE VISUALIZATION

- Slag eye size:

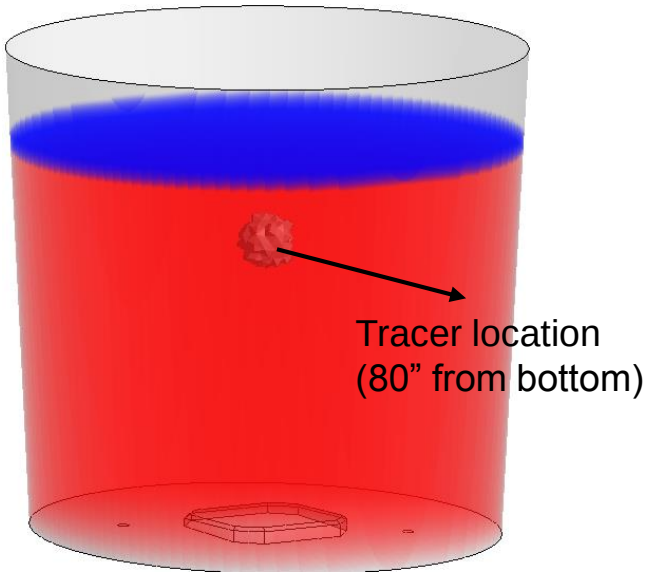


- Velocity vector:



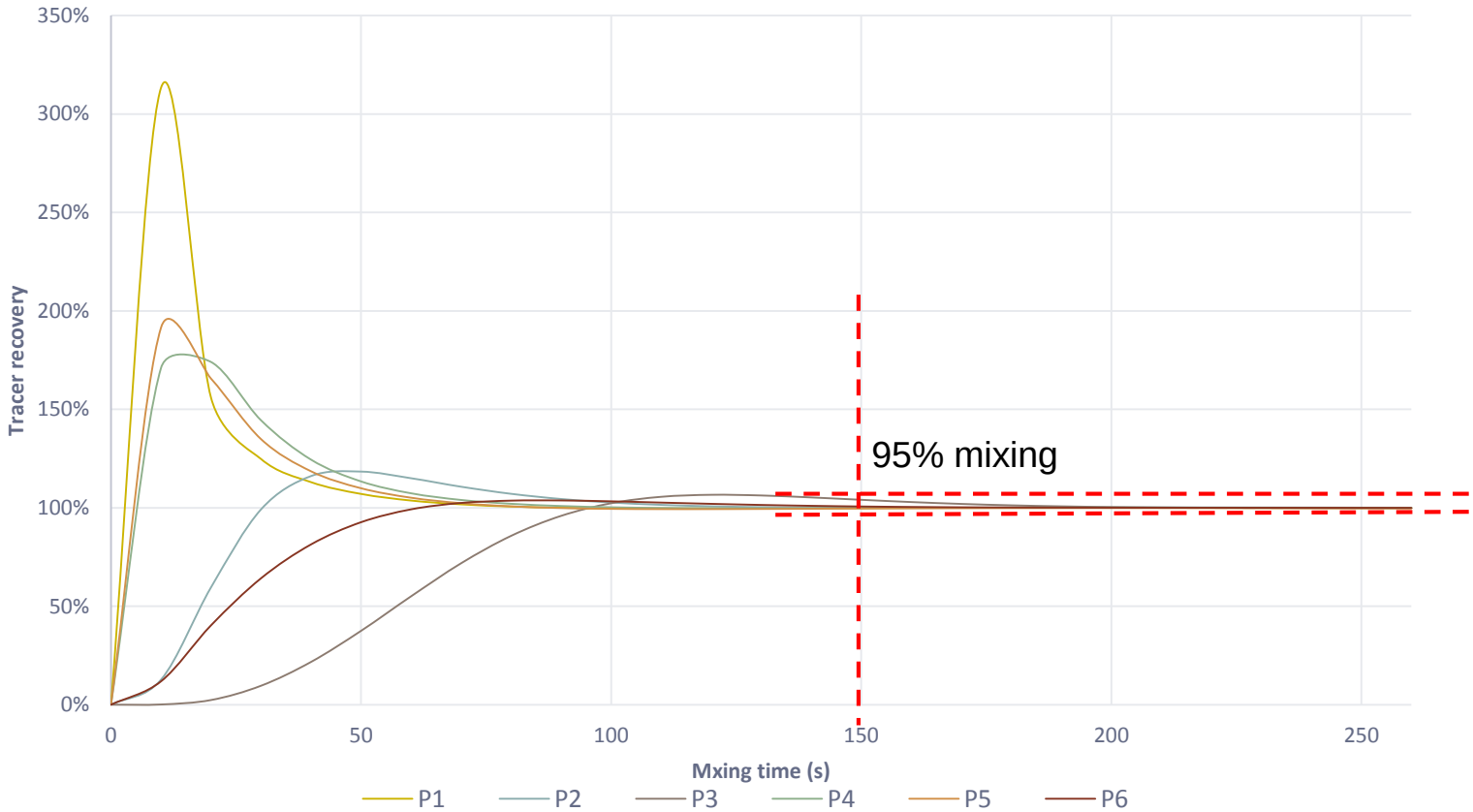
MIXING PROCESS-METHODOLOGY

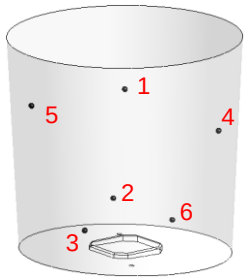
- The flow reached quasi-steady state after 9s
- A tracer was introduced at the upper center of the ladle
- Tracer recovery was calculated
- The mixing time is defined as the time of attaining a 95% degree of homogenization



$$\text{Tracer recovery } (\%) = \frac{Current\ tracer\ concentration}{Equilibrium\ tracer\ concentration}$$

MIXING TIME



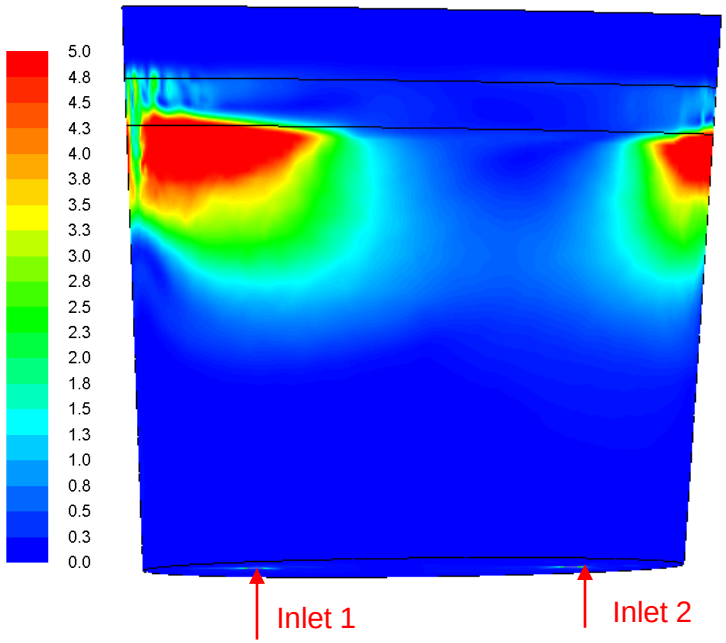


Point 1 (0, 2.8, 0)
Point 2 (-1, 1.5, 1)
Point 3 (0, 0.4, -1)
Point 4 (1, 2.2, 1)
Point 5 (-1, 2.5, -1)
Point 6 (0.5, 0.8, 0.5)

- The tracer recovery reached 95% after about 150 seconds.

WALL SHEAR STRESS

- Wall shear stress after Case 1B reached quasi-steady state:



	Volume flow rate per inlet (cfm)	Maximum shear stress (Pa)
Case 1B	30	9.5

- Argon gas pushed slag and steel against wall, and the strong flow of molten steel may wear off the refractory of ladle wall, thus reducing ladle life.

PARAMETRIC STUDY

BOUNDARY & INITIAL CONDITIONS

- Three more cases with 3 different argon flow rate were simulated (15 cfm, 7 cfm, and 5 cfm).

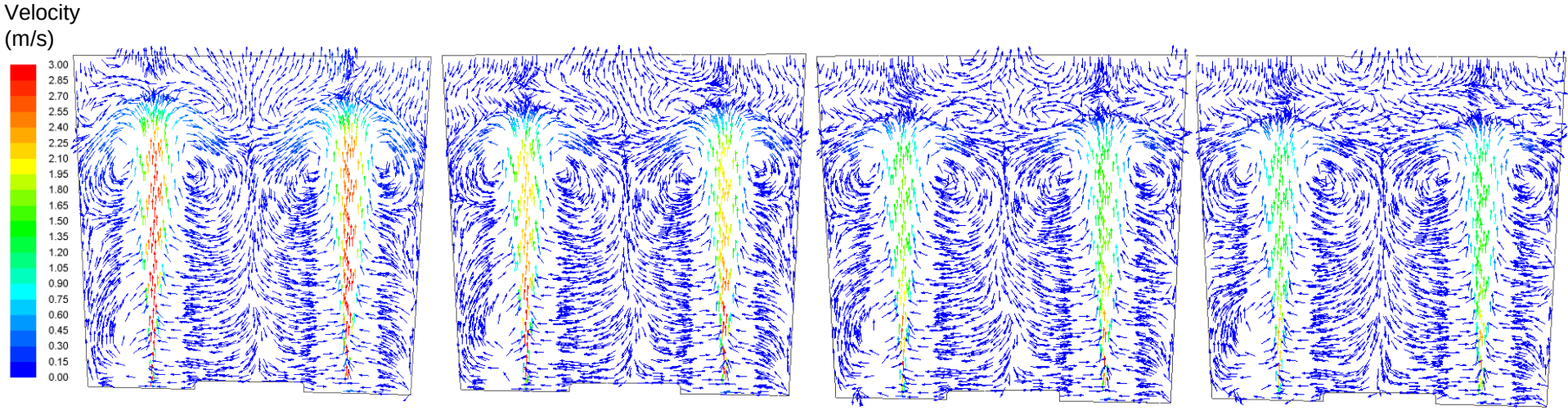
Name		Case 1B	Case 3	Case 4	Case 5
Boundary	Argon volume flow rate per inlet	30 cfm	15 cfm	7 cfm	5 cfm
	Outlet	1 atm	1 atm	1 atm	1 atm
	Wall	no-slip	no-slip	no-slip	no-slip
Initial	Bubble initial diameter	0.55 inch	0.41 inch	0.30 inch	0.26 inch
	Slag depth	11 inch	11 inch	11 inch	11 inch
	Melt depth	105 inch	105 inch	105 inch	105 inch

* Note: Initial bubble diameter is 2in, based on $d_{bubble} = \frac{1}{4} * (0.35({}^{Q^2}/_{g})^{0.2})$, where Q is the volume flow rate of argon gas. (Johansen et al., 1988)

S.T.Johansen, F.Boysan. “Fluid dynamics in bubble stirred ladles: part II. Mathematical modeling”, METALLURGICAL TRANSACTIONS B, 1988

RESULTS – EFFECT OF GAS FLOW RATE ON MOLTEN STEEL VELOCITY

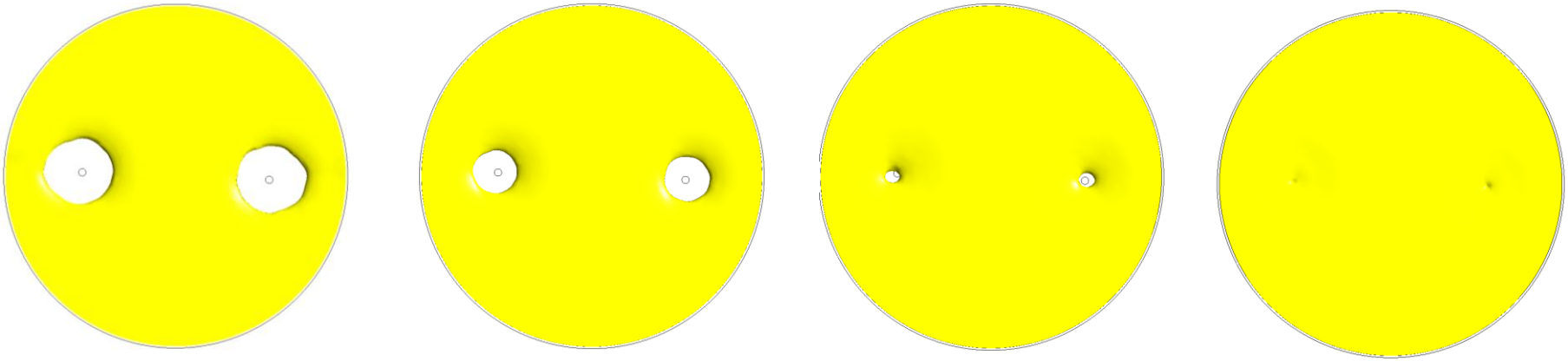
- Case 1B (30 cfm)
- Case 3 (15 cfm)
- Case 4 (7 cfm)
- Case 5 (5 cfm)



- When gas flow rate was higher, the molten velocity moved faster, which facilitated alloying process.

RESULT – TIME-AVERAGE SLAG EYES

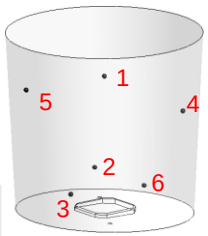
- Time-average results from 9s to 20s used to determined slag eye size.
- Case 1B (30 cfm)
- Case 3 (15 cfm)
- Case 4 (7 cfm)
- Case 5 (5 cfm)

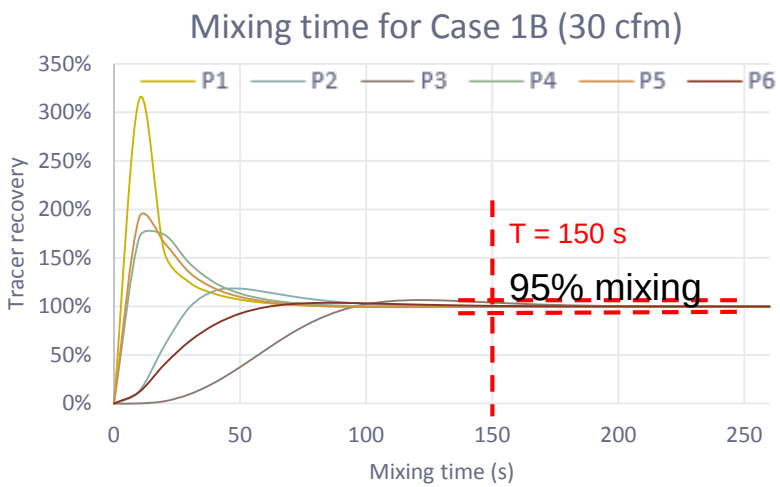


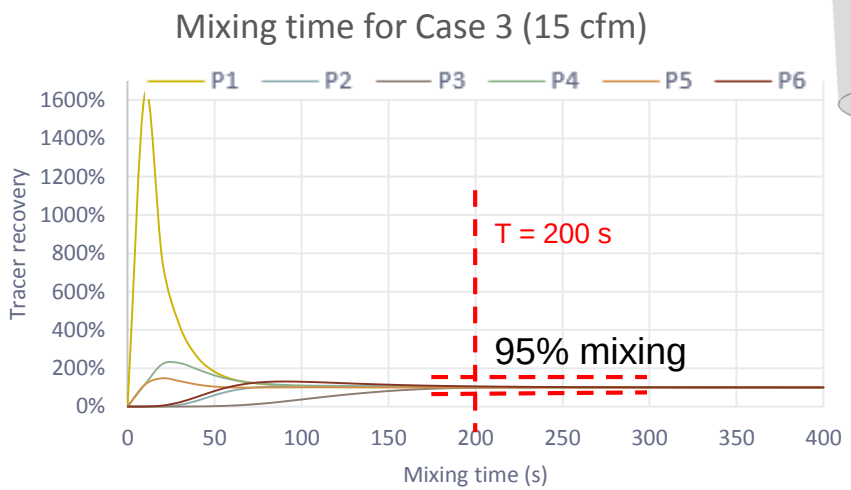
	Argon volume flow rate per inlet (cfm)	Slag eye size (in)		
		CFD	Plant data	Difference
Case 1B	30	31.0	28.8	7.64 %
Case 3	15	17.8		
Case 4	7	5.8		
Case 5	5			

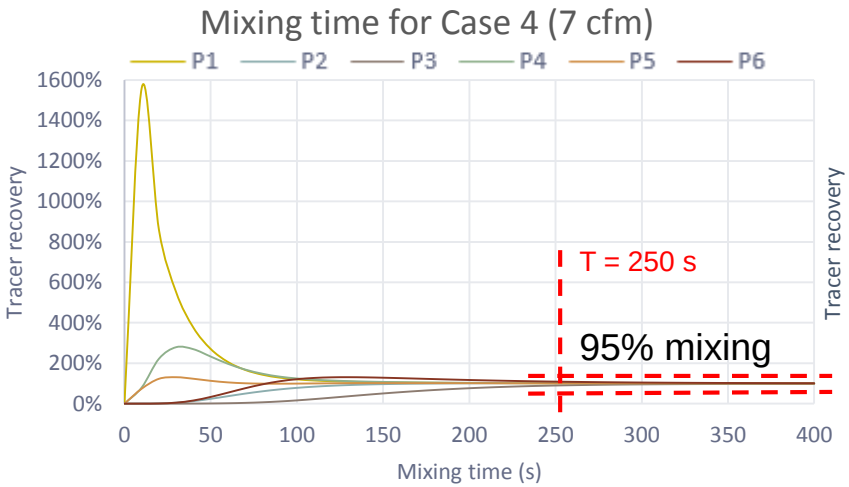
- 5 cfm argon flow rate was too small to open the slag eyes.
- Larger flow rate made the slag eye sizes bigger.

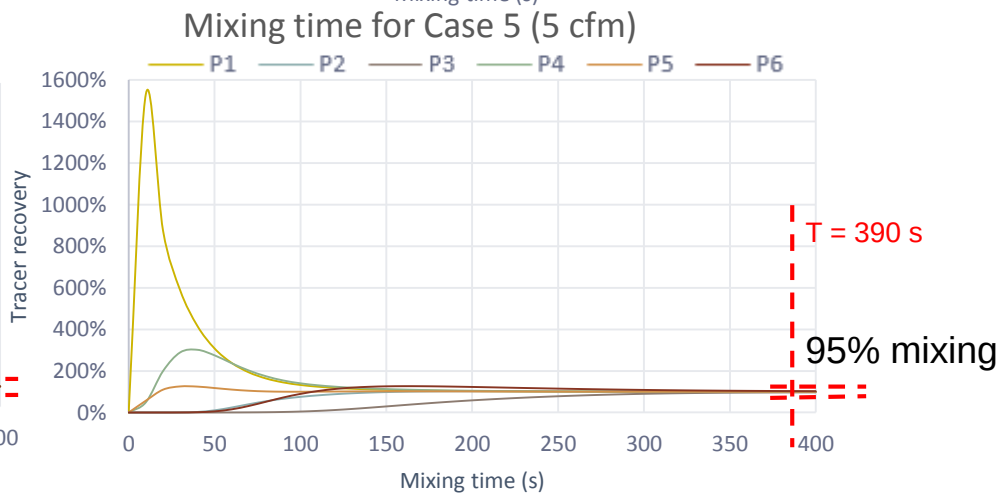
MIXING TIME





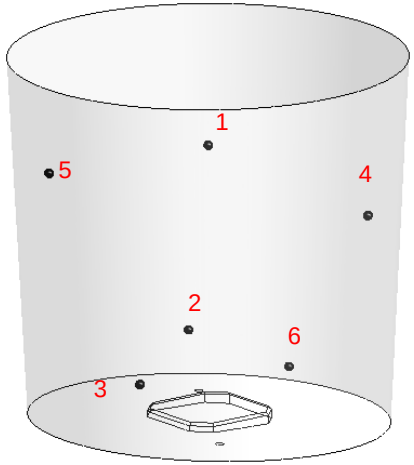






- The tracer recovery reached 95% later at point 3 for all the four cases, this is because point 3 is located at dead zone.

MIXING TIME



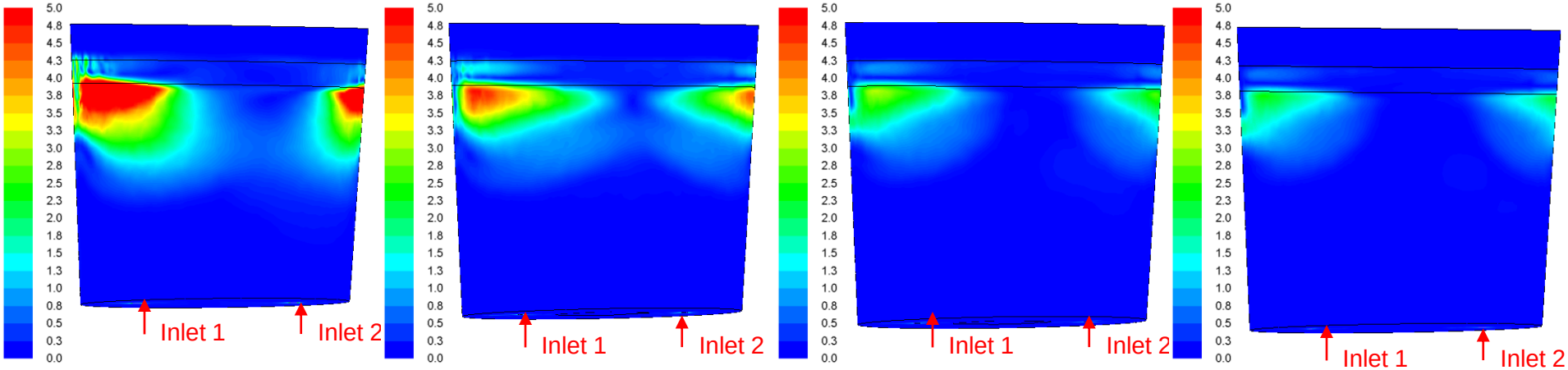
Point 1 (0, 2.8, 0)
Point 2 (-1, 1.5, 1)
Point 3 (0, 0.4, -1)
Point 4 (1, 2.2, 1)
Point 5 (-1, 2.5, -1)
Point 6 (0.5, 0.8, 0.5)

	Volume flow rate per inlet (cfm)	Mixing time (s)
Case 1B	30	150
Case 3	15	200
Case 4	7	250
Case 5	5	390

- When argon flow rate decreased, mixing time would be longer.
- 30 cfm and 15 cfm had a shorter mixing time, which was more suitable for homogenization.

WALL SHEAR STRESS

- Case 1B (30 cfm)
- Case 3 (15 cfm)
- Case 4 (7 cfm)
- Case 5 (5 cfm)



	Volume flow rate per inlet (cfm)	Maximum shear stress (Pa)
Case 1B	30	9.5
Case 3	15	4.9
Case 4	7	3.2
Case 5	5	2.5

- 30 cfm argon gas flow pushed slag and steel against wall, and the strong flow of molten steel may wear off the refractory of ladle wall, thus reducing ladle life.

SUMMARY

- The DPM-VOF model predicts the slag eye size more precisely compared with Eulerian-VOF model.
- The slag eye diameter is bigger when volume flow rate is larger.
- Dead zone is located at the corner of the bottom of ladle, which will extend the mixing time of alloying.
- A volume flow rate at 30 cfm or 15 cfm is good for homogenization since the mixing time is relatively shorter, However, 30 cfm has a tendency to entrap slag and reduce ladle life.
- A Volume flow rate at 7 cfm or 5 cfm is good for removing inclusions.

YEAR 2 TASKS

- 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.
- Develop EMS ladle model
  - Develop magnetic field.
  - Develop forces exerting on melt.

TIMELINE – YEAR 2

Tasks:
1.Literature research 2. Modify DPM-VOF coupled model 3. Baseline case for EMS ladle model 4. Add desulfurization and deoxidation 5.Model Validation 6. Parametric study 7. Analysis and optimize.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Task1	→	→										
Task2	→	→	→									
Task3	→	→	→									
Task4		→	→	→	→	→						
Task5												
Task6					→	→	→	→	→	→		
Task7												