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"

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

STATE OF THE ART

- **Simplified gas injection CFD simulation**
  - The VOF multiphase model was employed to simulate the interaction among the phases (Carlos A., et al., ISIJ International, 2010)
  - Transient numerical simulation was conducted to clarify the gas injection into the molten steel (Yan-He, et al., Advances in Mechanical Engineering, 2014)
- **Particle bubble injection CFD simulation**
  - The DPM-VOF coupled model could predict the unsteady bubble movement and slag eye formation (L. Li, et al., The Minerals, Metals & Materials Society 2015)
  - The Eulerian-PBM coupled model was used to calculated the bubble size distribution (H. MATSUURA, et al., ISIJ International, 2015)
- **Gap:**
  - No complete comparison between existing multiphase models for ladle applications

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

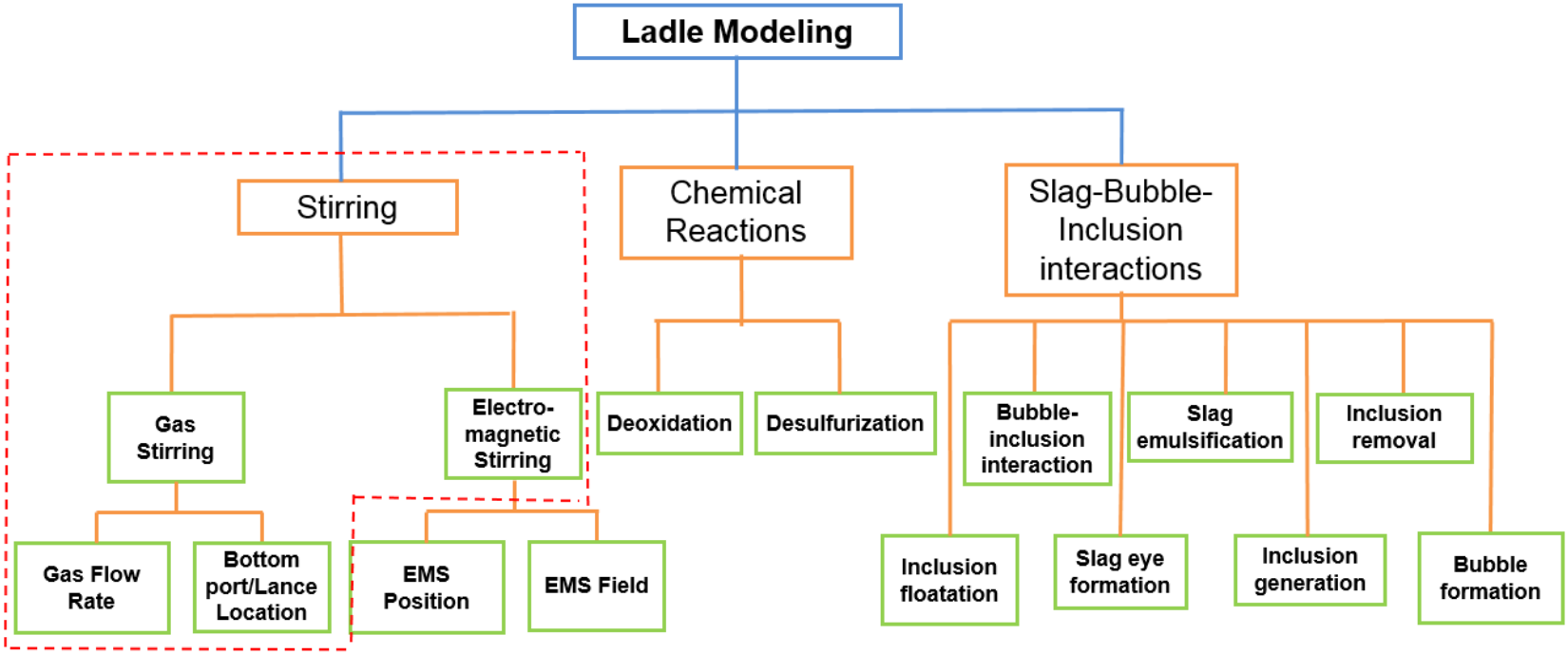
PROJECT TIMELINE

- **Year 1:**
  - Ladle model and condition selection
  - Multiphase mixing model simulating gas stirring process
  - Parametric studies under various stirring operating conditions
  - Development of Electromagnetic stirring (EMS) ladle simulation
- **Year 2:**
  - Desulfurization and deoxidation
  - Species concentration in steel bath
  - Numerical model for bubble formation and interaction
- **Year 3:**
  - Numerical model of inclusion generation due to reactions between steel and alloys
  - Slag eye formation and slag properties
  - Numerical model for slag composition and emulsification
  - Correlation between fluid flow and slag physical properties

PROJECT TIMELINE

- **Year 4:**
  - Inclusion removal and/or generation during hard and gentle stirring
  - Effects of different stirring conditions on the inclusion removal efficiency
  - Validate numerical model with field samples or literature
- **Year 5:**
  - Model thermos-tracking, model integration and simulation, visualization using HPC
  - Ladle transfer time and minimal residence time for cleanliness
  - Inclusion entrapment and interaction with slag under tapping
  - Heat transfer model for ladle refractory/steel shell heat transfer
  - Preheating effect on the refractory performance
  - Integrate the developed numerical model with various physics phenomena

EXPECTED OUTCOMES - YEAR 1



- Development of the baseline gas stirring case based on the NUCOR ladle
- Identification of any dead zone in the standard flow condition
- Correlation between geometrical parameters and mixing time
- Development of EMS ladle simulation

TIMELINE – YEAR 1

- Tasks: 1.Literature research; 2. Ladle selection; 3. Baseline case; 4. Model validation; 5. Analysis and optimize; 6. Parametric study; 7. Develop EMS ladle model

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Task 1												
Task 2												
Task 3												
Task 4												
Task 5												
Task 6												
Task 7												

ACCOMPLISHMENTS

- **Literature Research**

  Several papers and journals related to gas stirring and bubble formation were reviewed and summarized

- **Geometry Development**

  The 3D geometry was developed based on the drawings provided by NUCOR.

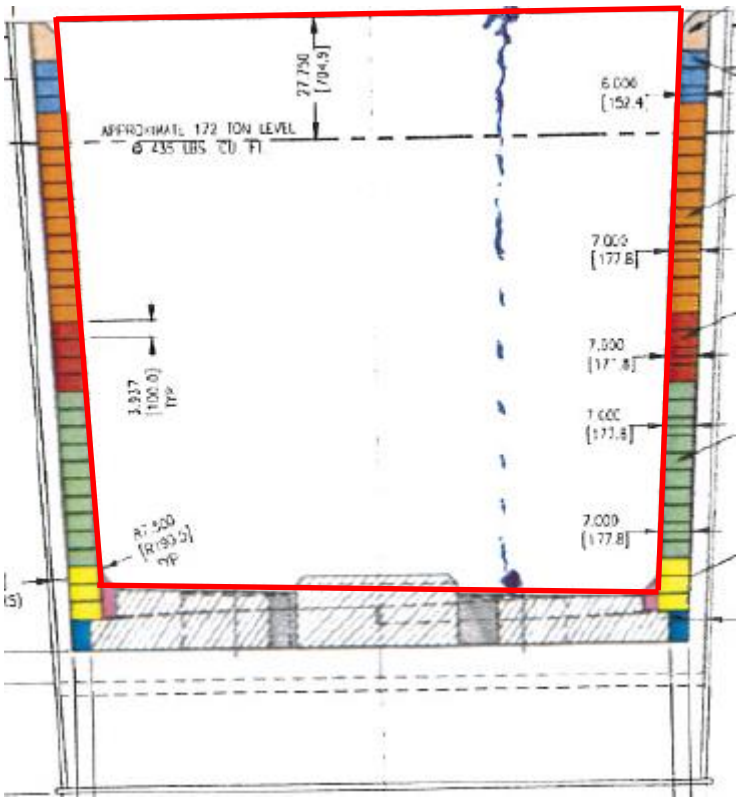
- **Bubble Formation Simulation**

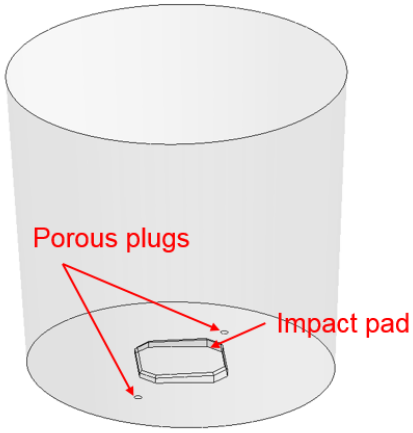
  The baseline cases using different multiphase models were calculated to track the bubble formation in the bath of the ladle.

- **Mixing Process Simulation**

  The mixing time based on current condition was calculated by monitoring the tracer concentration distribution in the ladle.

GEOMETRY



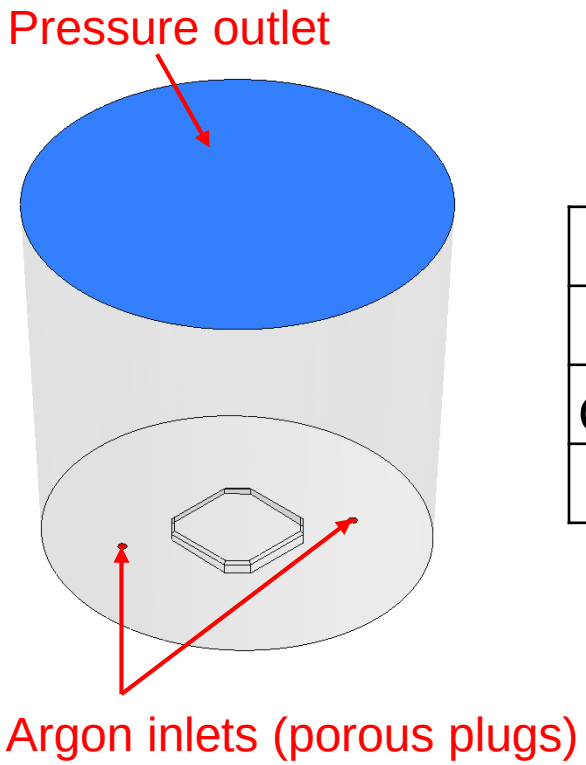


- Technical drawing from NUCOR
- Computational domain

CFD MODELS

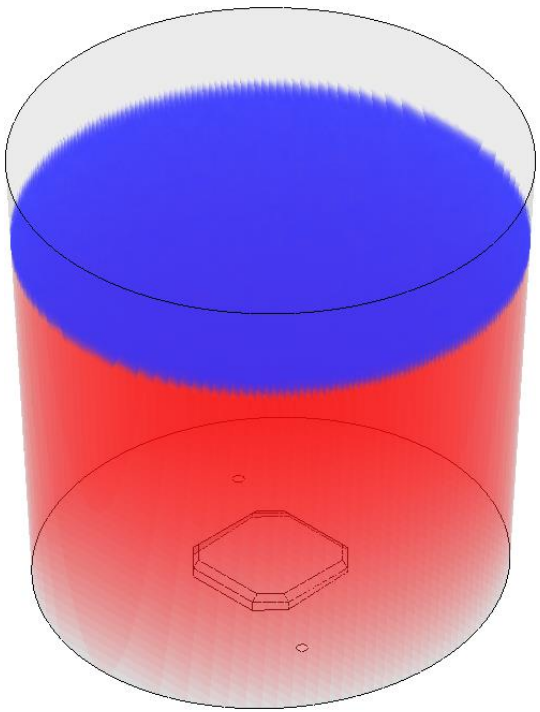
- 3 Dimensional
- Isothermal
- Transient
- Euler-VOF multiphase model
- Species transport
- Realizable k–ε turbulence model

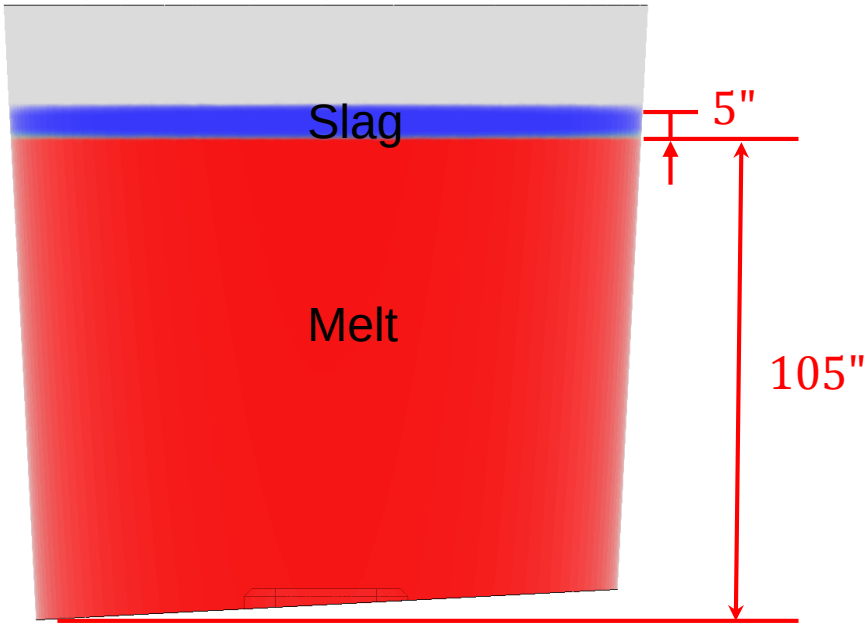
BOUNDARY CONDITIONS



	Condition
Inlet	Mass flow rate, 0.02336 kg/s per inlet
Outlet	Pressure-outlet, 1 atm
Wall	Stationary wall (no-slip)

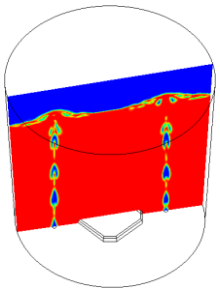
INITIAL CONDITION

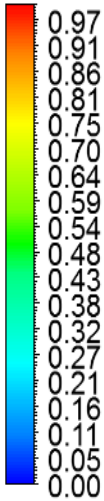




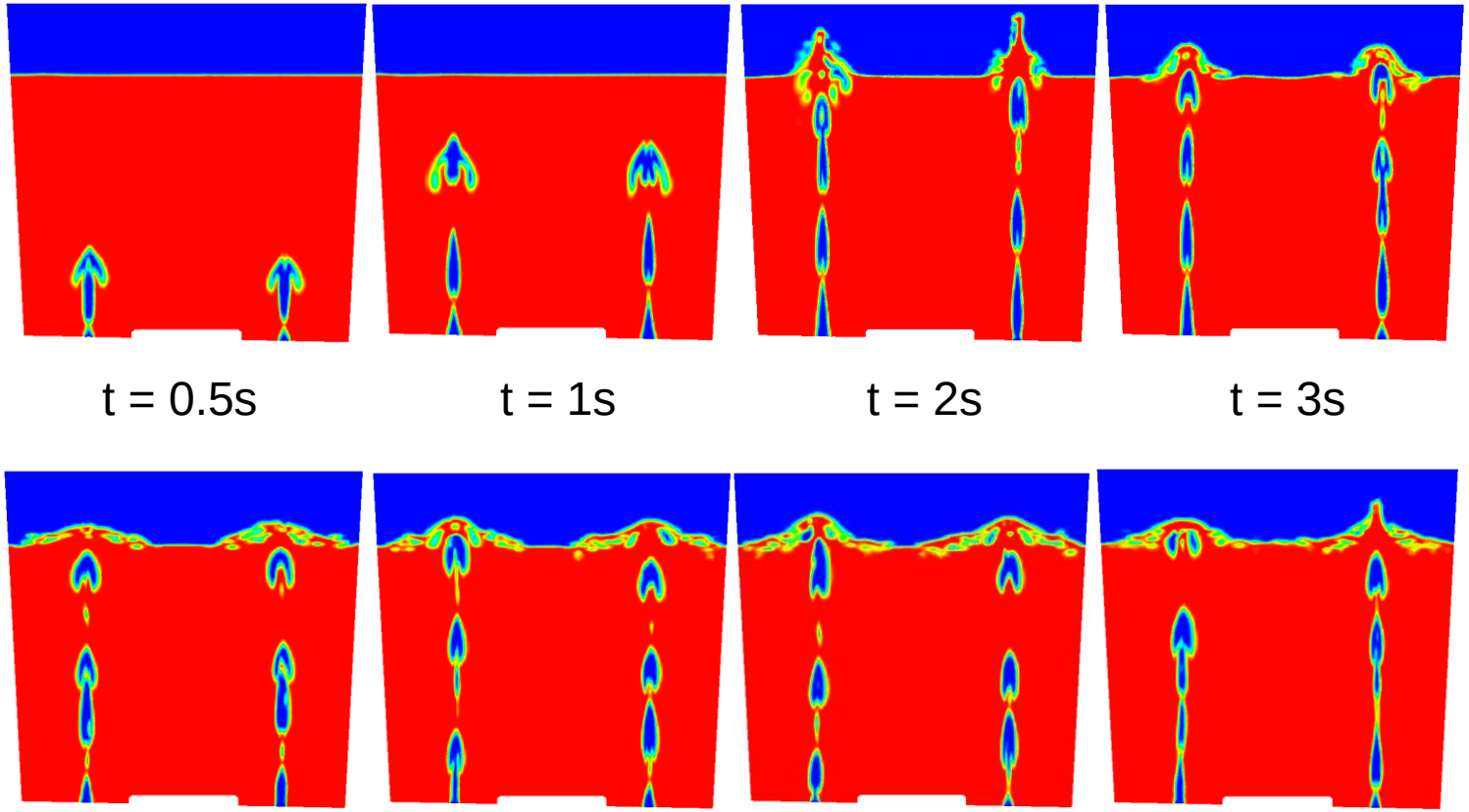
Melt depth is 105 inches, and slag depth is 5 inches.

RESULTS - STEEL DISTRIBUTION





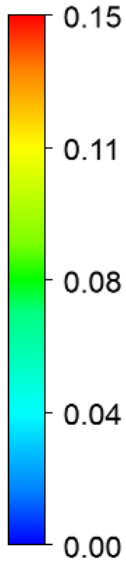
Volume Fraction

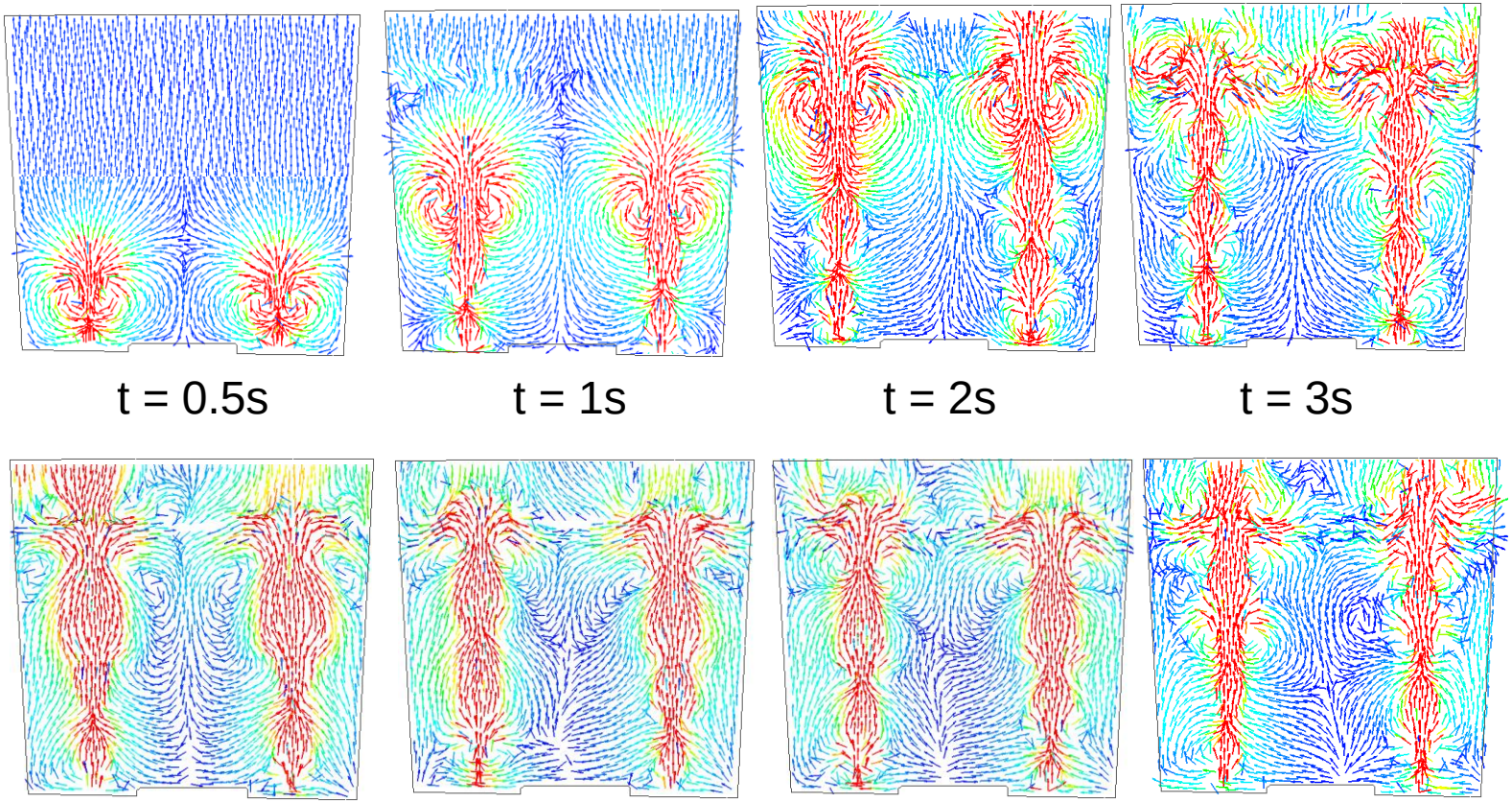


t = 0.5s | t = 1s | t = 2s | t = 3s

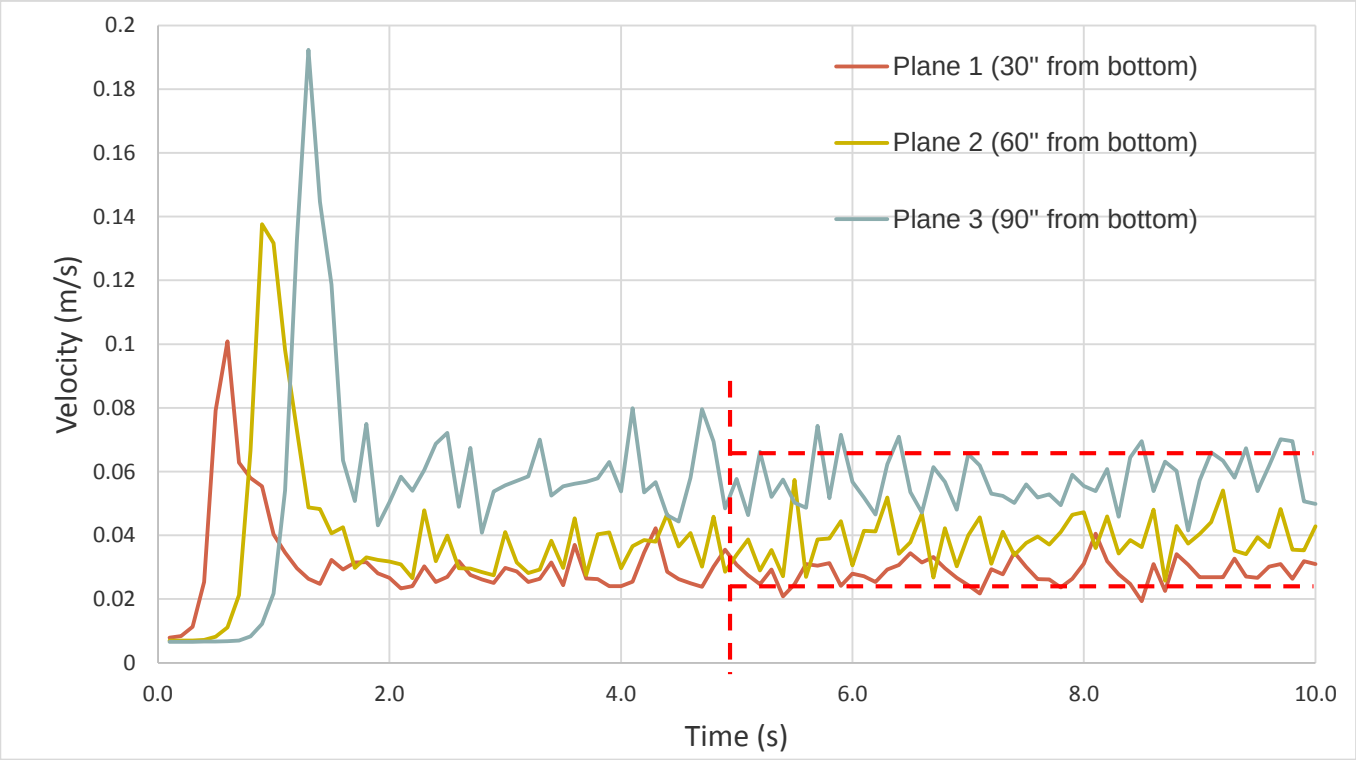
t = 4s | t = 6s | t = 8s | t = 10s

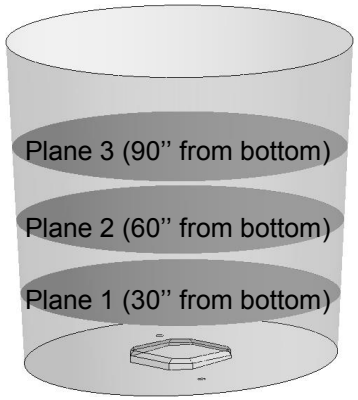
RESULTS – VELOCITY VECTOR





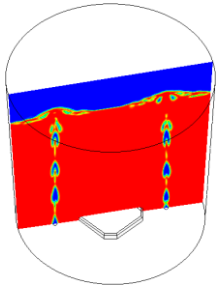
RESULT-VELOCITY MONITOR



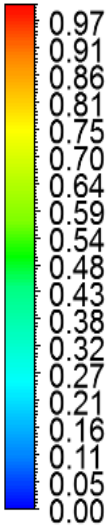


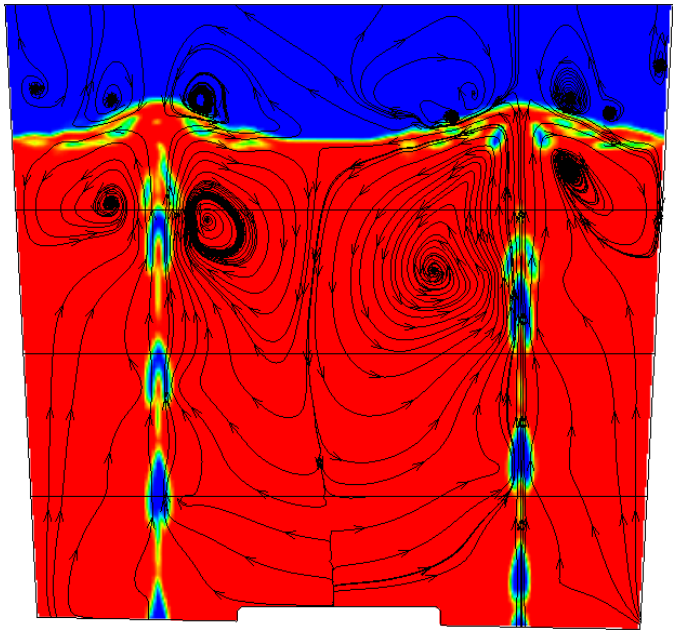
- The flow reached quasi-steady state after approximately 5s.

STREAMLINE ON DIFFERENT SECTIONS



- t = 8s

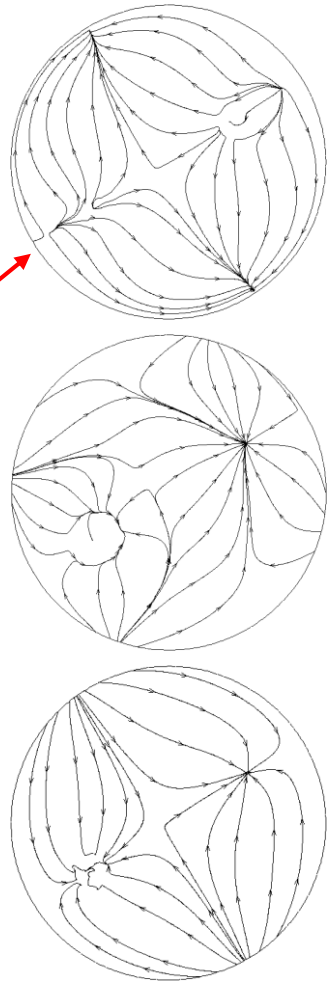




90" from the bottom

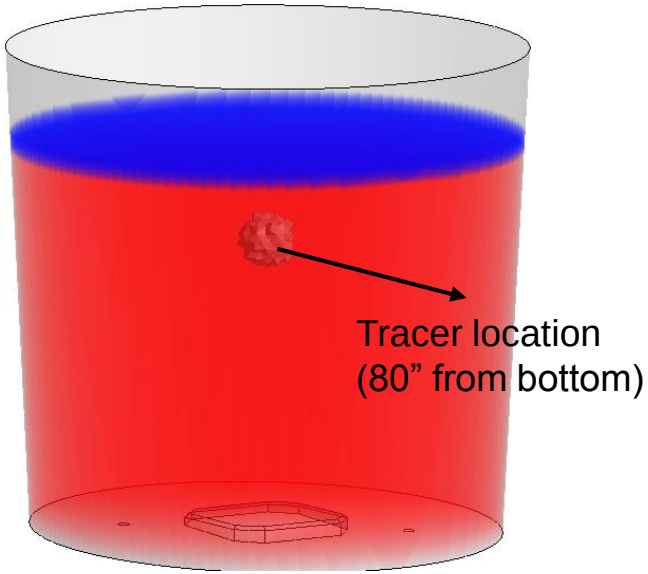
60" from the bottom

30" from the bottom



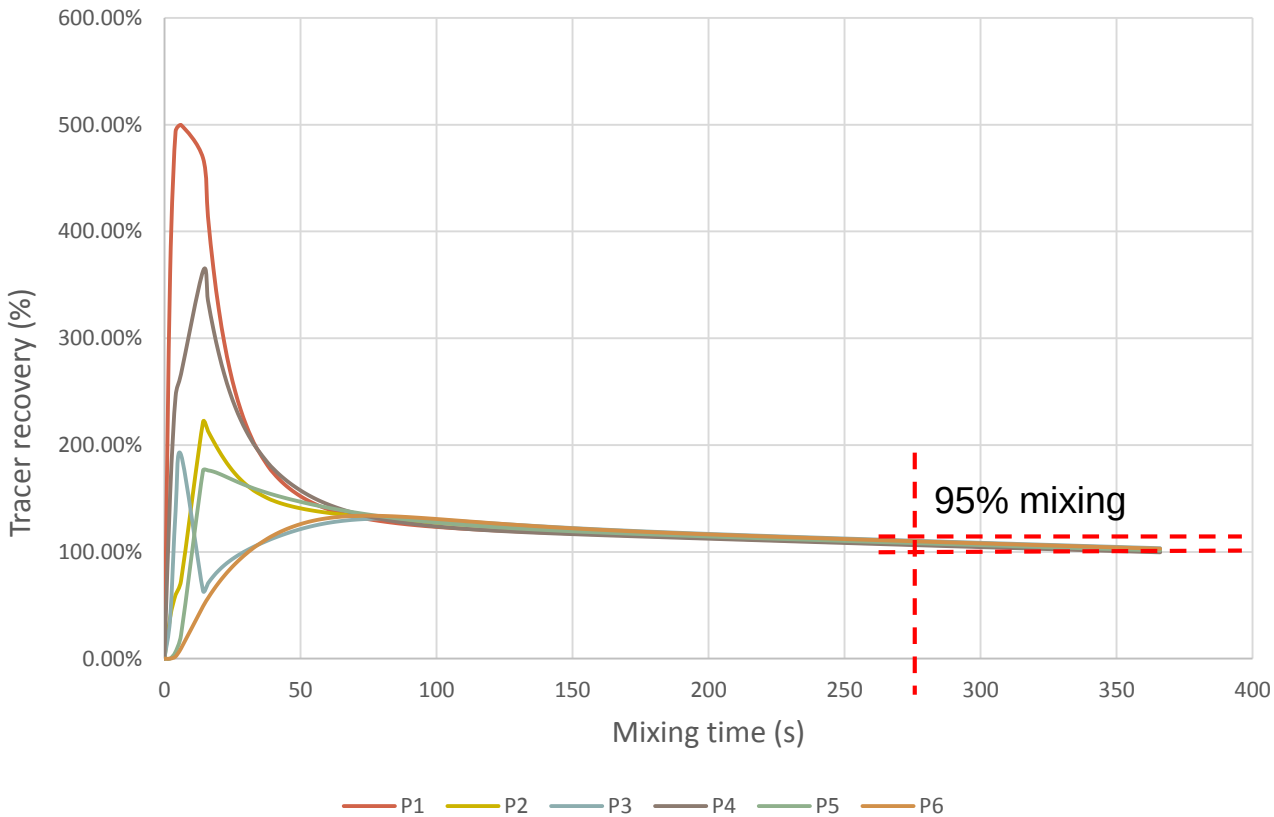
MIXING PROCESS-METHODOLOGY

- The flow reached quasi-steady state after 5s
- 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

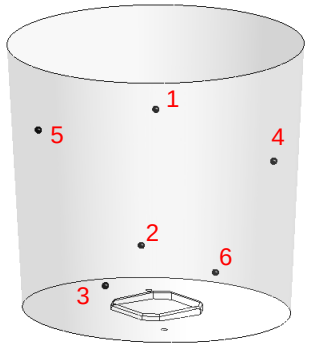


Tracer recovery(%) = Current tracer concentration / Equilibrium tracer concentration

MIXING PROCESS-TRACER RECOVERY



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)



- After approximately 270s, the tracer distribution reached 95% mixing.

NEXT STEPS

- Develop the bubble formation simulation using DPM-VOF model
- Validate the mixing time with experimental data
- Begin development of the EMS ladle simulation

SUMMARY

- Literature research about gas stirring ladle was achieved
- 3D Geometry model for the ladle with bottom porous plugs has been developed.
- Multiphase flow model has been developed, and the flow pattern inside the ladle under typical operating condition has been investigated.
- The mixing process for current operating condition has been computed.

COMMENTS FROM INDUSTRIL REPRESENTATIVE

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Thank you !