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

Project Technical Committee (PTC):

- **Helmut Oltmann (Nucor)**
- Paul Wu (AK Steel)
- Hoyong Hwang (ArcelorMittal)
- Rui Liu (ArcelorMittal)
- April Pitts (Nucor)
- Abhishek Bhansali (Nucor)
- Eugene Pretorius (Nucor)
- Vivek Thapliyal (Nucor)
- Chase Ault (SDI)
- Sunday Abraham (SSAB)
- Alyssa Briere (Stelco)
- Richard Zhang (Stelco)
- Jeffrey Becker (USS)

CIVS Team:

- **Justina Lee**
- Dan Yan
- Armin Silaen
- Chenn Zhou

"Where Ideas Become Reality"

OUTLINE

- Introduction
  - Project objective
  - Project outcomes
  - Current work
  - Timeline
- Methodology and CFD Models
- Gas-stirred ladle model
- Inclusion removal model
- Parametric study on mixing efficiency
- 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 SUBPROJECTS

	Subprojects	2016	2017	2018	2019	2020
1	Isothermal gas-stirring ladle model					
2	Heat transfer model					
3	Gas-stirred isothermal inclusion removal					
4	Inclusion interaction mechanisms					
5	EMS isothermal inclusion removal					
6	Ladle chemical reaction					
7	Heat transfer effect on inclusion removal					

PROJECT OUTCOMES (Year 1 and Year 2)

- **Subproject 1 – Isothermal Gas-stirring Ladle Model (completed)**
  - **Models:**
    - 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.
    - Bubble breakup and coalescence model based on Laux and Johansen theory.
    - Model validation with water model, cold metal model experimental data and plant measurement. Average percentage of 8.71% different compared with plant measurement.

PROJECT OUTCOMES (Year 1 and Year 2)

- **Research Findings:**
  - Effects of argon flow rate
    - Argon flow rate ↑, slag eyes size ↑
    - Argon flow rate ↑, wall shear stress ↑
    - Argon flow rate ↑, mixing time ↓
  - Effects 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 reach equilibrium diameters as time elapse
  - Effects 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 ↑

PROJECT OUTCOMES (Year 1 and Year 2)

- **Subproject 2 – Heat Transfer Model (completed)**
  - **Models:**
    - Heat transfer gas-stirring ladle model. The temperature stratification is reduced with gas-stirring
  - **Research Findings:**
    - Effect of initial wall temperature – Temperature stratification decrease faster with higher wall initial temperature

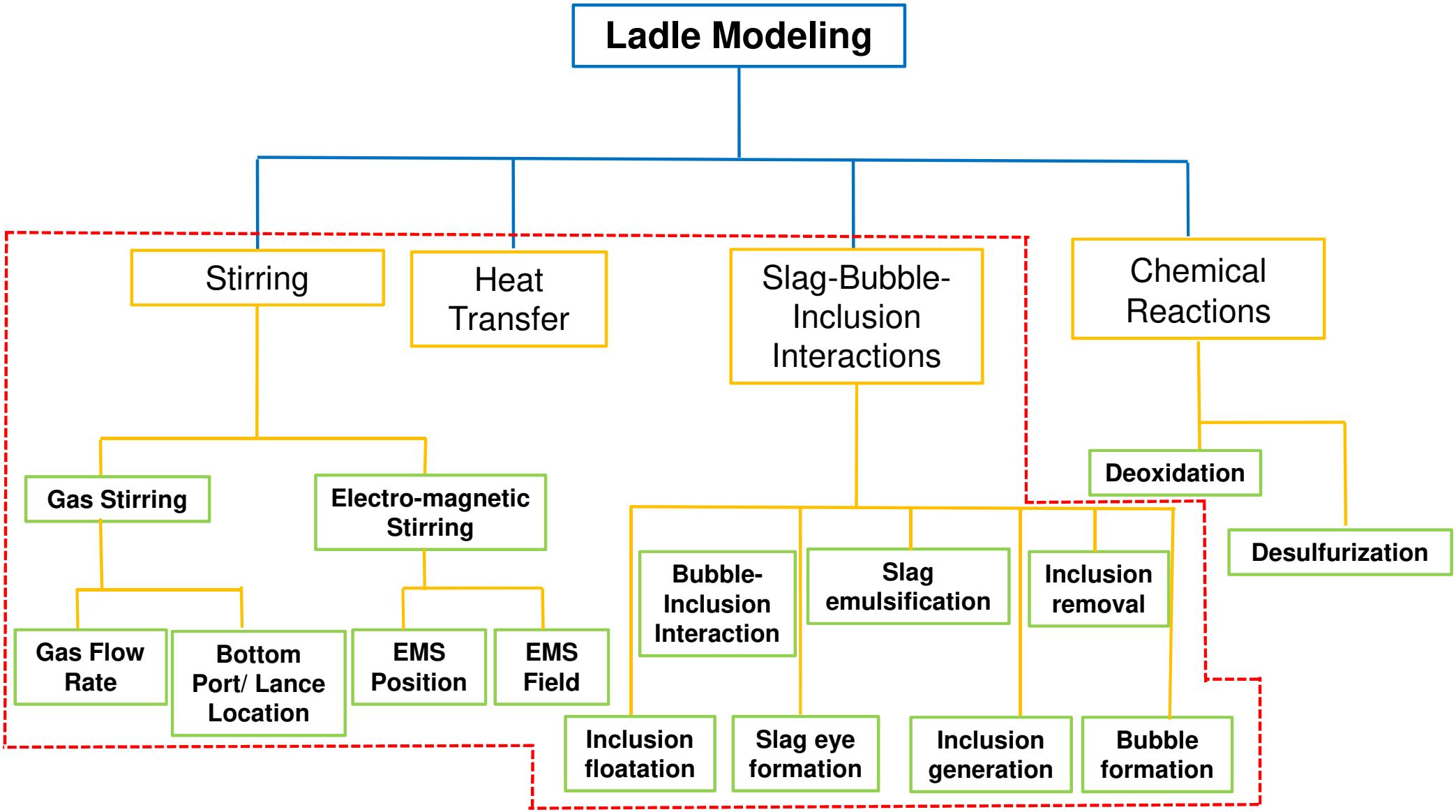
OBJECTIVES – 3rd YEAR

- **Subproject 3 – Gas-Stirred Isothermal Inclusion Removal**
  - Develop basic inclusion removal model in isothermal conditions, with predefined initial inclusion size distribution and simplified inclusion removal criteria.
- **Subproject 4 – Inclusion Interaction Mechanisms**
  - Develop inclusion growth mechanism from multiple sources such as inclusion-inclusion collision, as well as refine inclusion-bubble interactions and removal mechanisms.
- **Subproject 5 – EMS Isothermal Inclusion Removal**
  - Develop a working multiphase EMS model with included slag layer.

TIMELINE FOR 2018

	Task	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Subproject 3 Gas-Stirred Isothermal Inclusion Removal	Literature research												
	Develop geometry												
	Develop base case												
	Model validation												
	Parametric study												
Subproject 4 Inclusion Interaction Mechanisms	Literature research												
	Inclusion growth mechanism												
	Inclusion-inclusion interaction												
	Inclusion- bubbles interaction												
	Improve inclusion removal												
Subproject 5 EMS Isothermal Inclusion Removal	Develop magnetic field												
	Multiphase EMS												
	EMS with imported field												
	EMS with inclusion												

ROADMAP


Ladle Modeling
Stirring
Heat Transfer
Slag-Bubble-Inclusion Interactions
Chemical Reactions
Gas Stirring
Electro-magnetic Stirring
Gas Flow Rate
Bottom Port/ Lance Location
EMS Position
EMS Field
Bubble-Inclusion Interaction
Slag emulsification
Inclusion removal
Inclusion floatation
Slag eye formation
Inclusion generation
Bubble formation
Deoxidation
Desulfurization

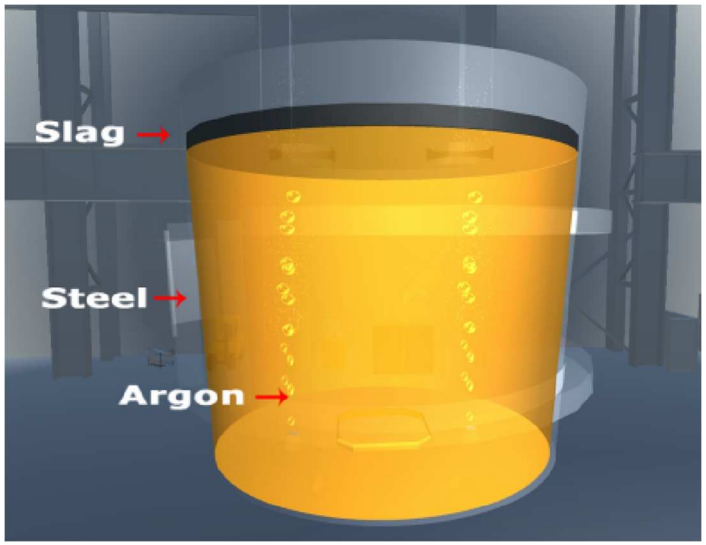
STATE OF THE ART

- Gas-stirred ladle - flow field, slag eye or effect of ladle design on the mixing efficiency [1-3].
- Comparison of induction stirring (EMS) with gas stirred ladle and combined gas/EMS [4].
- Inclusion behavior modeled by 4 main methods.
  - Static numerical models of nucleation, growth and removal of inclusions [5-7]. **No consideration of inclusion transport.**
  - CFD-based trajectory method [8-10]. **No consideration of inclusion collision and agglomeration.**
  - CFD-based characteristic inclusion parameters [11-13]. **Inclusion distribution is simplified with exponential function with inclusion radius.**
  - CFD-based PBM coupled model [14-16]. Inclusion divided into multiple groups size. **Assumptions of flat free surface without slag and constant bubble size. Predefined initial inclusion distribution.**

CFD METHODOLOGY

Gas-stirred ladle model

- Fluid zones (slag, melt, inclusion and air)
  - Multiphase flow: **Eulerian-Eulerian**
  - Eulerian parameter: Multi-fluid VOF model
  - Turbulent model: Realizable k-epsilon
- Argon injection
  - Discrete phase model



1) Import quasi-steady velocity ($u_{x,y,z}$), volume fraction (α_{phase}), turbulence k & ε (for slag, melt and air)
2) Apply melt $u_{x,y,z}$, k & ε into inclusion phase

Inclusion removal model

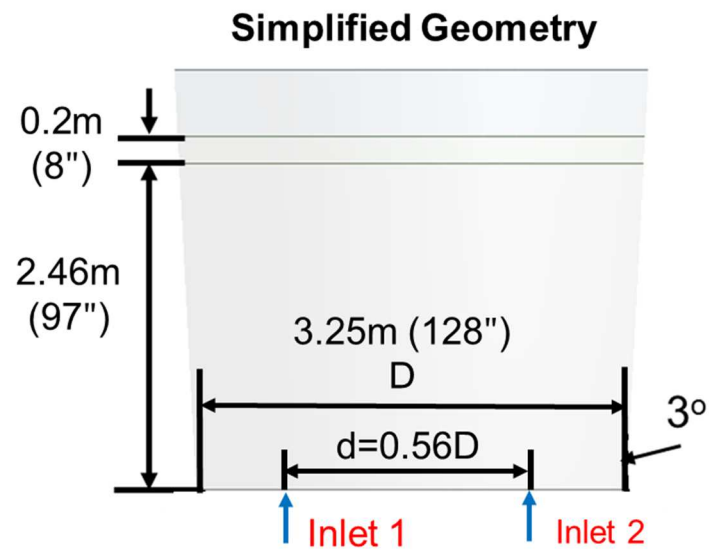
- **Inclusion transport**
  - **Population balance model (PBM) - discrete method**
- **Inclusion removal**
  - **Removal from slag and wall only**

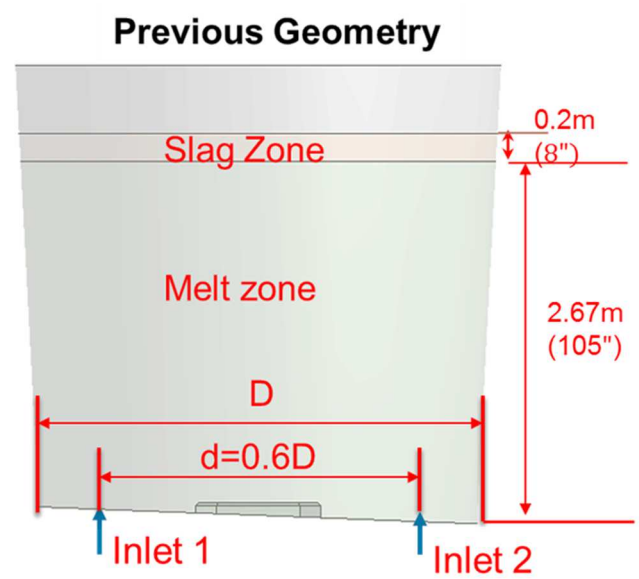
GAS-STIRRED LADLE MODEL

LADLE GEOMETRY

- Simplified geometry based on NS Decatur ladle

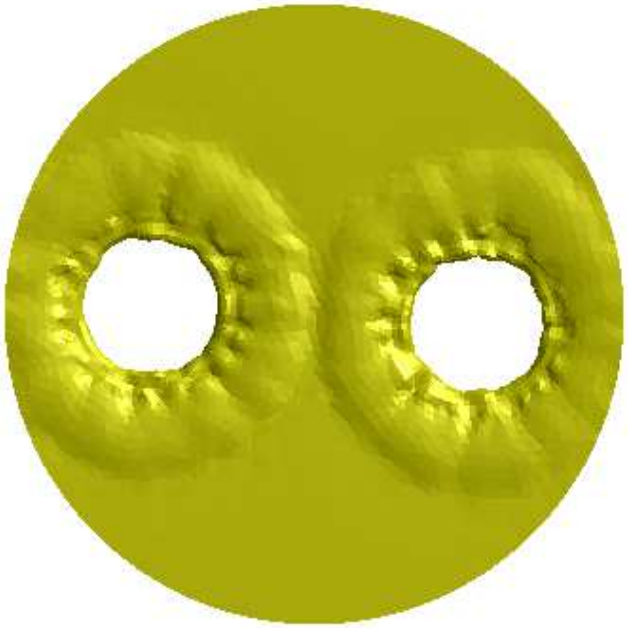
Parameters	Simplified Geometry
Melt depth (m)	2.46
Slag depth (m)	0.2
Wall taper angle (°)	3
Plug distance ratio $\left(\frac{\text{Distance between plugs}}{\text{Floor diameter}}\right)$	0.56
Aspect ratio $\left(\frac{\text{Melt height}}{\text{Diameter @ slag} - \text{metal interface}}\right)$	0.7



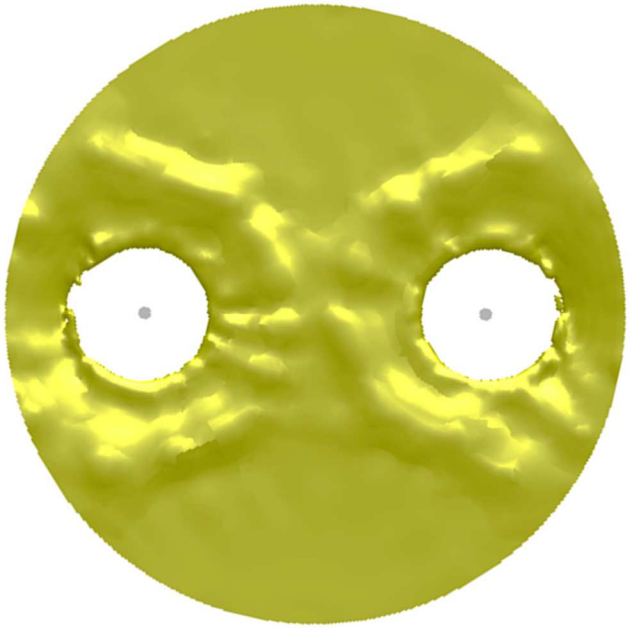


SLAG EYES COMPARISON

- Base Case
  - Argon flow rate: 30SCFM/plug



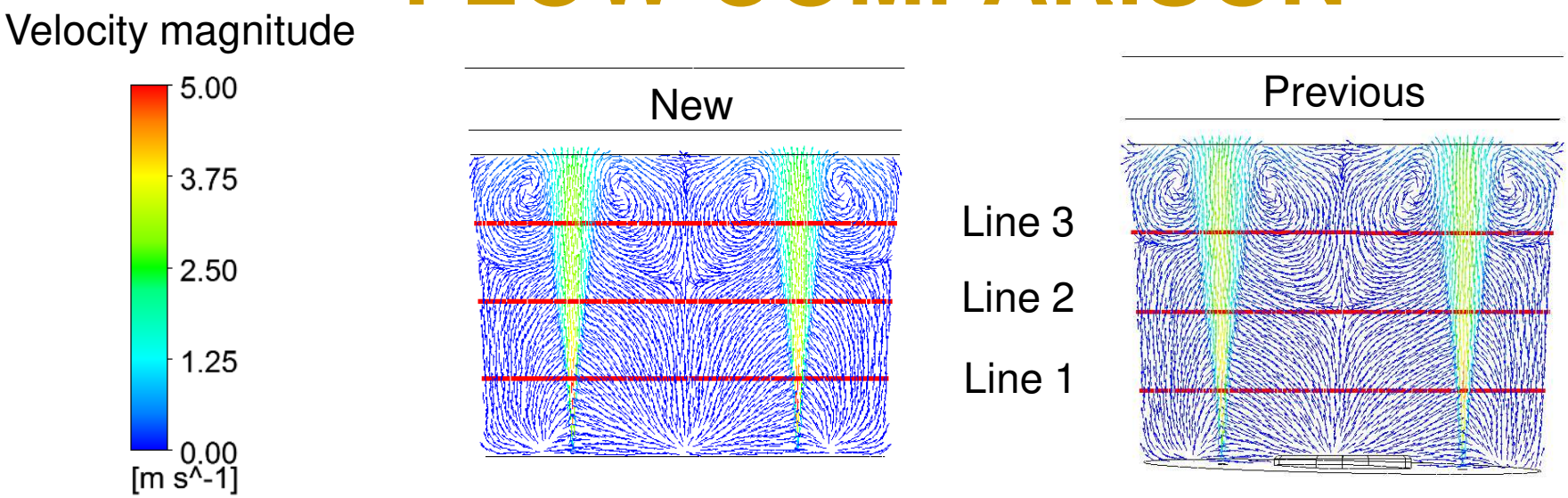
New geometry with Eulerian-Eulerian model

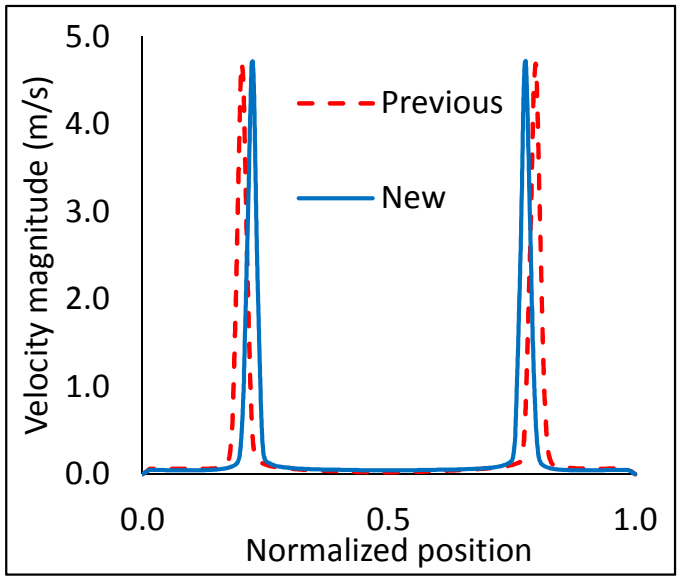


Previous geometry with Eulerian-VOF model

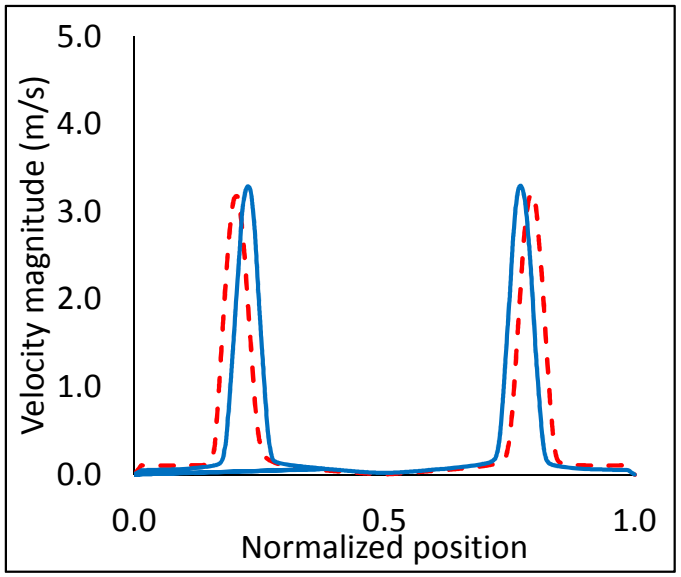
	Slag eye size (m)
New geometry with Eulerian-Eulerian model	0.80 (31.5 in)
Previous geometry with Eulerian-VOF model	0.79 (31.2 in)
Nucor plant measurements	0.7-0.79 (28-31 in) out of 5 measurement

FLOW COMPARISON

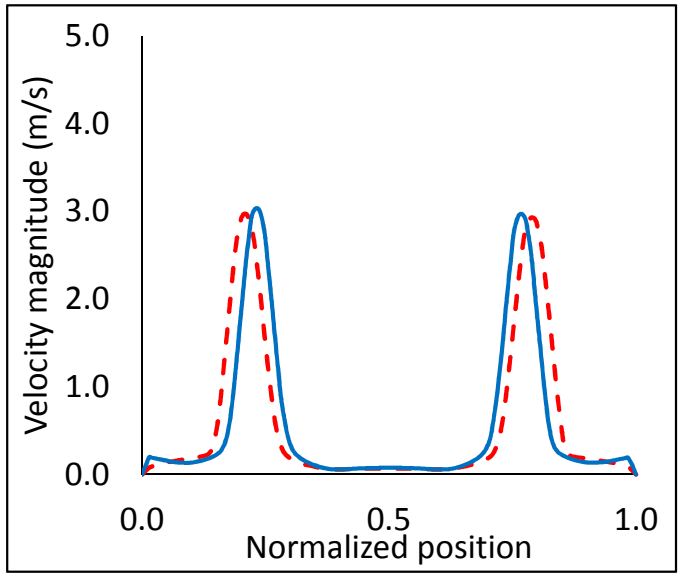




Line 1



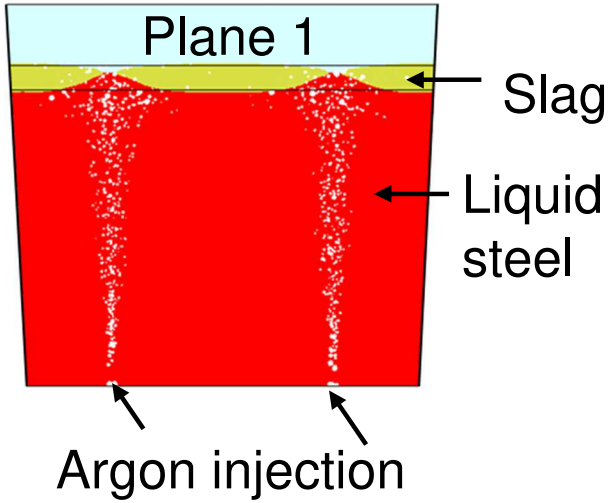
Line 2

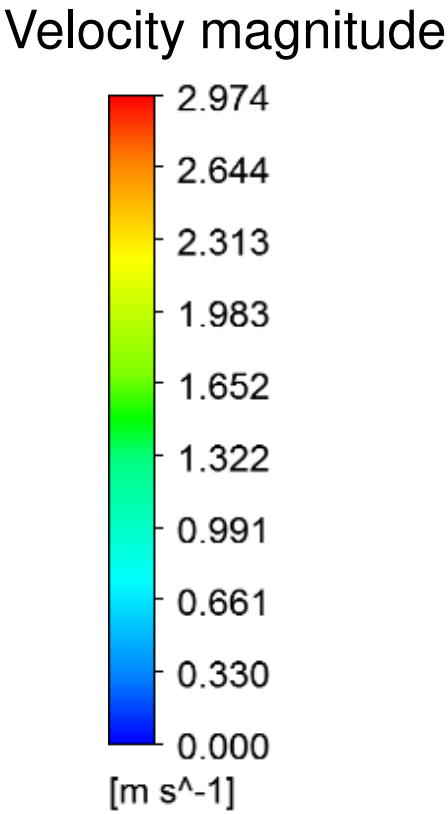


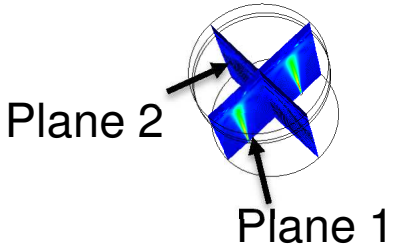
Line 3

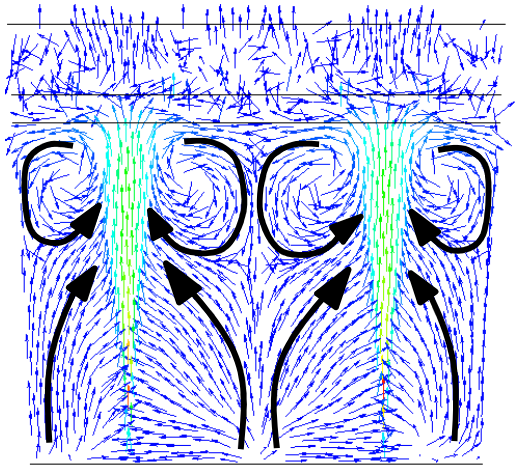
GENTLE STIRRING SIMULATION RESULTS

- For inclusion removal process gentle stirring is needed
  - Argon flow rate: **5SCFM**/plug

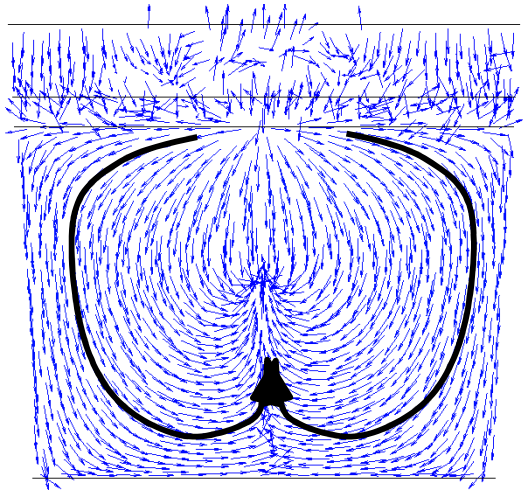








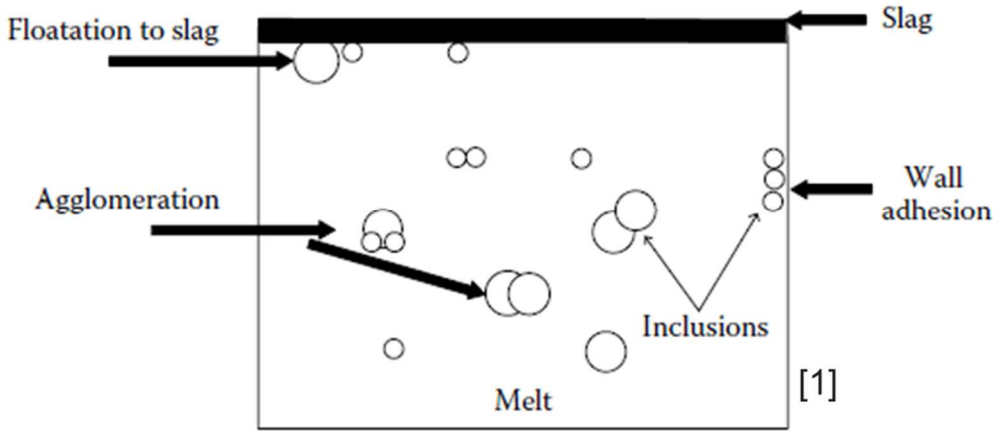
Plane 1



Plane 2

INCLUSION REMOVAL MODEL

INCLUSION REMOVAL MECHANISM



- Inclusion removal mechanisms
  - **Slag**
    - Inclusions reach the slag through flow motion and floatation.
  - **Wall**
    - Inclusion attachment to refractory
  - Collision and growth (Subproject 4)
    - Agglomeration from inclusion-inclusion collision
  - Bubble (Subproject 4)
    - Inclusion attachment to bubbles

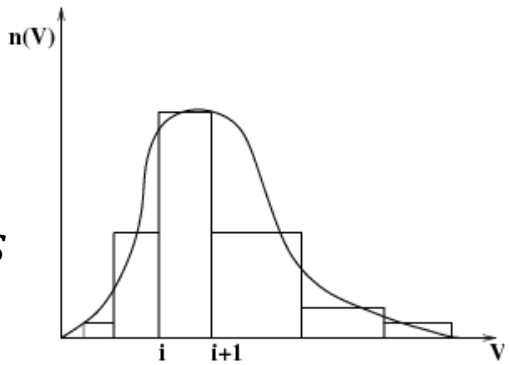
1. Mazumdar, Dipak, and James W. Evans. *Modeling of steelmaking processes*. CRC Press, 2009.

INCLUSION REMOVAL MODEL

- Population balance equation (PBE):

$$\frac{\partial}{\partial t}[n(V_i,t)] + \nabla \cdot [\vec{u}_p n(V_i,t)] = \mathrm{S_i^W} + \mathrm{S_i^S}$$

$$\frac{\partial}{\partial t}[\rho_p \alpha_i] + \nabla \cdot [\vec{u}_p \rho_p \alpha_i] = \rho_p V_i S_i^W + \rho_p V_i S_i^S$$



Particle size groups

- Mass conservation equation:

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla \cdot (\alpha_p \rho_p \vec{u}_p) = \rho_p V_i \mathrm{S_i^W} + \rho_p V_i \mathrm{S_i^S}$$

- Only inclusion removal through slag and wall are considered.
- Inclusion growth due to nucleation, diffusion and coalescence and removal through bubbles will be included in Subproject 4.

$n(V_i,t)$	:	inclusion number density (particle/m^3)	V_i	:	inclusion volume of size i (m^3)
$\vec{u}_p$	:	inclusion velocity (m/s)	α_i	:	inclusion volume fraction of size i
$\mathrm{S_i^W}$	:	inclusion removal at wall (1/m^3.s)	$\mathrm{S_i^W}$	:	Inclusion removal at slag (1/m^3.s)

INCLUSION REMOVAL RATE

- **Inclusion removal from wall through diffusion process [1]**

$$S_i^W = \frac{0.0062\varepsilon^{\frac{3}{4}}}{v^{\frac{5}{4}}} \frac{A_s}{V_{cell}} r_i^2 n(V_i, t) \ (1/\mathrm{m}^3.\mathrm{s})$$

- **Inclusion removal at slag/steel interface due to inclusion Stoke floatation [2]**

$$S_i^S = \frac{dn}{dt} = -\frac{n_i \cdot u_{st}}{h} \ (1/\mathrm{m}^3.\mathrm{s})$$

- Inclusions are assumed to remove from the slag by floatation.
- The factor on the ability of the inclusions to overcome interfacial energy at the interface during the separation process is currently neglected.

$n(V_i, t)$: inclusion number density (particle/m^3)
V_{cell} : cell volume of boundary layer (m^3)
h : local fluid height (m)
A_s : local interface area (m^2)
u_{st} : floating velocity calculated by Stokes' law (m/s)

1. W. T. Lou, and M. Y. Zhu. "Numerical simulations of inclusion behavior in gas-stirred ladles." *Metallurgical and Materials Transactions B* 44.3 (2013): 762-782.
2. Y.J. Kwon, J.Zhang, and H.G. Lee. ISIJ International, Vol. 48 (2008), No. 7, pp. 891–900

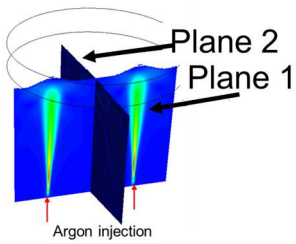
INCLUSION INITIAL CONDITION AND MATERIAL PROPERTIES

- Uniform size of 5 µm inclusion.
- Uniform initial inclusion number density:

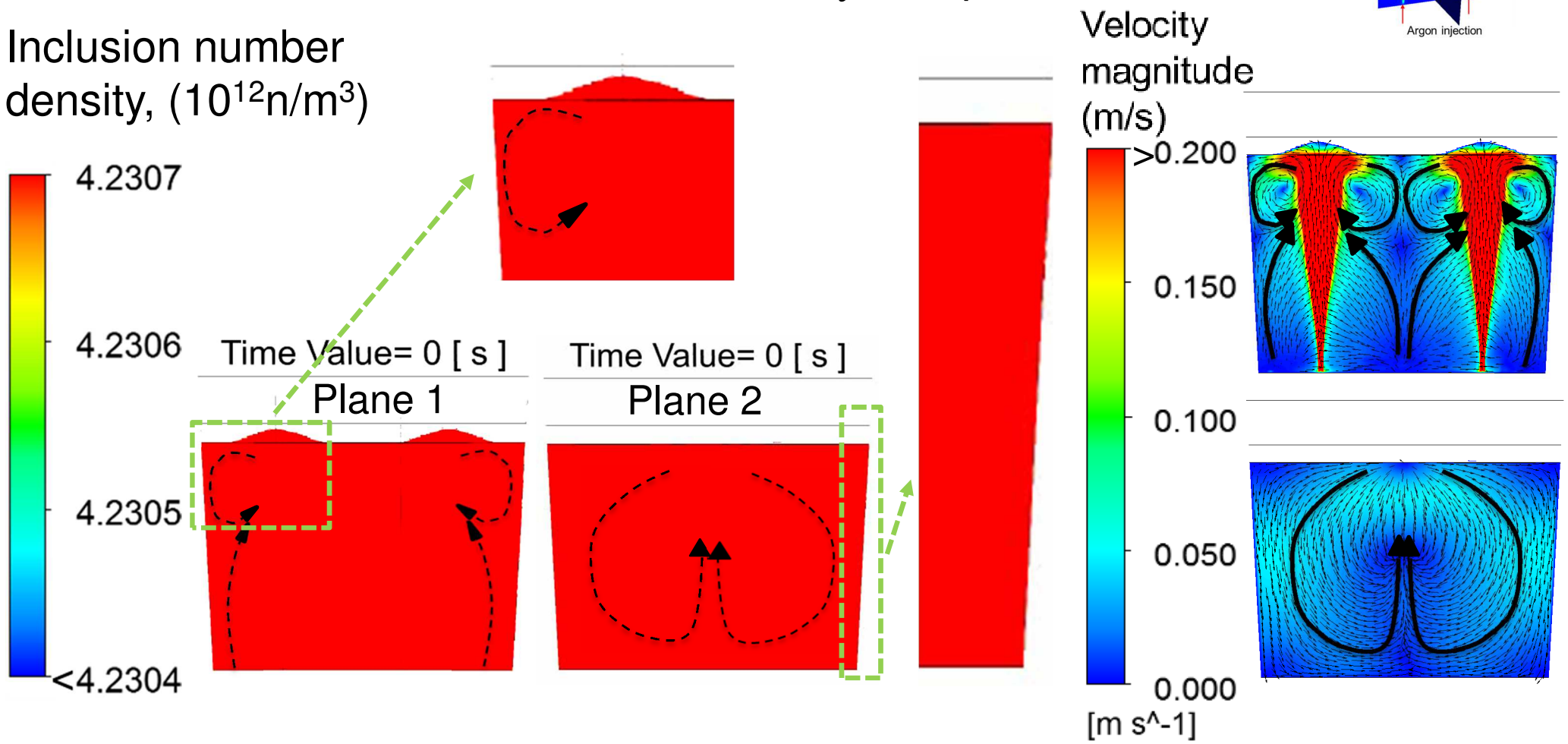
  $n \approx 4.23 \times 10^{12}\ /m^3$ [1,2]
- Density of inclusion, ρ_p = 3900 kg/m^3 [1]
- Density of liquid steel = 6975 kg/m^3

1. D. Q. Geng, H. Lei, and J. C. He. "Numerical simulation for collision and growth of inclusions in ladles stirred with different porous plug configurations." *ISIJ international* 50.11 (2010): 1597-1605.
2. L. T. Wang, Q. Y. Zhang, S. H. Peng and Z. B. Li. "Mathematical model for growth and removal of inclusion in a multi-tuyere ladle during gas-stirring." *ISIJ international* 45.3 (2005): 331-337.

REMOVAL FROM WALL ONLY



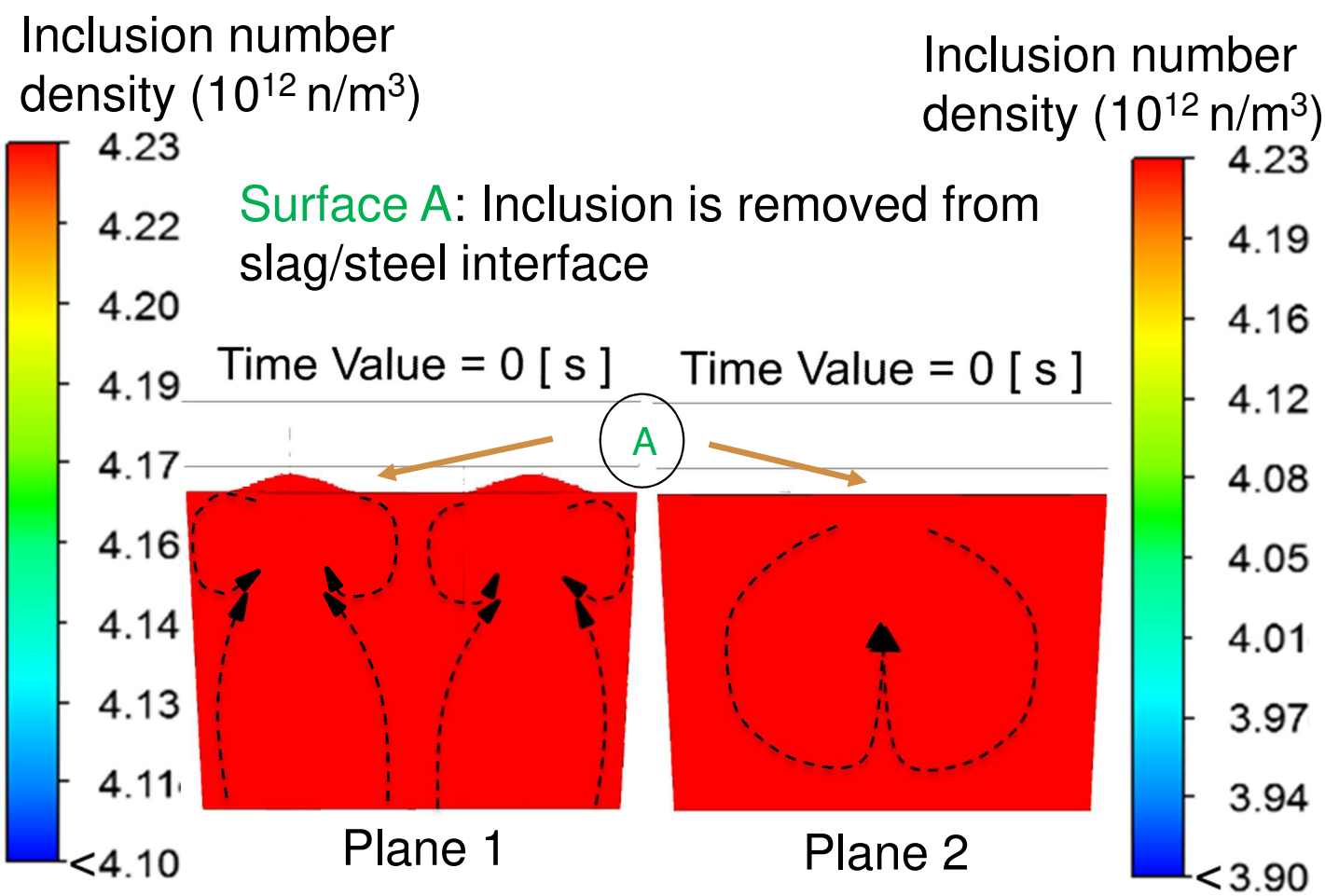
Inclusion diameter, $d_i = 5\ \mu m$

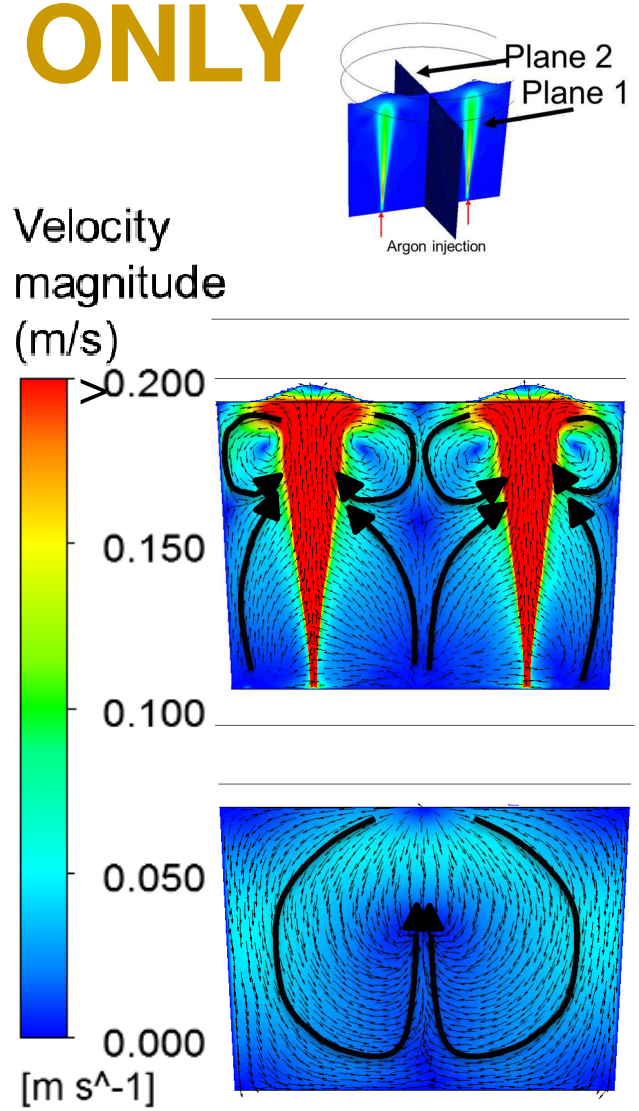


- Number density is reduced near to wall region.
- Higher removal rate at the region where velocity is higher.

REMOVAL FROM SLAG ONLY

Inclusion diameter, $d_i = 5\ \mu m$





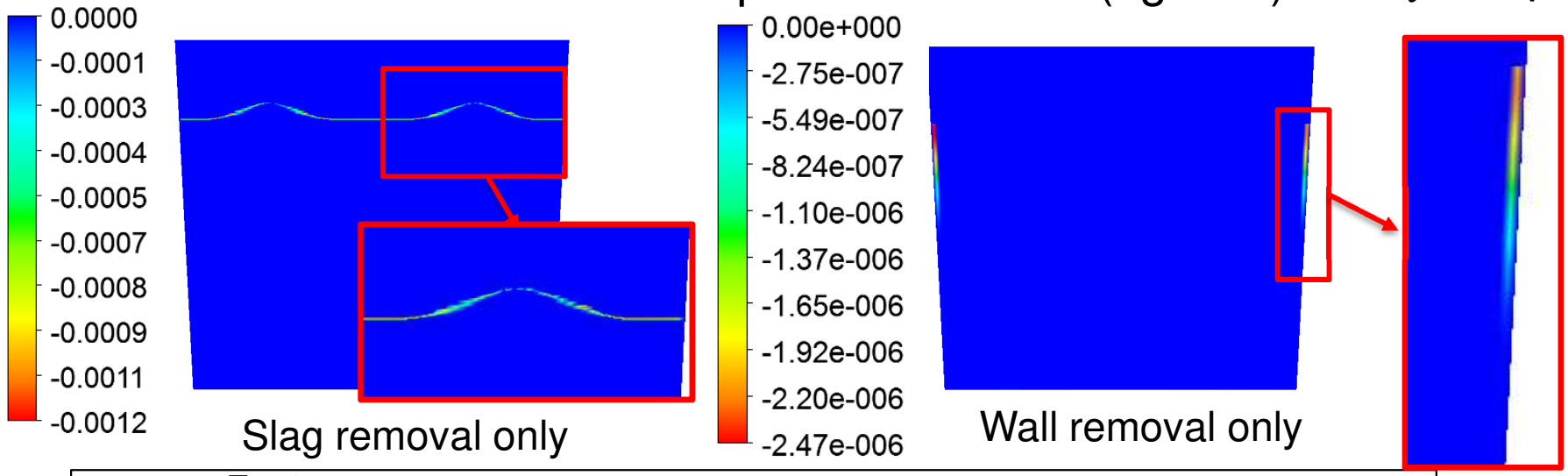
- Number density is reduced near to slag/steel interface.
- Clean steel from steel/slag interface is carried by the flow to the bottom of ladle.

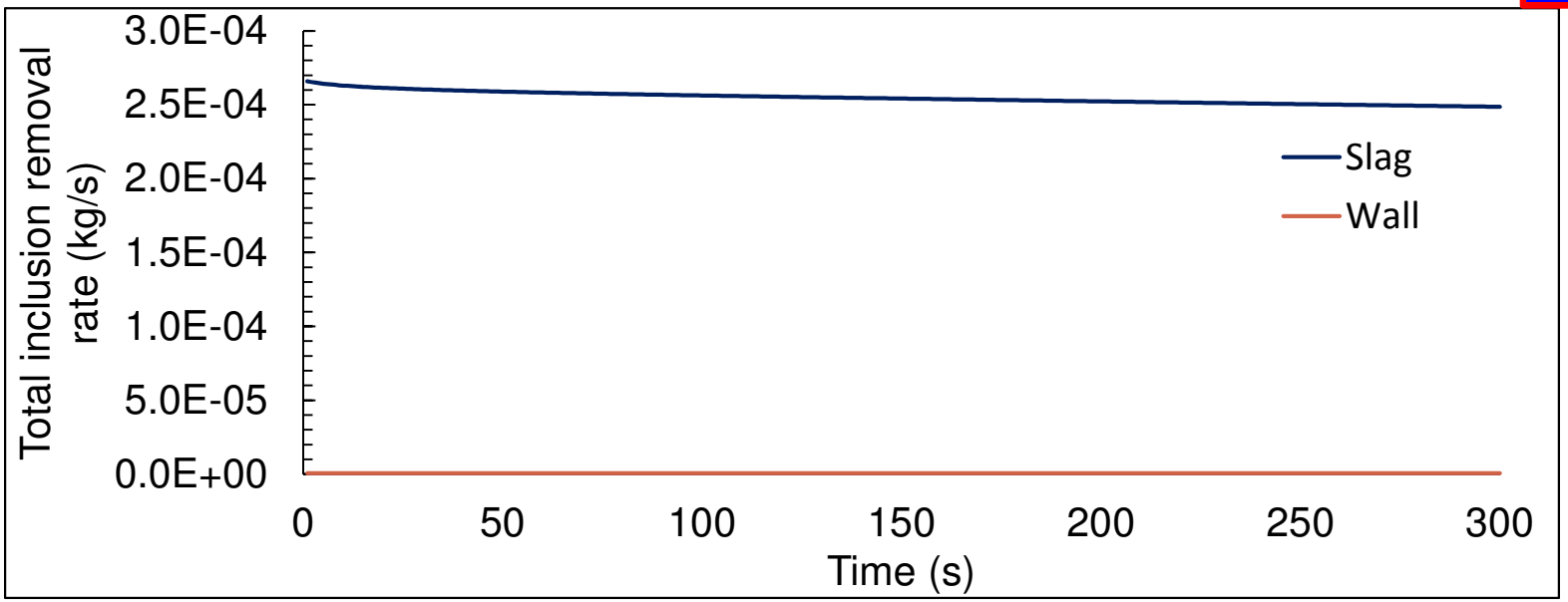
INCLUSION REMOVAL RATE

t = 300 s

Inclusion removal rate per cell volume (kg/m³s)

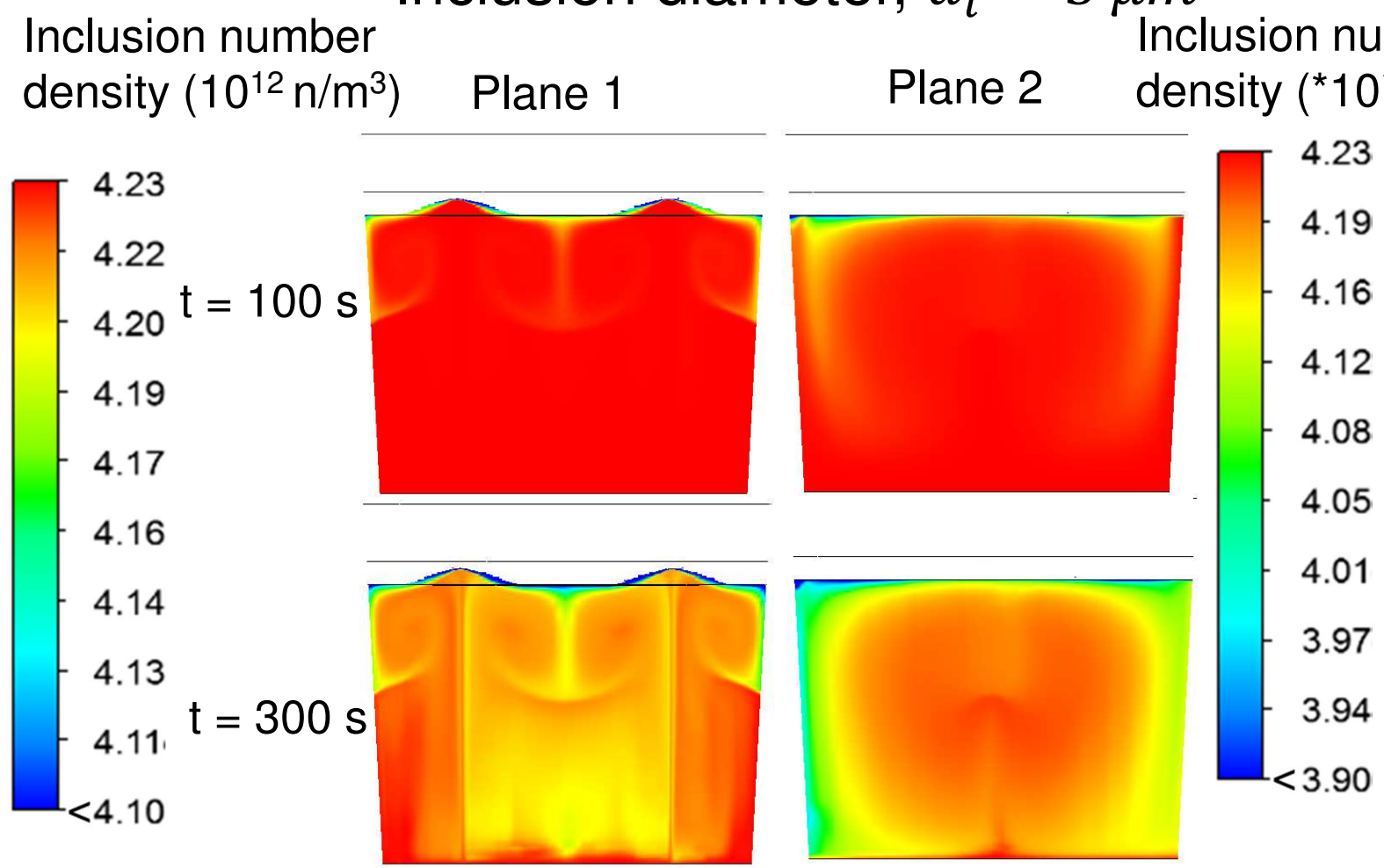
$d_i = 5\ \mu m$

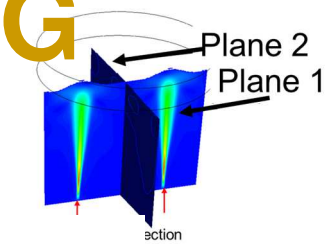




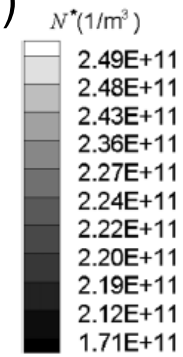
REMOVAL FROM WALL AND SLAG

Inclusion diameter, $d_i = 5\ \mu m$

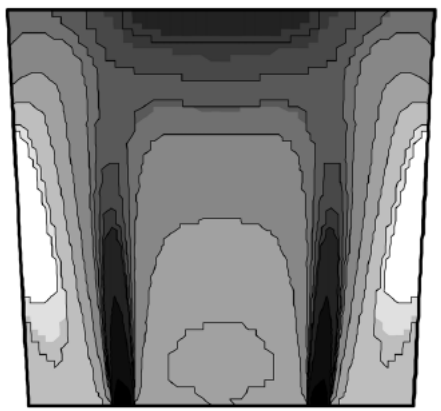




Inclusion number density (*10^{12} n/m^3)



[1]



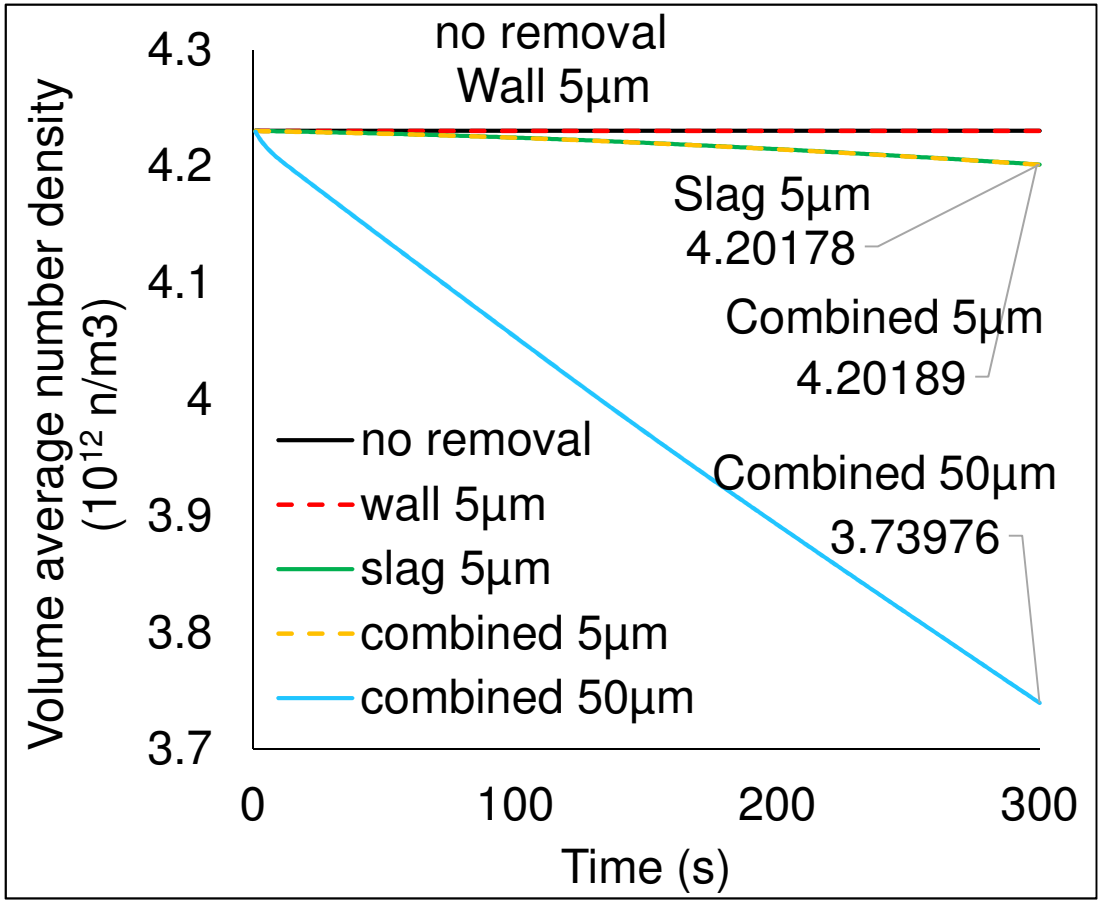
Geng et. al (2010)

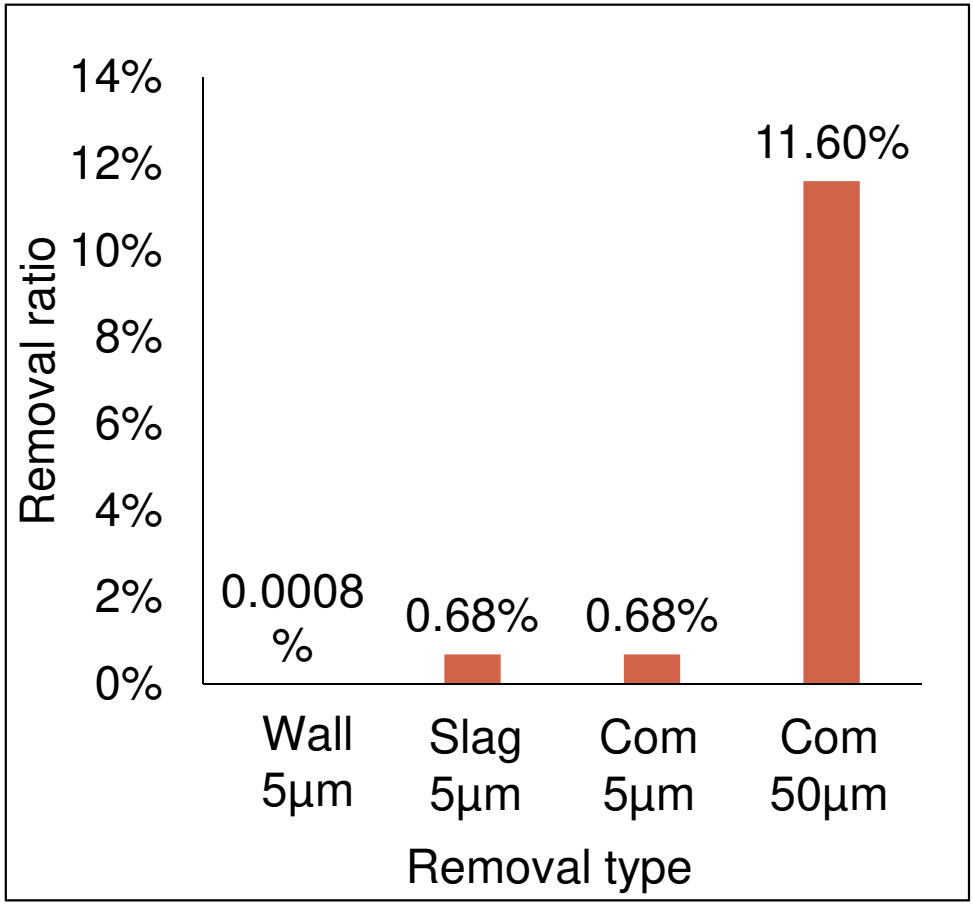
- Higher concentration of inclusion at the side wall and bottom of ladle where dead zone is present.
- Lower inclusion concentration in Geng et. al's work at argon plumes due to bubbles' removal.

1. D. Q. Geng, H. Lei, and J. C. He. "Numerical simulation for collision and growth of inclusions in ladles stirred with different porous plug configurations." *ISIJ international* 50.11 (2010): 1597-1605.

VOLUME AVERAGE NUMBER DENSITY

$$Removal\ ratio = \frac{n(V_i, 0) - n(V_i, t = 300s)}{n(V_i, 0)} * 100\%$$



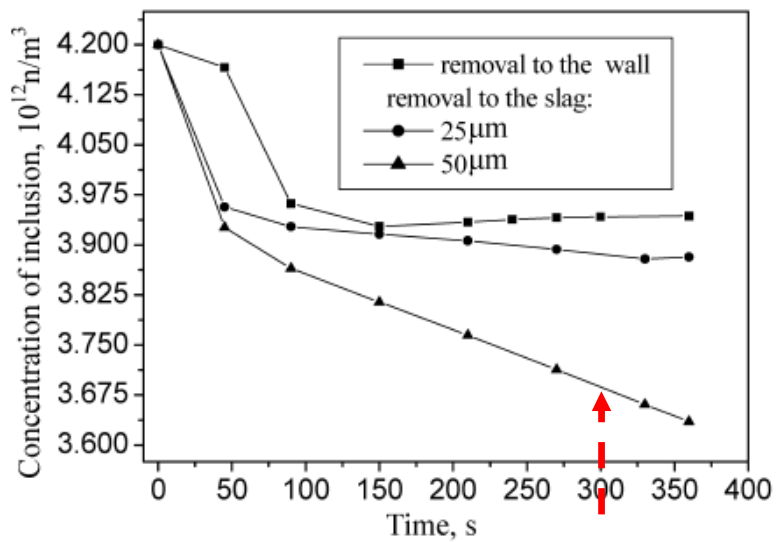


VALIDATION

Parameters	Current model	Wang et. al (2006)
Melt depth (m)	2.46	3.325
Slag depth (m)	0.2	-
Plug distance ratio $\left(\frac{\text{Distance from center to plug}}{\text{Floor radius}}\right)$	0.56	0.5
Aspect ratio $\left(\frac{\text{Melt height}}{\text{Diameter @ slag} - \text{metal interface}}\right)$	0.7	1.21
Plug separation angle (°)	180	90
Argon flow rate (m^3/s)	0.00472 (10 SCFM)	1.39 * (2945 CFM)
Removal ratio for 50 µm inclusion	11.5%	≈12

* Too high for gentle stirring. Need verification

Wang et. al (2006)



$$Removal\ ratio: = \frac{n(V_i, 0) - n(V_i, t = 300s)}{n(V_i, 0)} * 100\%$$

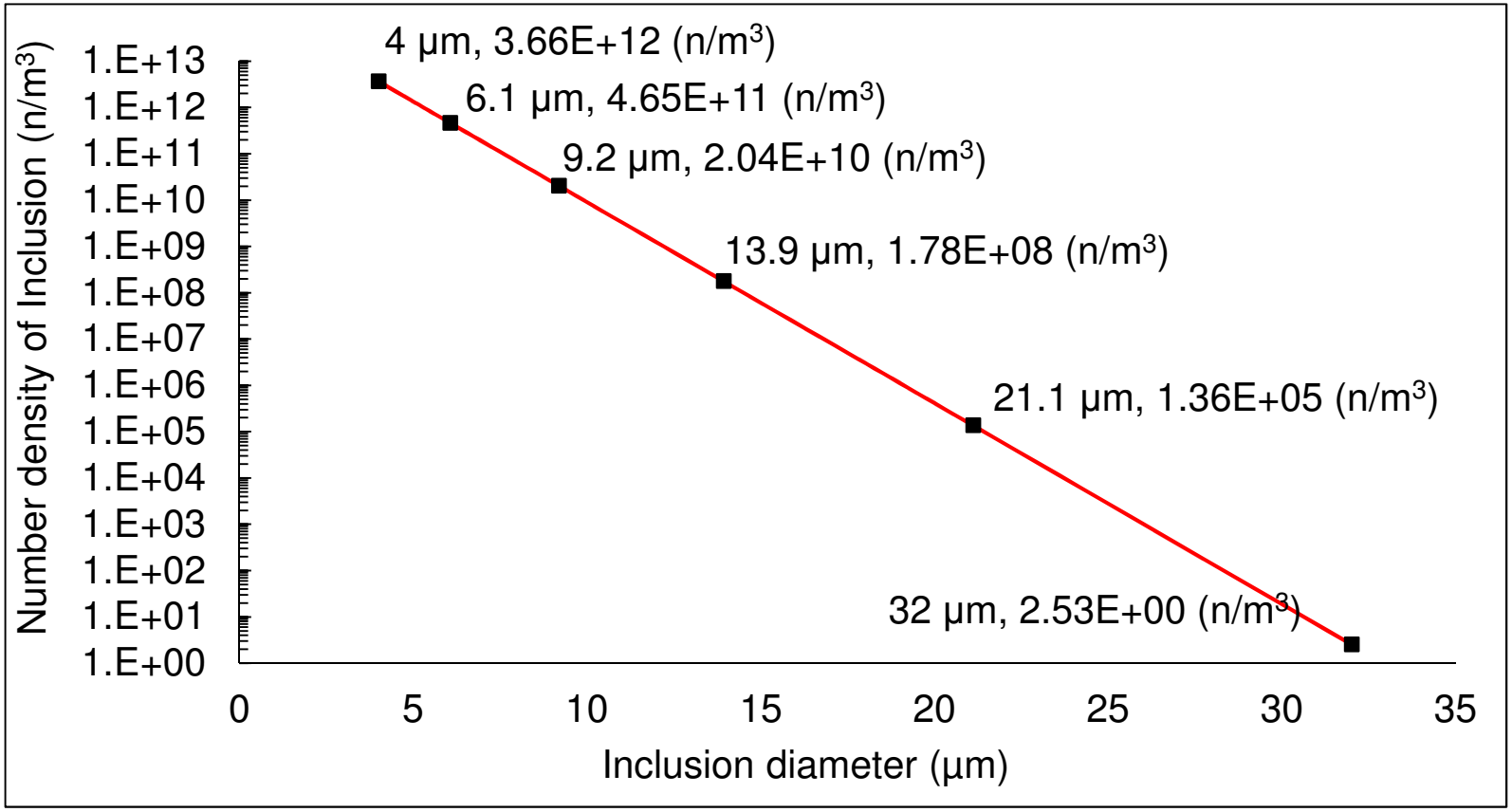
1. L. T. Wang, et al. "Mathematical model for growth and removal of inclusion in a multi-tuyere ladle during gas-stirring." *ISIJ international* 45.3 (2005): 331-337

LOG-NORMAL INCLUSION DISTRIBUTION

- Initial size distribution of inclusion in ladle

$$n(d_i)_{t=0} = 2 \times 10^{14} e\text{^}(-1.0 d_i \times 10^6) \quad [1]$$

- Total of 6 groups size of inclusion (6 bins)

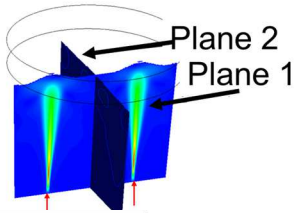


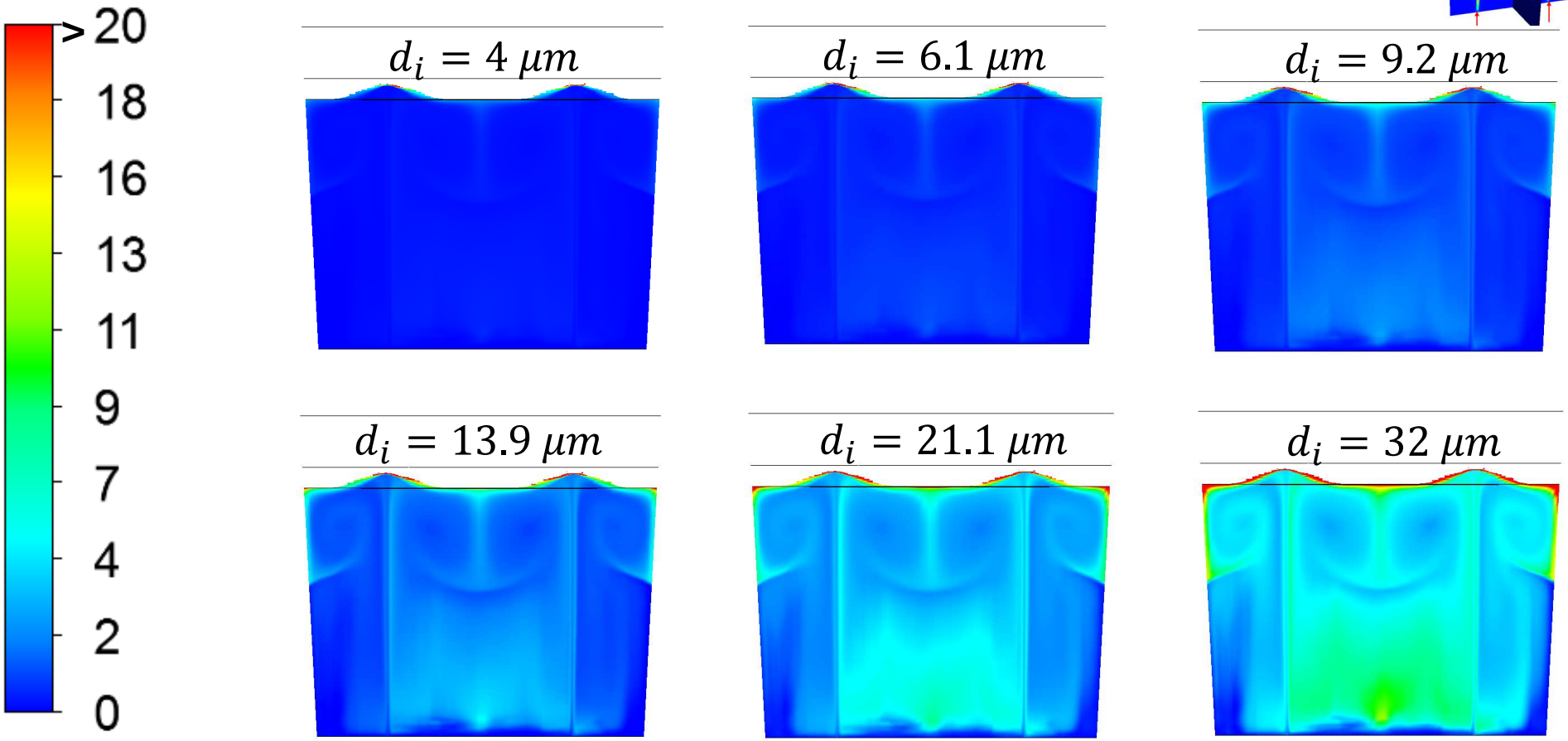
1. W. T. Lou and M. Y. Zhu: Metall. Mater. Trans. B, 44B (2013), 762

INCLUSION REMOVAL RATIO

t = 300 s

$$Removal\ ratio = \frac{n(V_i, 0) - n(V_i, t = 300s)}{n(V_i, 0)} * 100\%$$



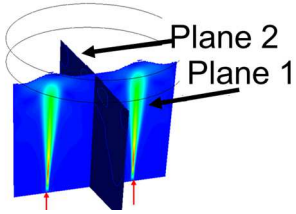


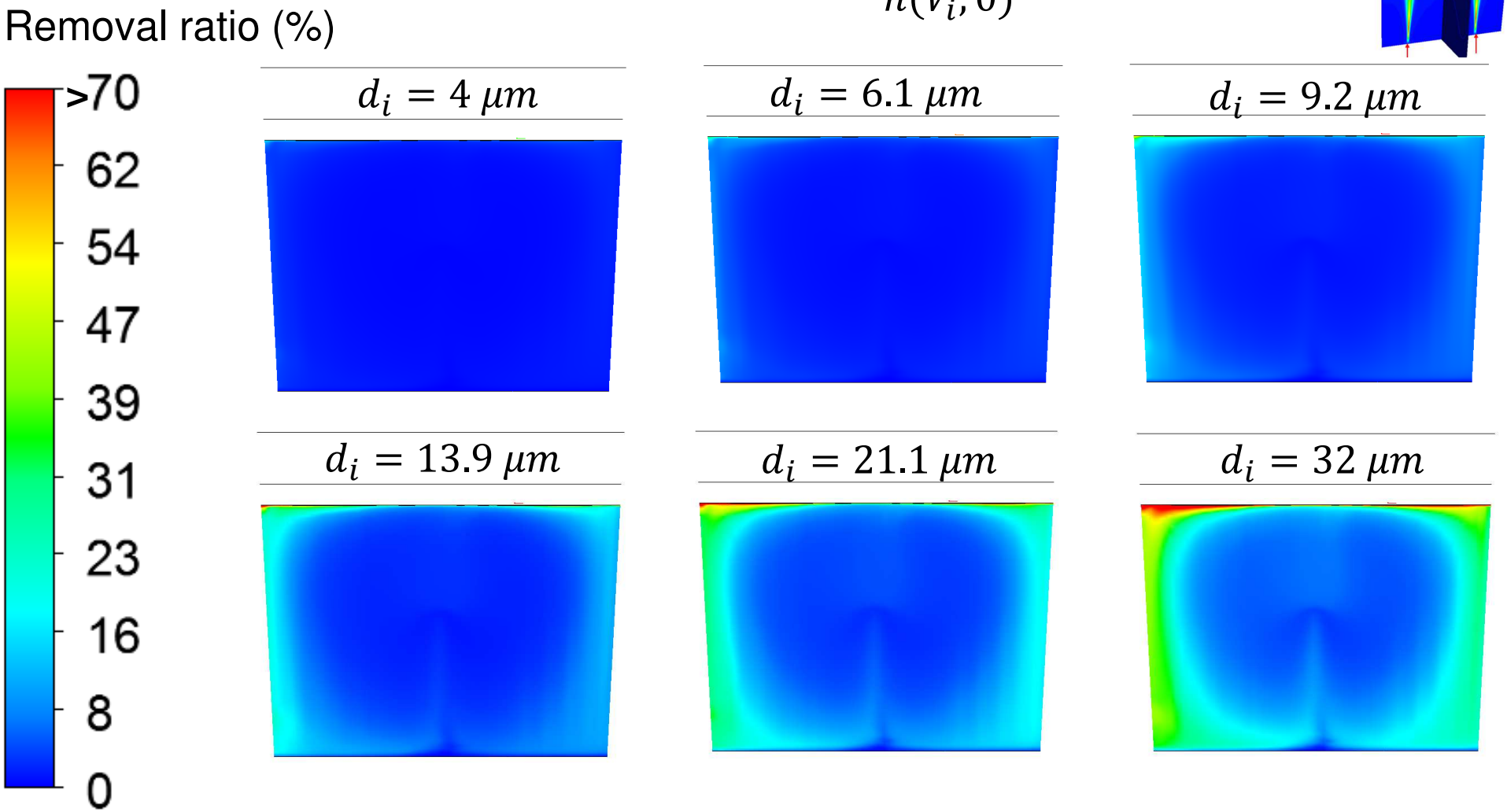
- Larger inclusion size group shows higher removal ratio.
- Higher removal rate for larger inclusions.

INCLUSION REMOVAL RATIO

t = 300 s

$$Removal\ ratio = \frac{n(V_i, 0) - n(V_i, t = 300s)}{n(V_i, 0)} * 100\%$$

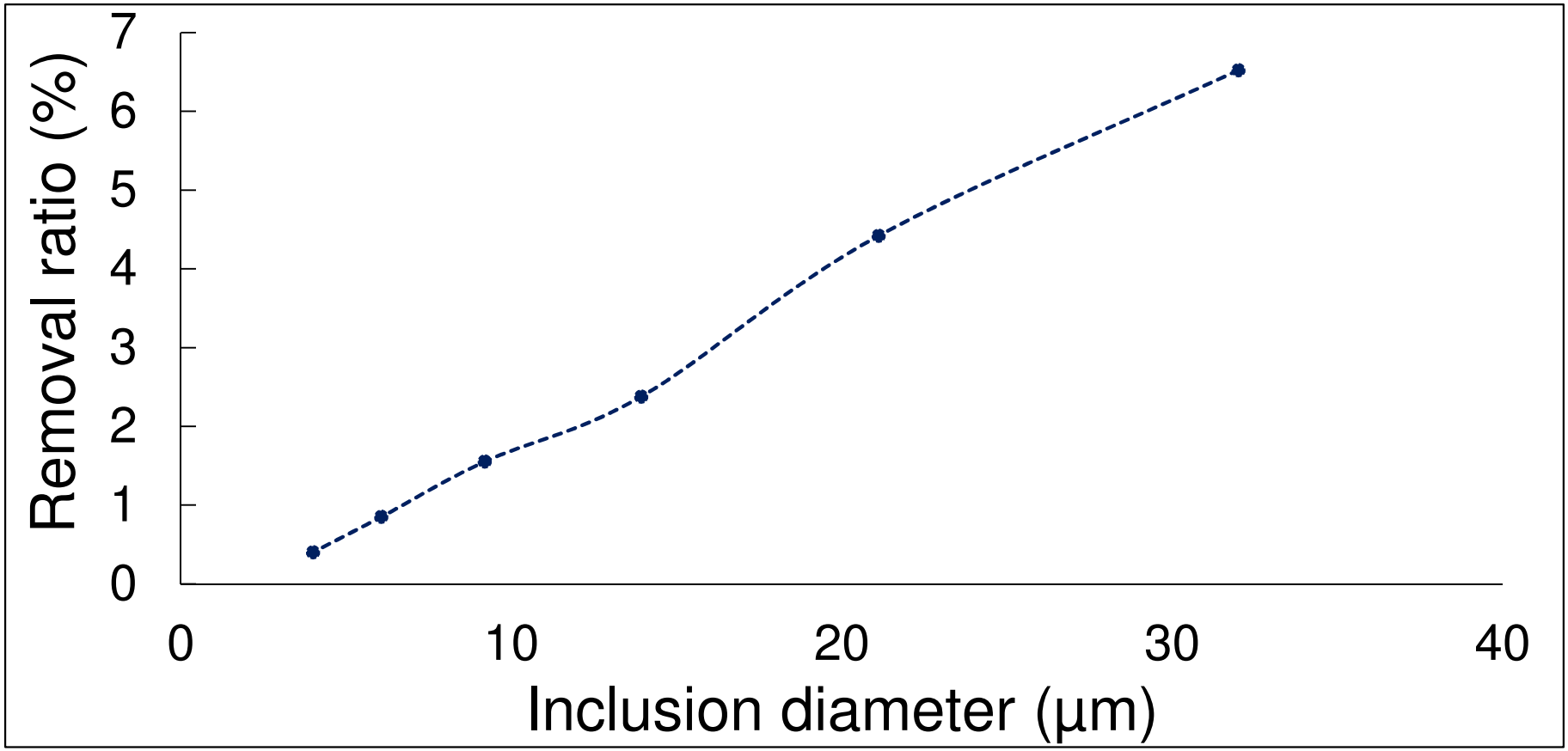




REMOVAL RATIO

$$Removal\ ratio = \frac{n(V_i, 0) - n(V_i, t = 300s)}{n(V_i, 0)} * 100\%$$

Removal ratio per inclusion group size



INTERFACIAL TENSION ON SLAG REMOVAL

- **Inclusion removal at interface with separation time[1]**

- Inclusion is removed when thin steel film ruptures during the collision

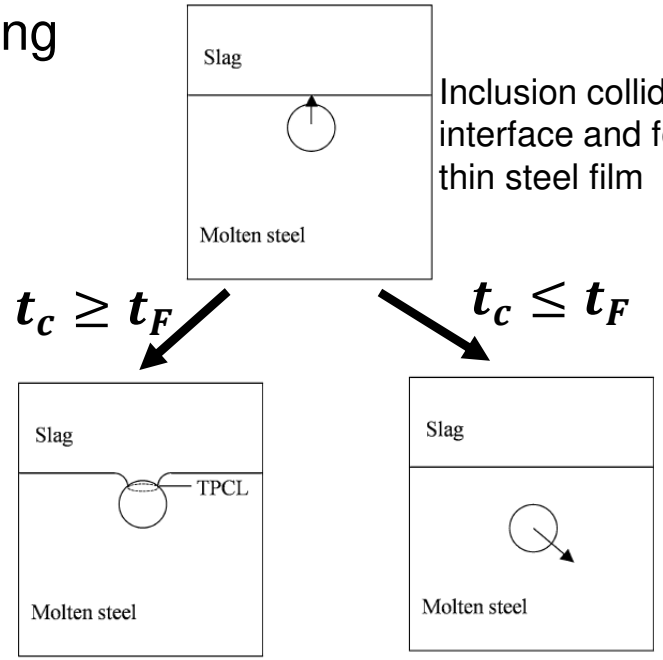
$$\textbf{if } \boldsymbol{u_R > 0,\ t_c \geq t_F}$$

Removal flux $= -\rho_M * u_R * n_i$ (kg/s.m²)

- Collision time (t_c) and rupture time (t_F):

$$\boldsymbol{t_c} = \left(\frac{d_i^3 \cdot \rho_l}{12\sigma_{MS}}\right)^{\frac{1}{2}} \cdot \left\{\pi + 2\arcsin\left[1 + \frac{12 u_R^2 \sigma_{MS} \rho_l}{d_i^3 g^2 (\rho_i - \rho_M)^2}\right]^{-\frac{1}{2}}\right\}$$

$$\boldsymbol{t_F} = \frac{3}{64}\mu_M \frac{\phi^2}{\sigma_{MS} h_{CR}^2} d_i^3, \qquad \phi = \arccos\left\{1 - 1.02 \cdot \left(\frac{\pi d_i \rho_i u_R^2}{12\sigma_{MS}}\right)^{\frac{1}{2}}\right.$$



Drainage and rupture of thin film during separation process

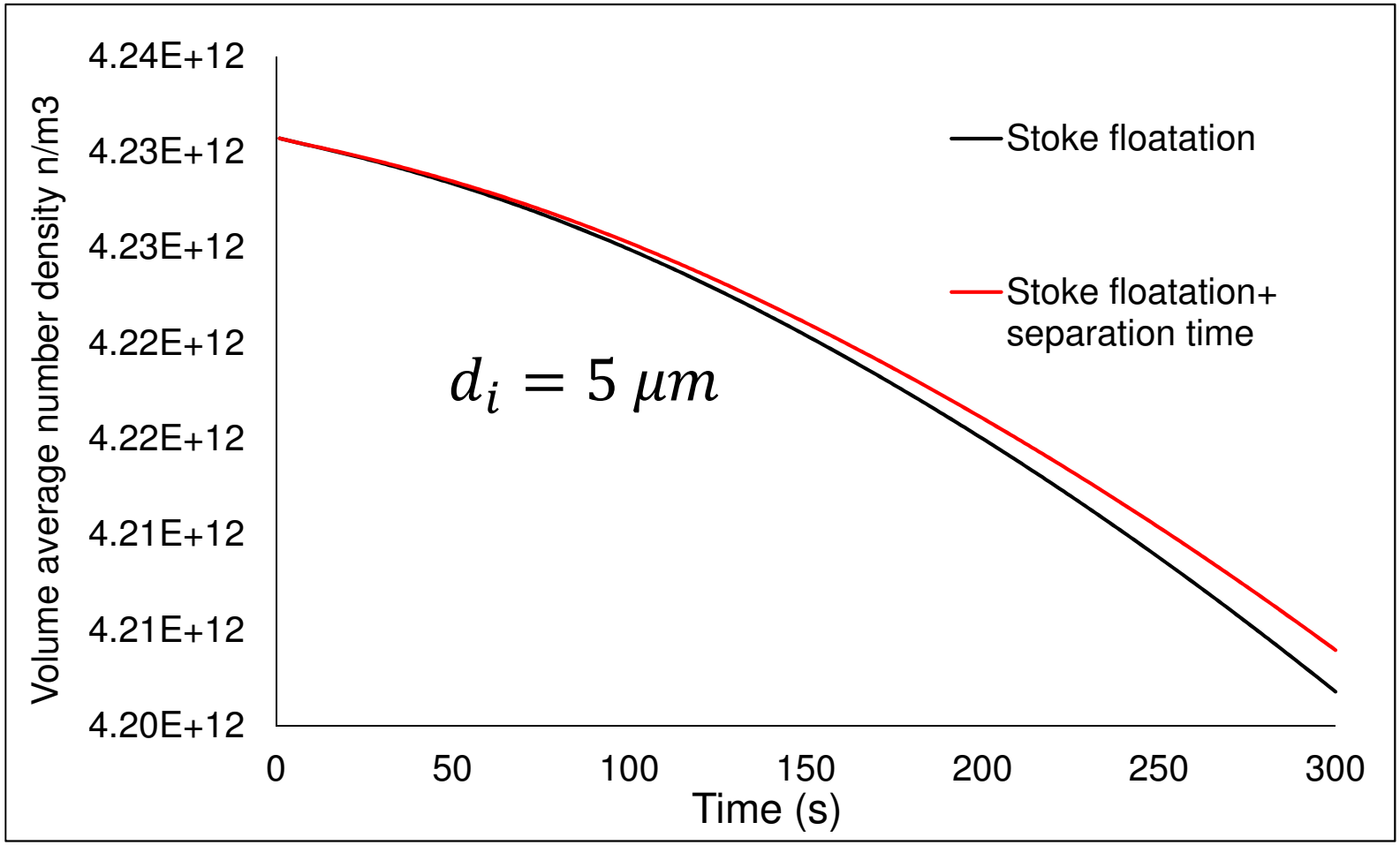
Inclusion return to melt if film is not ruptured

u_R : relative velocity between slag and inclusion
σ_{Ms} : melt/slag interfacial tension
$h_{Cr}(\sigma_{Ms}, \theta)$: critical thickness of liquid film

1. H.T. Ling, L.F. Zhang, and H. Li. "Mathematical modeling on the growth and removal of non-metallic inclusions in the molten steel in a two-strand continuous casting tundish." *Metallurgical and Materials Transactions B* 47.5 (2016): 2991-3012.

SLAG REMOVAL MODEL COMPARISON

Volume average number density (n/m^3)

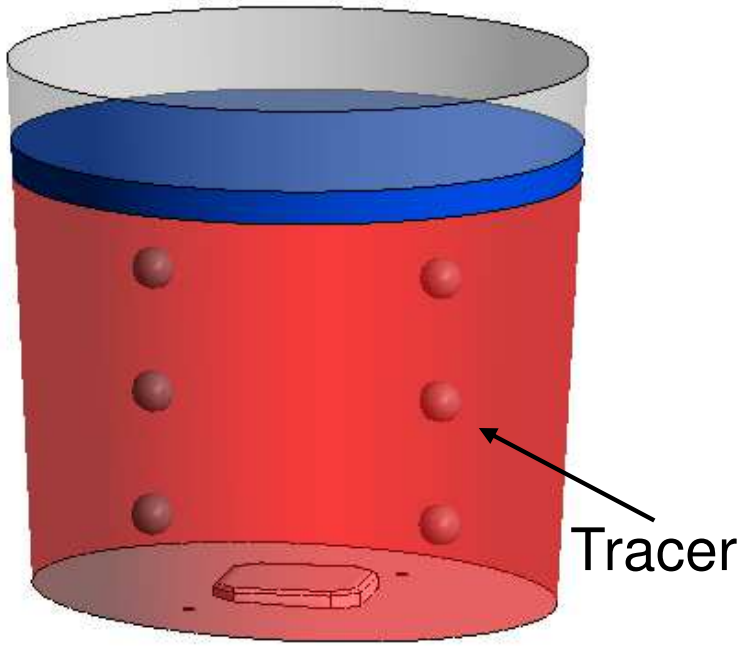


- The effect of liquid steel/ slag interfacial energy will be studied.

PARAMETRY STUDY ON MIXING EFFICIENCY

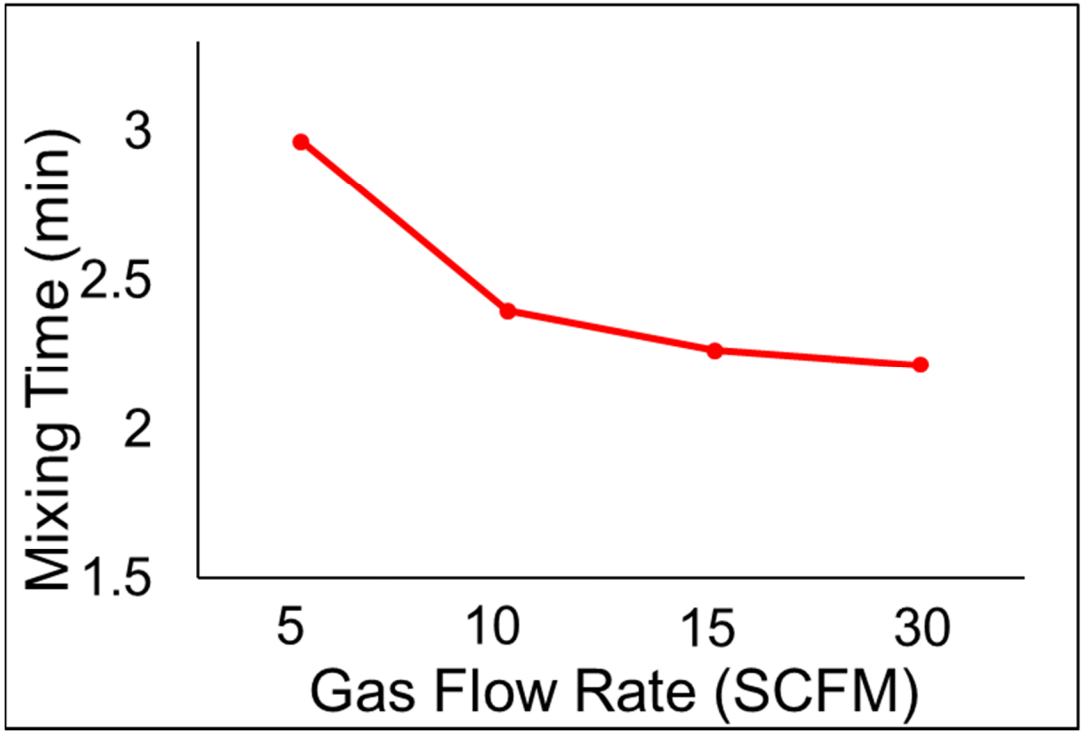
MIXING PROCESS-METHODOLOGY

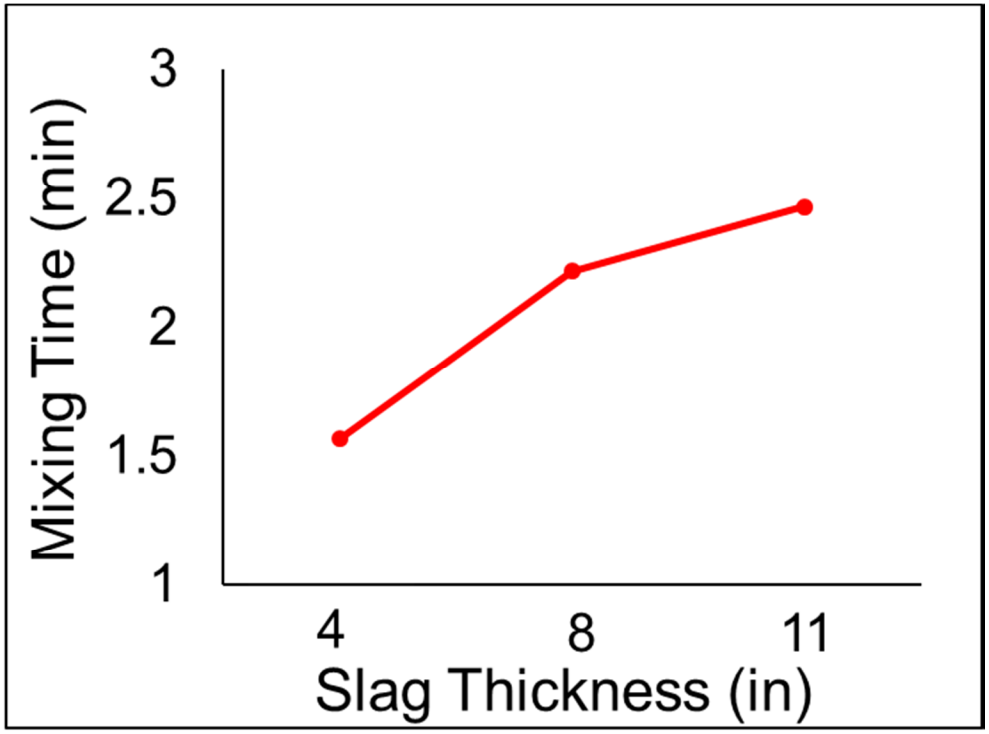
- The flow reached quasi-steady state.
- Six tracers are introduced in the ladle
- Tracer recovery was calculated.
- The mixing time is defined as the time of attaining a 95% degree of homogenization.



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

EFFECT OF GAS FLOW RATE AND SLAG THICKNESS





- Mixing time decreases with the increasing of gas flow rate, increases with the increasing of slag thickness.
- Higher gas flow rate can promote the mixing process, while thinner slag thickness can promote mixing process.

SUMMARY SINCE NOV

Subproject 3 - Gas-Stirred Isothermal Inclusion Removal:

- The inclusion removal model through slag and wall by Population Balance Method (PBM) is developed.
- The inclusion removal rate from the slag and the wall is studied.
- Inclusion removal from slag shows higher contribution compared to removal from wall.
- Multiple size of inclusion distribution at initial time is studied.
- Removal rate of inclusion is higher with larger size of inclusions.

Subproject 1 - Isothermal Gas-stirring Ladle Model:

- Further parametric study is conducted to study effect of gas flow rate and slag thickness on mixing efficiency.
- Mixing time decreases with the increasing of gas flow rate, increases with the increasing of slag thickness.

FUTURE WORK (YEAR 3)

Subproject 4 - Inclusion Interaction Mechanisms:

- Further develop the inclusion removal model by adding inclusion growth mechanism, inclusion-inclusion interaction, inclusion-bubbles interaction.
- Further improve the inclusion removal model with consideration of changing the slag/liquid steel interfacial energy on inclusion removal.

Subproject 5 - EMS Isothermal Inclusion Removal:

- Continue develop electromagnetic stirring (EMS) ladle and study inclusion removal in EMS ladle.

COMMENTS FROM INDUSTRY

Thank You
Questions and Comments

REFERENCES

1. D. Mazumdar, P. Dhandapani, and R. Sarvanakumar. "Modeling and Optimization of Gas Stirred Ladle Systems." ISIJ International 57.2 (2017): 286-295.
2. S. W. P. Cloete , J. J. Eksteen, and S. M. Bradshaw. "A numerical modelling investigation into design variables influencing mixing efficiency in full scale gas stirred ladles." Minerals Engineering 46 (2013): 16-24.
3. L. Jonsson, and P. Jönsson. "Modeling of fluid flow conditions around the slag/metal interface in a gas-stirred ladle." ISIJ international 36.9 (1996): 1127-1134.
4. U. Sand, H. Yang, J.-E. Eriksson, and R. B. Fdhila, “Numerical and Experimental Study on Fluid Dynamic Features of Combined Gas and Electromagnetic Stirring in Ladle Furnace.”
5. H. Lei, K. Nakajima, and J. C. He. "Mathematical model for nucleation, Ostwald ripening and growth of inclusion in molten steel." *ISIJ international* 50.12 (2010): 1735-1745.
6. H. Arai, K. Matsumoto, S. I. Shimasaki and S. Taniguchi. "Model experiment on inclusion removal by bubble flotation accompanied by particle coagulation in turbulent flow." *ISIJ international* 49.7 (2009): 965-974.
7. M. Söder, P. Jönsson, and L. Jonsson. "Inclusion Growth and Removal in Gas-Stirred Ladles." *steel research international* 75.2 (2004): 128-138.
8. Q. Cao, and L. Nastac. "Numerical modelling of the transport and removal of inclusions in an industrial gas-stirred ladle." *Ironmaking & Steelmaking* (2018): 1-8.
9. Q. Yuan, B. G. Thomas, and S. P. Vanka. "Study of transient flow and particle transport in continuous steel caster molds: Part II. Particle transport." *Metallurgical and Materials Transactions B* 35.4 (2004): 703-714.
10. Y. Miki, and B. G. Thomas. "Modeling of inclusion removal in a tundish." *Metallurgical and materials transactions B* 30.4 (1999): 639-654.
11. D. Q. Geng, H. Lei, and J. C. He. "Numerical simulation for collision and growth of inclusions in ladles stirred with different porous plug configurations." *ISIJ international* 50.11 (2010): 1597-1605.
12. M. Y. Zhu, S. G. Zheng, Z. Z. Huang and W. P. Gu. "Numerical Simulation of Nonmetallic Inclusions Behaviour in Gas-Stirred Ladles." *Steel research international* 76.10 (2005): 718-722.
13. H. Lei, L. Wang, Z. Wu and J. Fan. "Collision and coalescence of alumina particles in the vertical bending continuous caster." *ISIJ international* 42.7 (2002): 717-725.

REFERENCES

14. W. T. Lou, and M. Y. Zhu. "Numerical simulations of inclusion behavior in gas-stirred ladles." *Metallurgical and Materials Transactions B* 44.3 (2013): 762-782.
15. Y. J. Kwon, Z. Jian, and H. G. Lee. "A CFD-based nucleation-growth-removal model for inclusion behavior in a gas-agitated ladle during molten steel deoxidation." *ISIJ international* 48.7 (2008): 891-900.
16. L. T. Wang, Q. Y. Zhang, S. H. Peng and Z. B. Li. "Mathematical model for growth and removal of inclusion in a multi-tuyere ladle during gas-stirring." *ISIJ international* 45.3 (2005): 331-337.