

ANNUAL REPORT 2009

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Electromagnetic and Multi-phase flow effects on Particle Entrapment in the Slab Casting Mold

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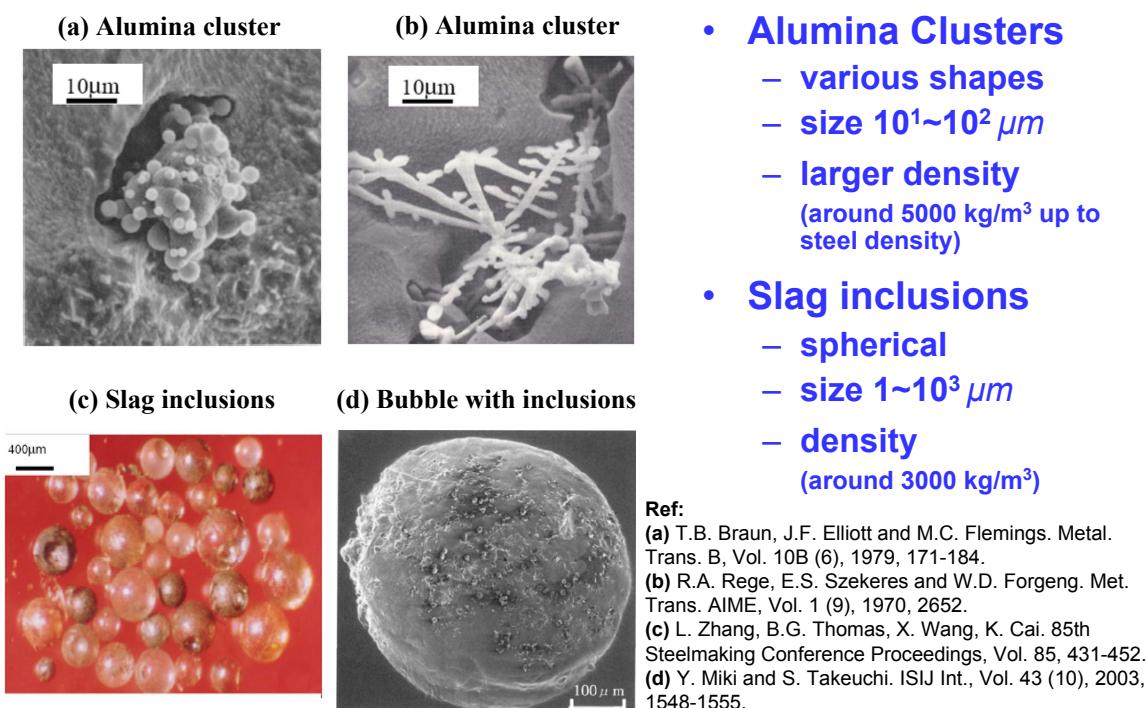
Background

- **Particle particles (slag, Alumina clusters and argon bubbles) entrapped in the shell will cause defects such as slivers, so particle transport and entrapment phenomena are important to study**
- **The fates of particles entering the mold include:**
 - captured into shell between dendrites to form defects
 - removed by liquid slag layer at top surface
- **Particle motion and entrapment is controlled by:**
 - particle size
 - density
 - shape
 - fluid flow pattern
 - dendrite arm spacing (entrapment)
- **Fluid flow pattern in the mold is affected by:**
 - nozzle and mold geometry
 - gas bubble injection
 - electromagnetic field

Objectives

- Starting with mold fluid flow patterns computed by R. Chaudhary, and compared with plant measurements:
- How is the percentage of particles removed by free surface affected by:
 - particle type and size
 - injecting gas into SEN
 - electromagnetic field
- How does particle type and size affect the entrapment
 - argon bubble, slag droplet, alumina cluster
- How is particle entrapment and distribution affected by:
 - multiphase flow (injection of gas bubbles)
 - electromagnetic field

Particle Types



Particle Motion Equations

- Particle trajectory computation (Lagrangian method)

$$m_p \frac{d\mathbf{v}_p}{dt} = \mathbf{F}_D + \mathbf{F}_L + \mathbf{F}_{\text{added-mass}} + \mathbf{F}_G + \mathbf{F}_{\text{press}} + \mathbf{F}_{\text{stress}}$$

Drag force Lift force Added mass force Gravitational force Pressure & Stress gradient force

Motion: $\mathbf{v}_p = \frac{d\mathbf{x}_p}{dt}$

$$\mathbf{F}_D = \frac{1}{8} \pi d_p^2 \rho_f C_D |\mathbf{v}_f - \mathbf{v}_p| (\mathbf{v}_f - \mathbf{v}_p)$$

$$C_D = f_{Re_p} \left(\frac{24}{Re_p} \right), Re_p = \left| (\mathbf{v}_f - \mathbf{v}_p) \frac{d_p}{\nu} \right|$$

$$f_{Re_p} = (1 + 0.15 Re_p^{0.687})$$

$$\mathbf{F}_G = \frac{\pi d_p^3}{6} \rho_f \mathbf{g}$$

$$\mathbf{F}_{\text{press}} + \mathbf{F}_{\text{stress}} = -\frac{\pi d_p^3}{6} \frac{D\mathbf{v}_f}{Dt}$$

$$\mathbf{F}_{\text{added-mass}} = \frac{\rho_p \pi d_p^3}{12} \left(\frac{d\mathbf{v}_f}{dt} - \frac{d\mathbf{v}_p}{dt} \right)$$

$$\mathbf{F}_L = -\frac{9}{4\pi} \mu d_p^2 \mathbf{U}_s \operatorname{sgn}(G) \left[\frac{|G|}{V} \right]^{\frac{1}{2}} J^u$$

$$G = \mathbf{U}_s \times (\nabla \times \mathbf{v}_f), \quad \nabla \cdot \mathbf{v}_f = \operatorname{sgn}(G) \frac{\sqrt{|G| \nu}}{U_s}, \quad \mathbf{U}_s = \mathbf{v}_p - \mathbf{v}_f$$

$$J(\varepsilon) = 0.6765 * (1 + \tanh[2.5 \lg \varepsilon + 0.191]) (0.667 + \tanh[6(\varepsilon - 0.32)])$$

Ref:
 (1) Maxey, M.R. and Riley, J.J.: Physics of Fluids, 1983, vol. 26 (4), pp. 883-889.
 (2) Crowe, C., Sommerfeld, M. and Tsintsi, Y.: Multiphase Flows with Droplets and Particles, CRC Press, 1998, pp. 23-95.

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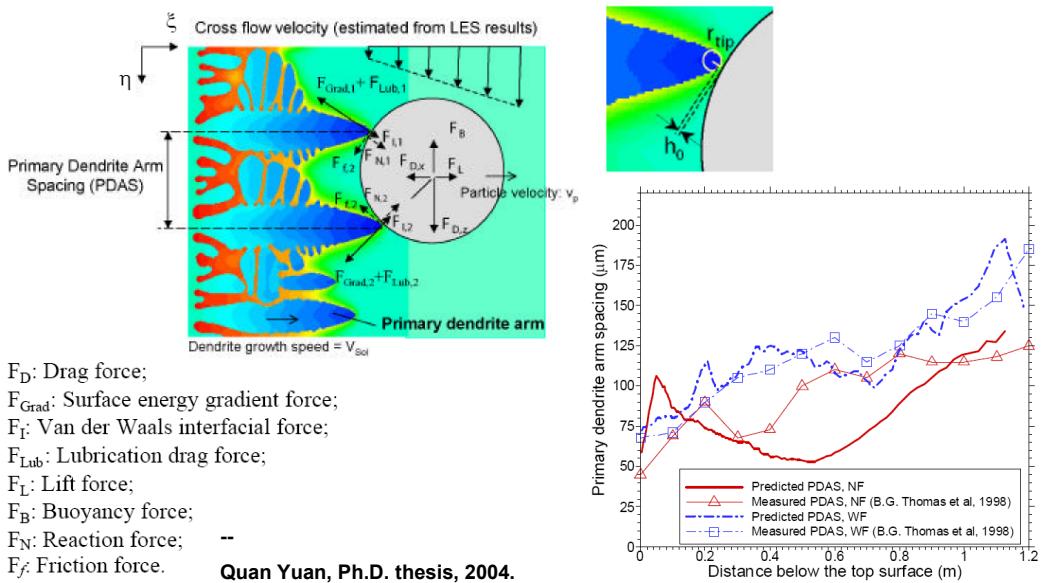
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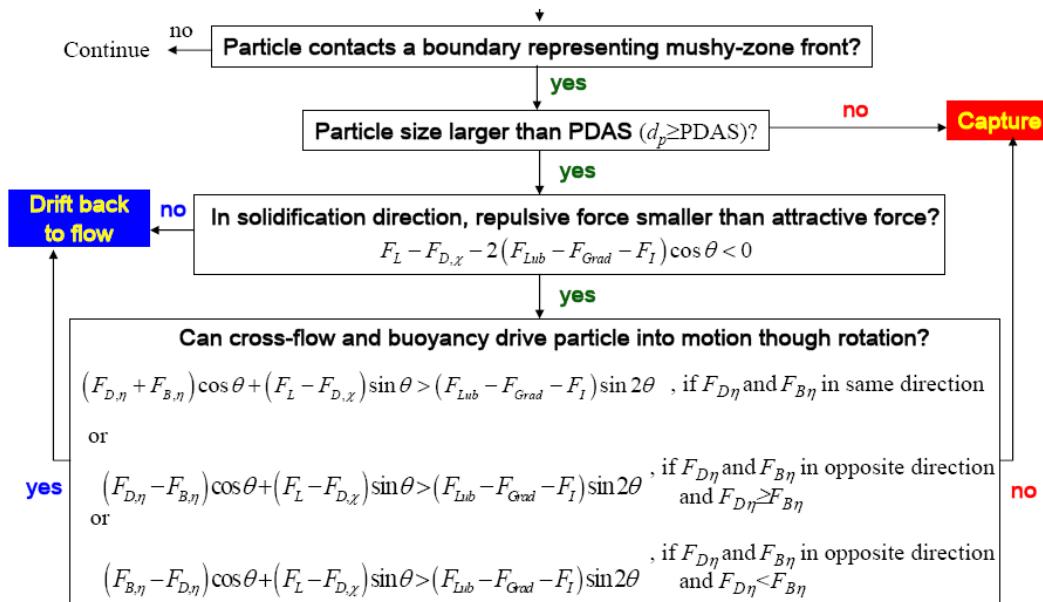
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Force Balance Calculation

- Force balance near shell and PDAS vs. distance below meniscus:



Shell entrapment criterion



Quan Yuan, Ph.D. thesis, 2004

Figure from Sana Mahmood, Master thesis, 2006

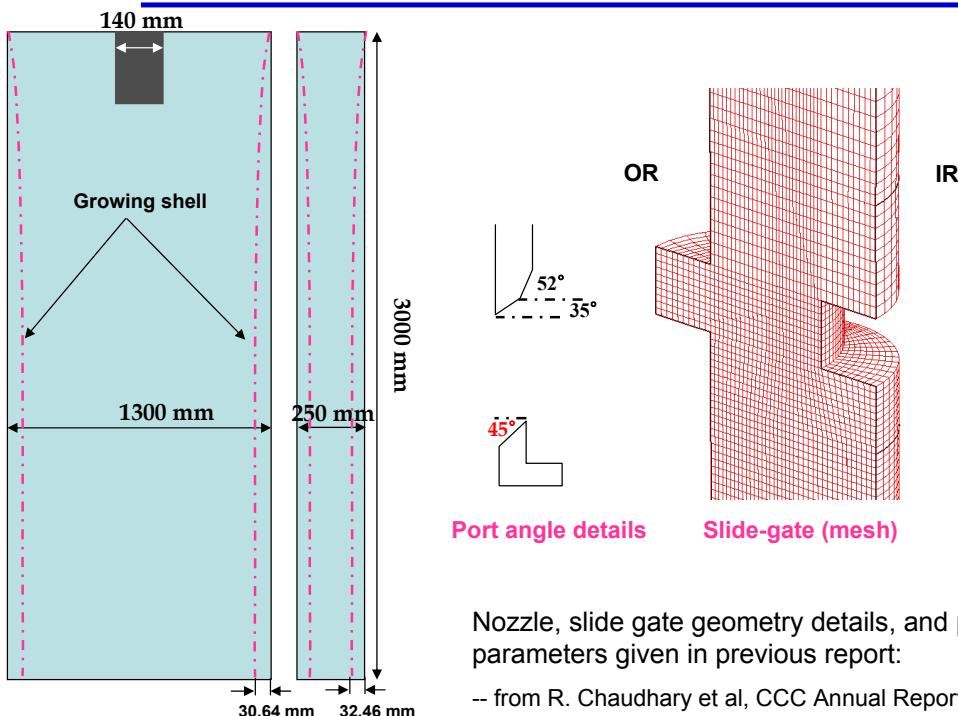
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Mold and Nozzle Geometry



Process parameters

Casting speed	1.64 m/min	→
Steel flow rate	533 LPM	→
Argon gas injection rate	9.2 SLM: STP (1 atm Pr and 273K)	→
Nozzle inner diameter	90 (at UTN top) to 80 (at bottom well) mm	→
Nozzle outer diameter	140 mm	→
Nozzle height	1330 mm	→
Nozzle type and port angles	Bifurcated type: 52 to 35 degree step angles at the top 45 degree port angle at the bottom	→
Nozzle port area	85 mm (height) x 80 mm (width) each	→
Port to bore (at UTN top) area ratio	2.13	→
SEN depth	178 mm	→
Mold width	1300 mm	→
Mold thickness	250 mm	→
Domain width	650 mm	→
Domain thickness	250 mm	→
Domain length	3000 mm	→
Density (argon gas) Density (molten steel)	0.55 kg/m ³ (at gas gas injection pressure (1.99e05 N/m ² , &1550°C) 0.30 kg/m ³ (at SEN depth pressure (1.13e05 N/m ² , &1550°C) 7020 kg/m ³ (molten Steel temperature=1550°C)	→
Dynamic viscosity (argon gas) Dynamic viscosity (molten steel)	7.42e-05 kg/m-s 0.006 kg/m-s	↓

List of Cases Simulated (24 total)

Particle type	Density (kg/m ³)	Diameter (μm)
1 Slag droplet	2700	40, 100
2 Slag droplet	2700	400
3 Alumina cluster	5000	40, 100
4 Argon bubble	0	2300*

* represents mean of a bubble size distribution shown on next slide

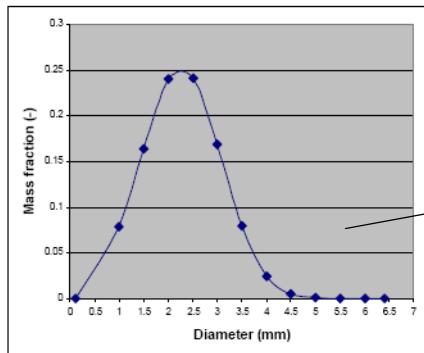
simulate the above particle types and sizes for

- CASE1 single phase flow, no MHD
- CASE2 multiphase flow, no MHD
- CASE3 single phase flow with MHD
- CASE4 multiphase flow with MHD

Total particles injected: 5000

Bubble size distribution

- Minimum bubble diameter : 0.112mm
- Maximum bubble diameter : 6.4mm
- Mean bubble diameter : 2.3mm
(Mean liquid velocity = 2m/s)
- Spread parameter : 3



Bubble size distribution in this case :

Diameter (mm)	Bubble number
0.1	1567
1	1500
1.5	917
2	567
2.5	300
3	116
3.5	33

Total bubble number: 5000

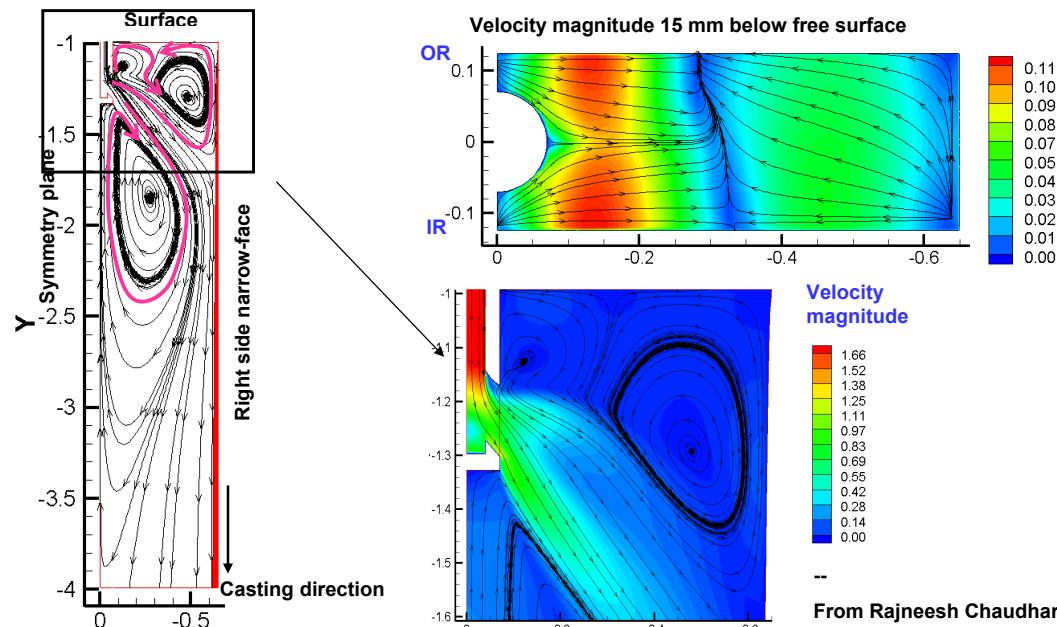
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Total gas flow rate (cold) = 9 SLPM, (hot) = 36 LPM

Bubble size distribution by Gogi Lee, CCC, 2007

Total gas mass (hot) = 2.68e-7 kg/ms

Case 1 – Fluid Flow in the mold

Case 1: Single Phase Flow Model WITHOUT MHD



CASE1-1: 100 micron Slag particles

Computation Model:

single phase flow, no MHD

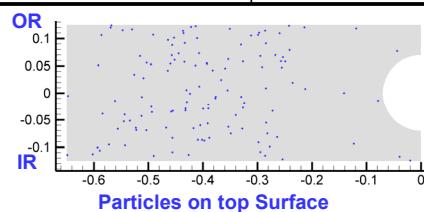
Particle density: 2700 kg/m³

Diameter: 100 microns

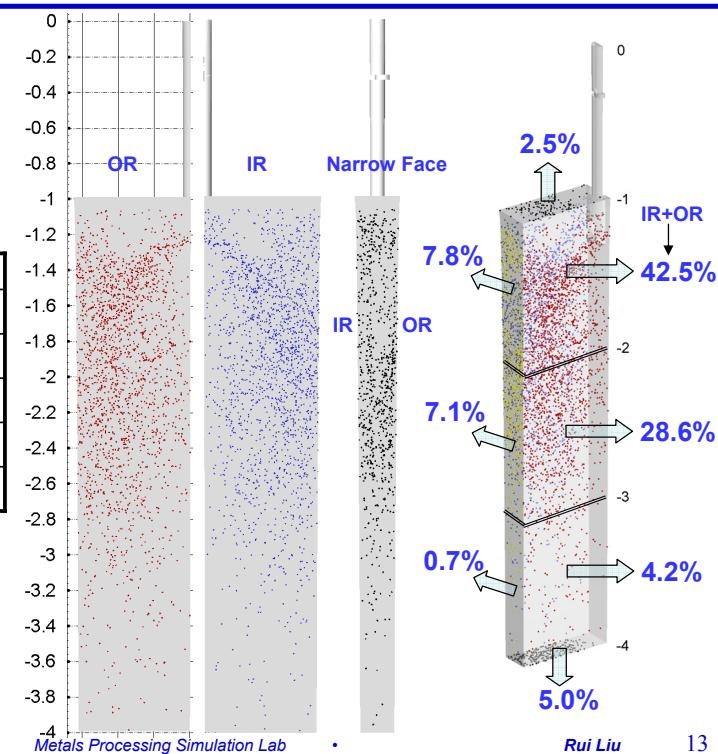
Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	37.7%
Shell (wide face OR)	37.6%
Shell (narrow face)	15.6%
Outer SEN walls	1.6%
Free Surface	2.5%



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CASE1-2: 400 microns Slag particles

Computation Model:

single phase flow, no MHD

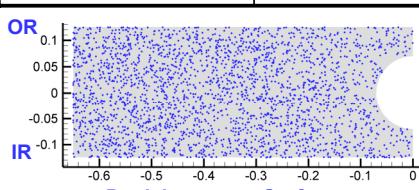
Particle density: 2700 kg/m³

Diameter: 400 microns

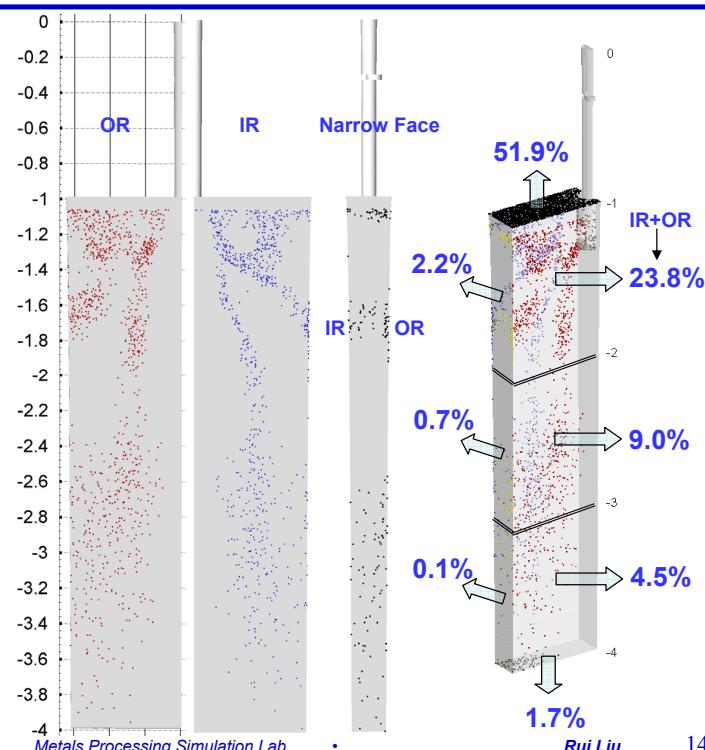
Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	16.9%
Shell (wide face OR)	20.4%
Shell (narrow face)	3.0%
Outer SEN walls	5.2%
Free Surface	51.9%



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CASE1-3: 100 microns Alumina cluster

Computation Model:

single phase flow, no MHD

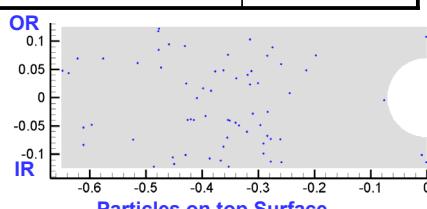
Particle density: 5000 kg/m³

Diameter: 100 microns

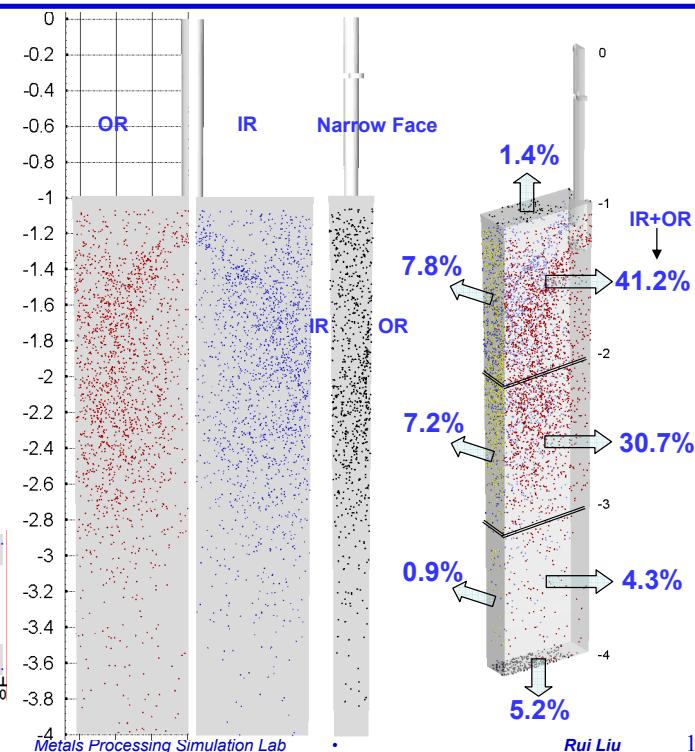
Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	38.9%
Shell (wide face OR)	37.3%
Shell (narrow face)	15.9%
Outer SEN walls	1.4%
Free Surface	1.4%



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CASE1-4: Argon bubbles

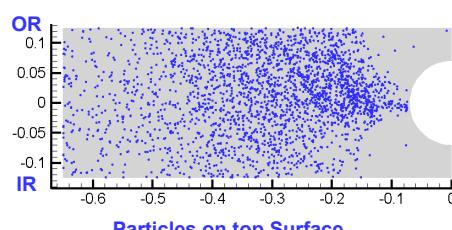
Computation Model:

single phase flow, no MHD

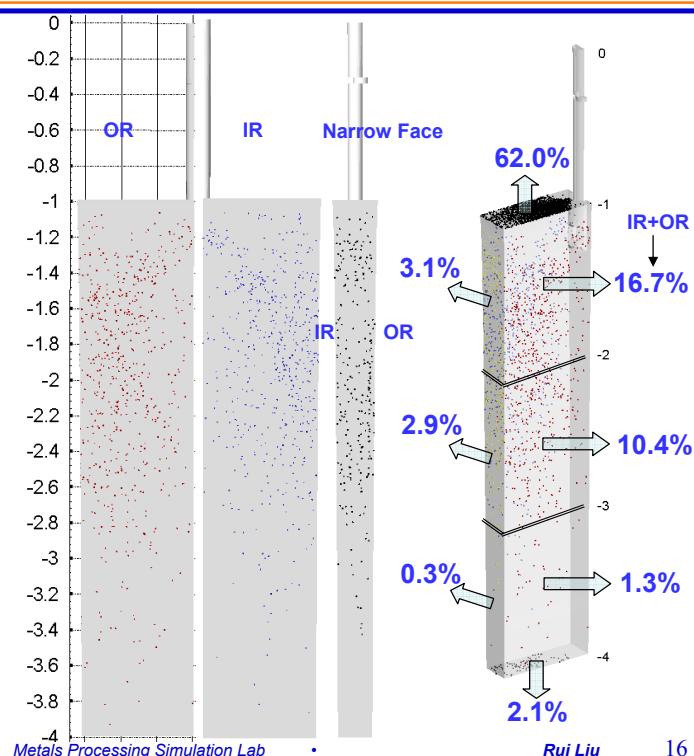
Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	13.9%
Shell (wide face OR)	14.6%
Shell (narrow face)	6.3%
Outer SEN walls	1.2%
Free Surface	62.0%



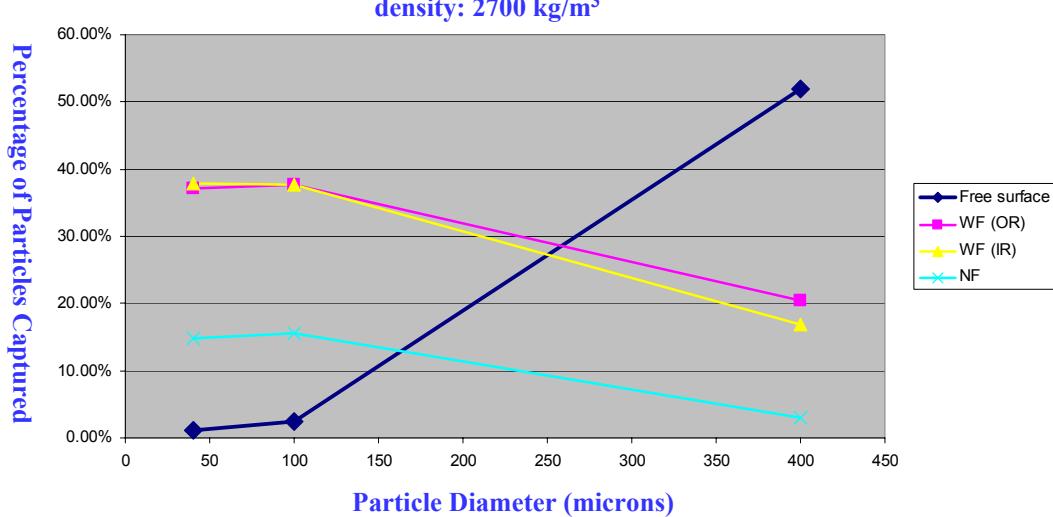
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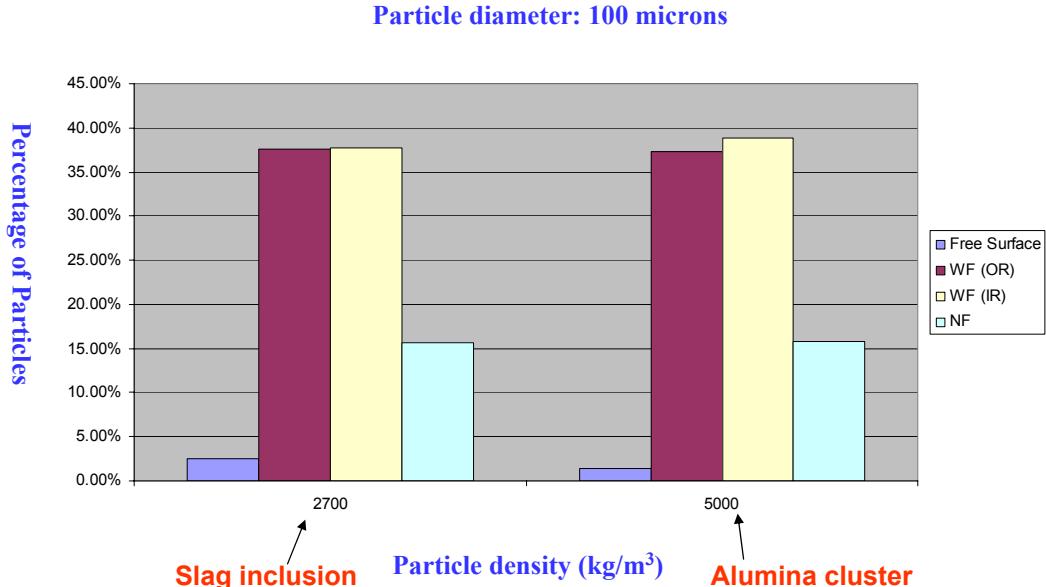
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Particle size effect on Slag particle distribution– CASE 1



- Small particles (40 and 100 micron diameter) are mainly captured by the wide-face shell, and under 4% are removed by the top surface
- Larger particles (400 microns) are mostly (52%) removed by free surface, 20 times more than smaller particles

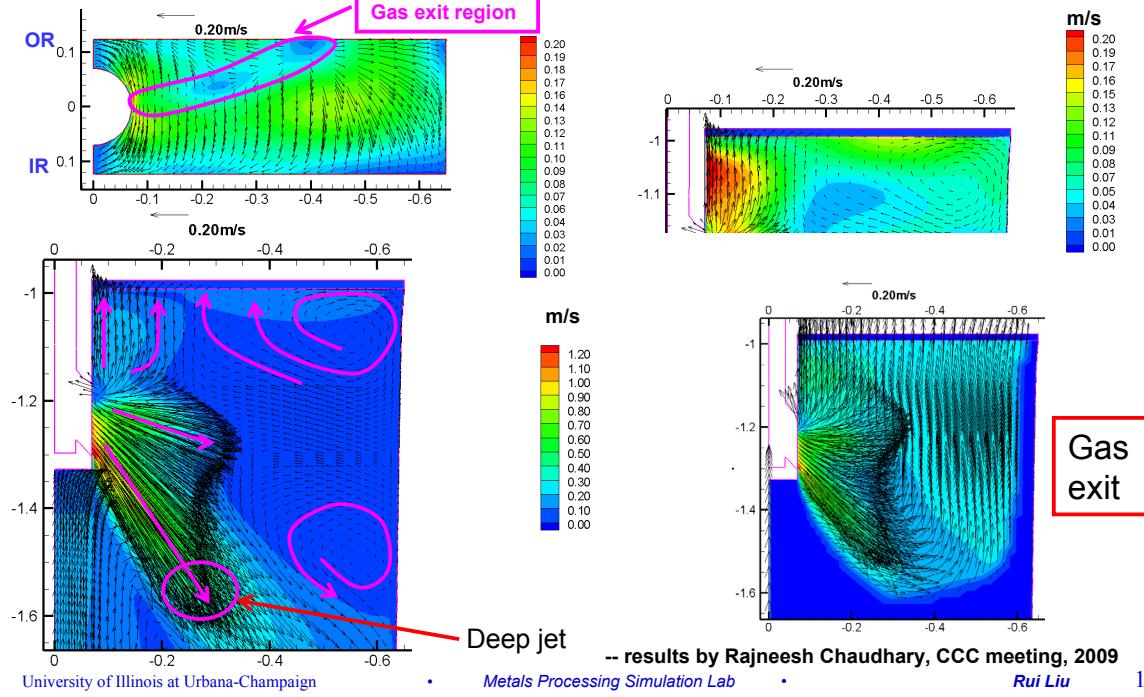
Effect of density on particle distributions – CASE 1



- Only 1.5% of dense particles (5000 kg/m³) and 2.5% of 2700kg/m³ particles are removed at top surface.
- Density of particles has little effect on percentage captured by shell

Case 2 – Fluid Flow in the mold

Case 2: Multiphase Flow Model WITHOUT MHD (30 LPM, 2.4 mm bubble)



Case 2-1 : 100 microns Slag particles

Computation Model:

multiphase flow, no MHD

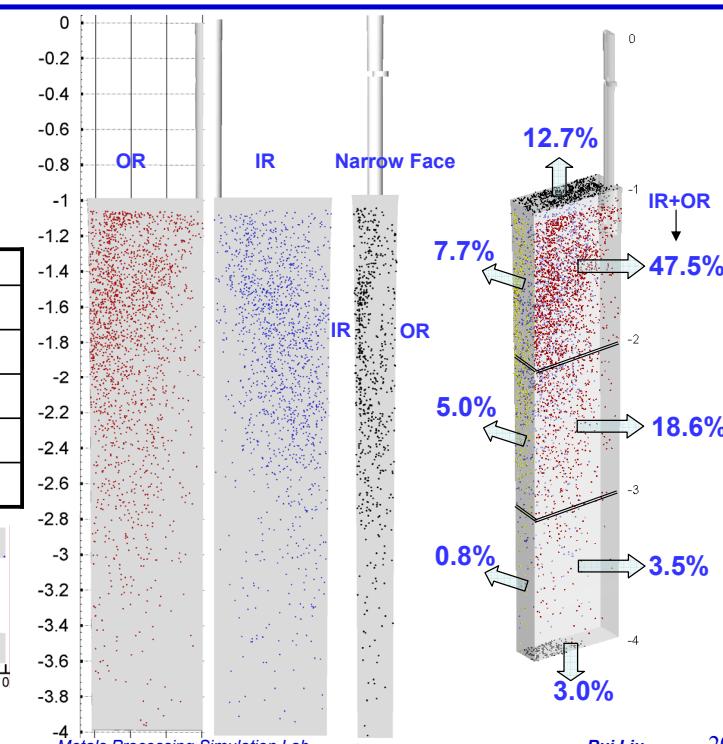
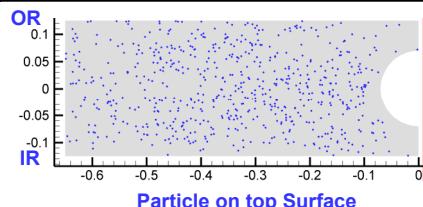
Particle Density: 2700 kg/m³

Diameter: 100 microns

Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	30.9%
Shell (wide face OR)	38.7%
Shell (narrow face)	13.5%
Outer SEN walls	1.2%
Free Surface	12.7%



Case 2-2 : 400 microns Slag particles

Computation Model:

multiphase flow, no MHD

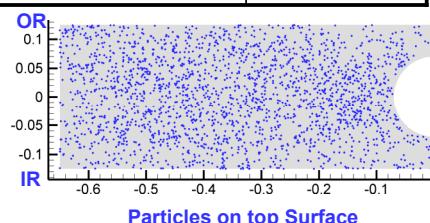
Particle density: **2700 kg/m³**

Diameter: **400 microns**

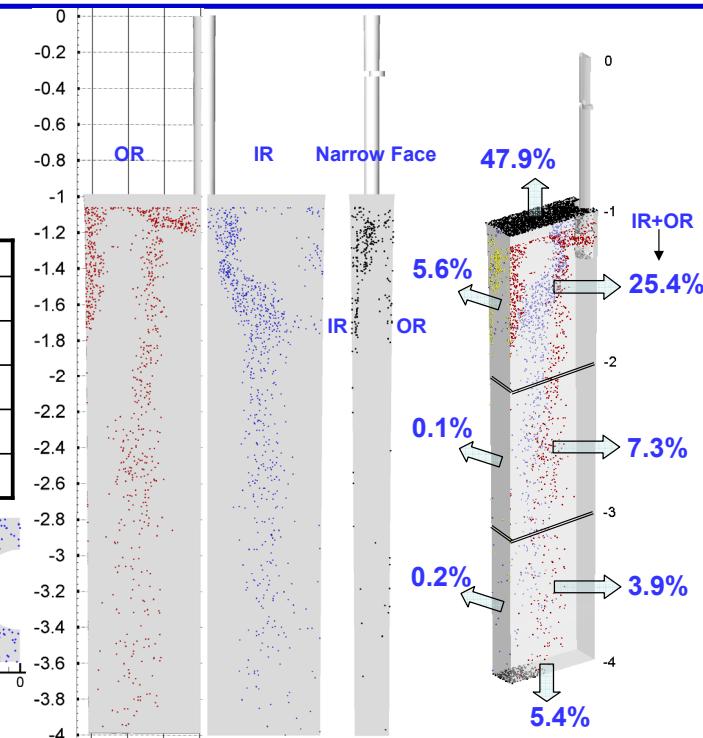
Length unit: **m**

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	18.1%
Shell (wide face OR)	18.4%
Shell (narrow face)	5.9%
Outer SEN walls	4.2%
Free Surface	47.9%



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Case 2-3 : 100 microns Alumina cluster

Computation Model:

multiphase flow, no MHD

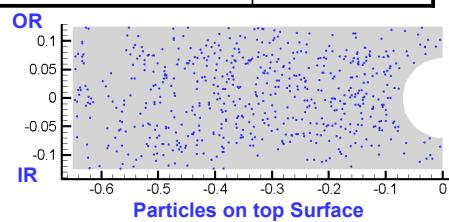
Particle density: **2700 kg/m³**

Diameter: **100 microns**

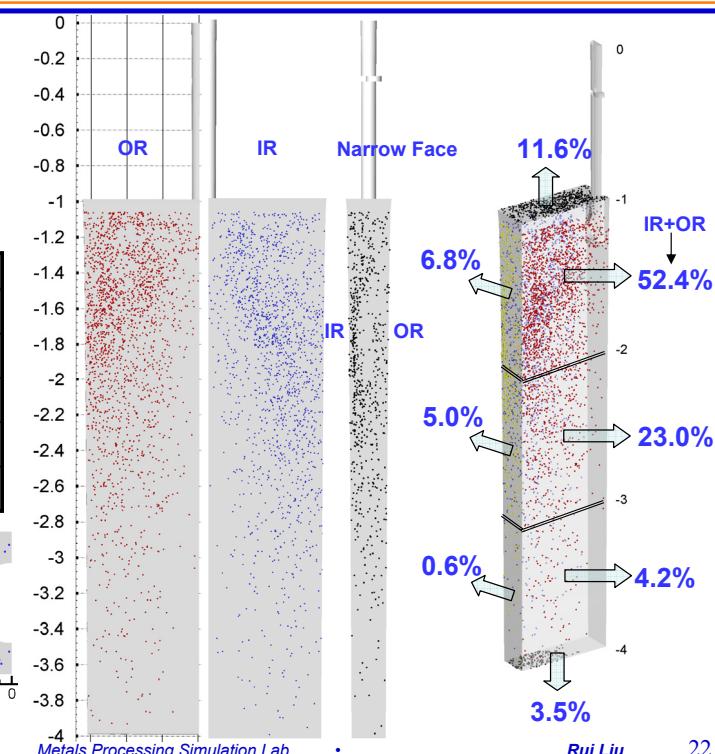
Length unit: **m**

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	30.2%
Shell (wide face OR)	37.0%
Shell (narrow face)	12.4%
Outer SEN walls	5.3%
Free Surface	11.6%



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Case 2-4 : Argon bubble

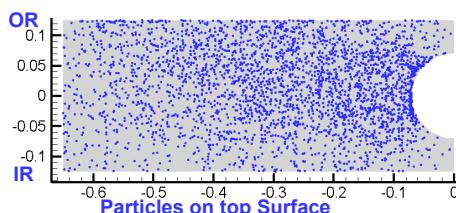
Computation Model:

multiphase flow, no MHD

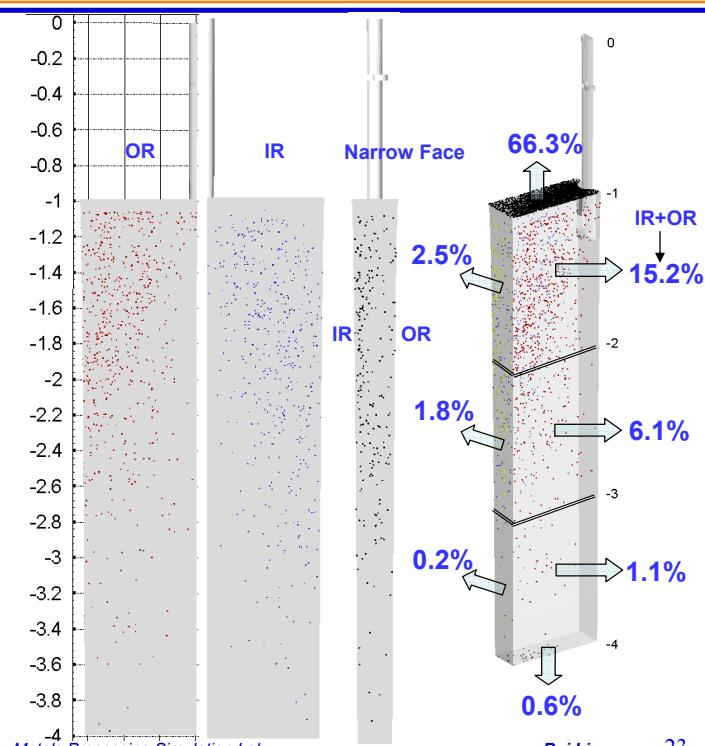
Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	9.9%
Shell (wide face OR)	12.5%
Shell (narrow face)	4.5%
Outer SEN walls	6.0%
Free Surface	66.3%



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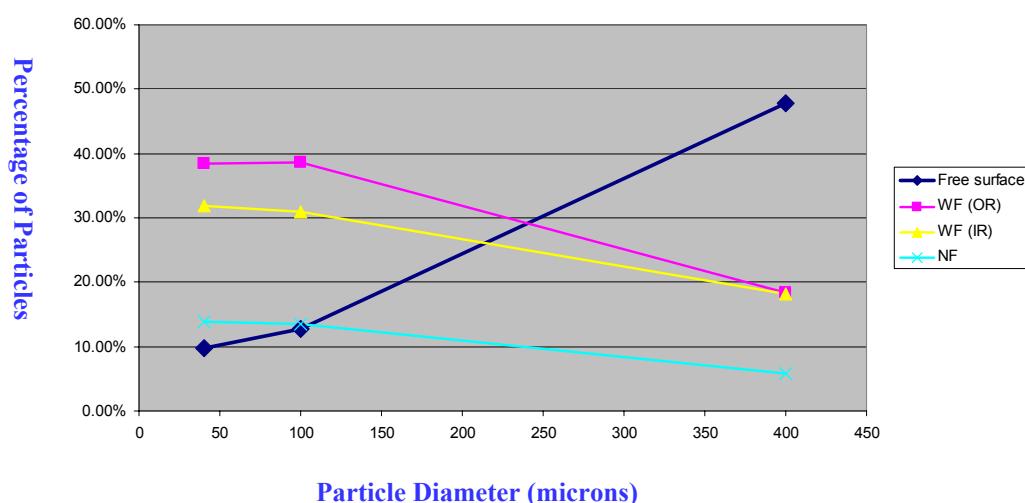
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Particle size effect on Slag particle distribution– CASE 2

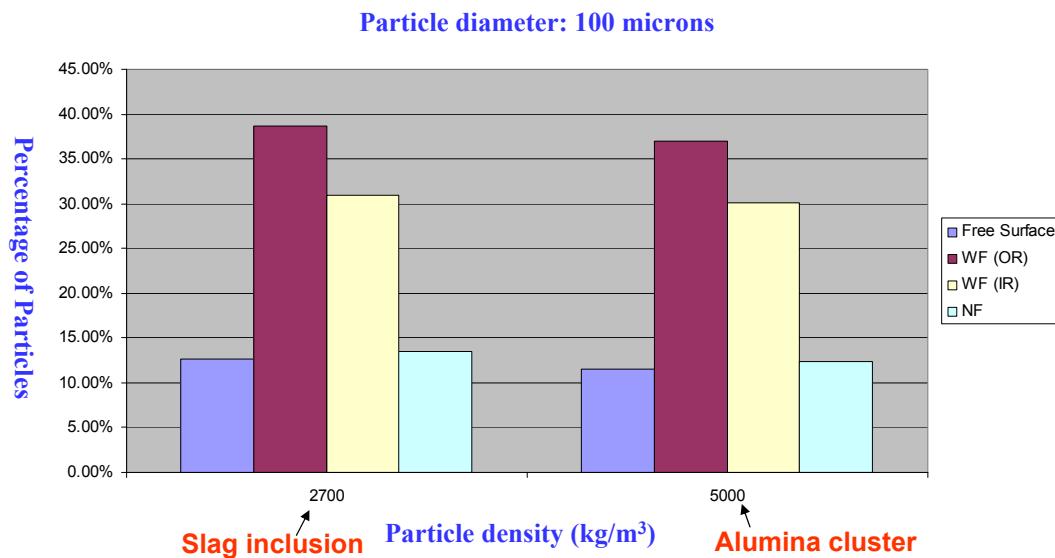
density: 2700 kg/m^3



Particle Diameter (microns)

- Outer radius of shell captures more particles with smaller sizes (40 and 100 microns)
- Larger particles have a much higher removal rate (48%) by the top surface.

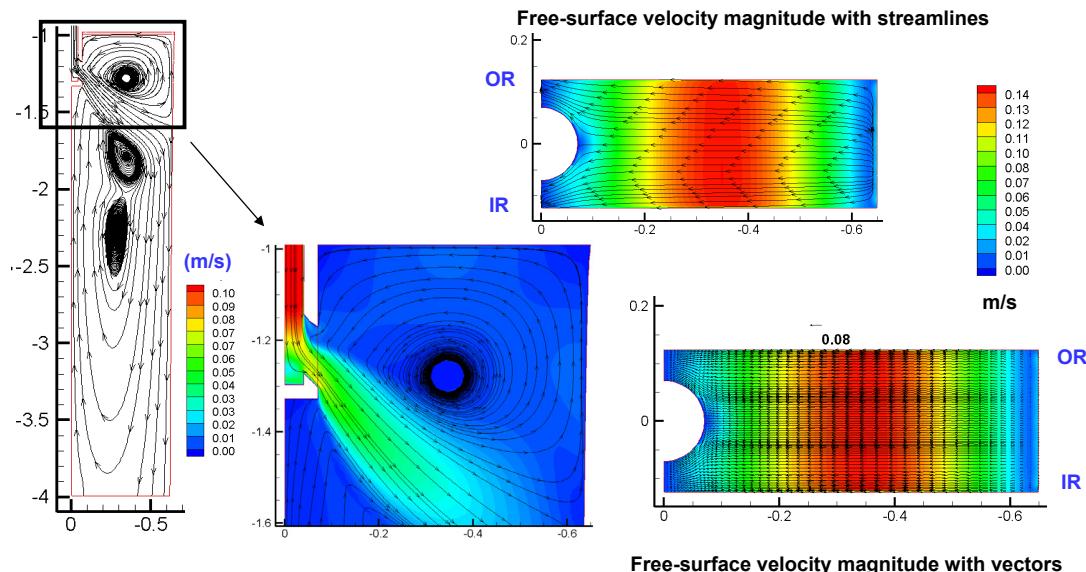
Effect of density on particle distributions – CASE 2



- Slightly fewer (1%) denser particles (with density of 5000 kg/m^3) are removed at top surface compared with 2700 kg/m^3 particles

Case 3 – Fluid Flow in the mold

Case 3: Single phase Flow Model WITH MHD (U:300A, L:300A)



-- results by Rajneesh Chaudhary, CCC meeting, 2009

Case 3-1: 100 microns Slag particles

Computation Model:

Single phase flow, with MHD

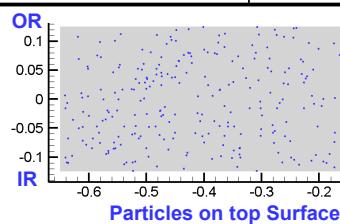
Particle density: 2700 kg/m³

Diameter: 100 microns

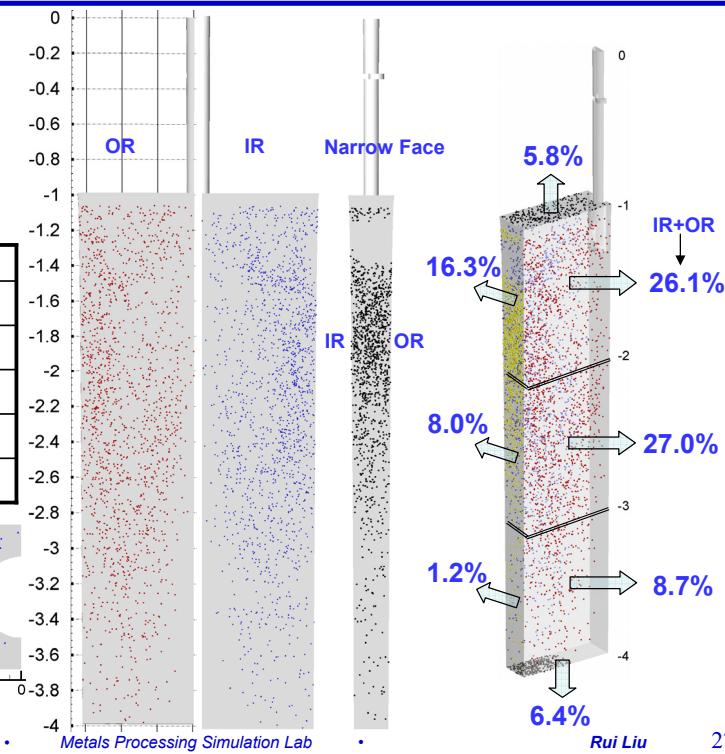
Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	31.4%
Shell (wide face OR)	30.4%
Shell (narrow face)	25.5%
Outer SEN walls	0.6%
Free Surface	5.8%



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Case 3-2: 400 microns Slag particles

Computation Model:

Single phase flow, with MHD

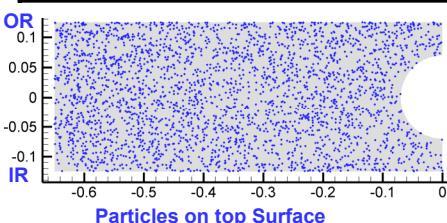
Particle density: 2700 kg/m³

Diameter: 400 microns

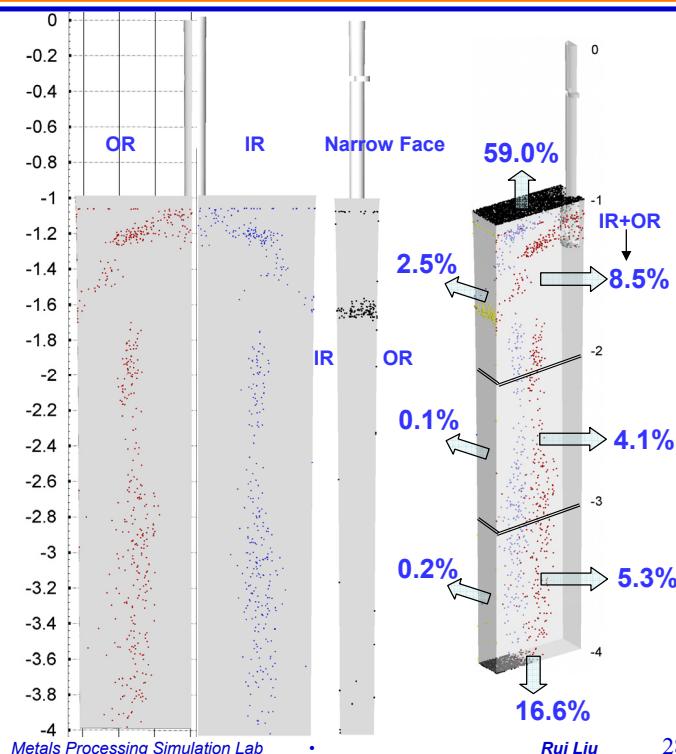
Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	8.2%
Shell (wide face OR)	9.6%
Shell (narrow face)	2.8%
Outer SEN walls	3.8%
Free Surface	59.0%



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Case 3-3: 100 microns Alumina cluster

Computation Model:

Single-phase flow, with MHD

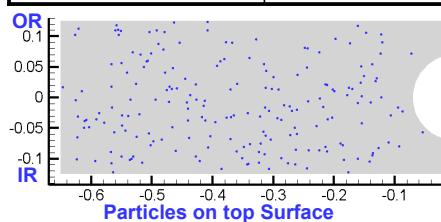
Particle density: 5000 kg/m³

Diameter: 100 microns

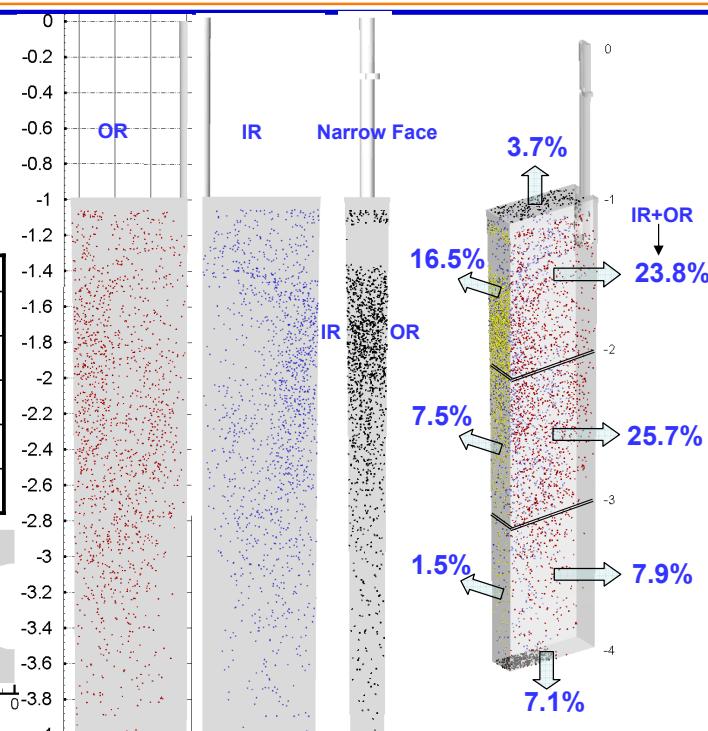
Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	28.7%
Shell (wide face OR)	28.8%
Shell (narrow face)	25.5%
Outer SEN walls	6.2%
Free Surface	3.7%



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Case 3-4: Argon bubble

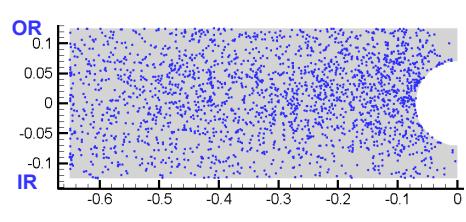
Computation Model:

single phase flow, WITH MHD

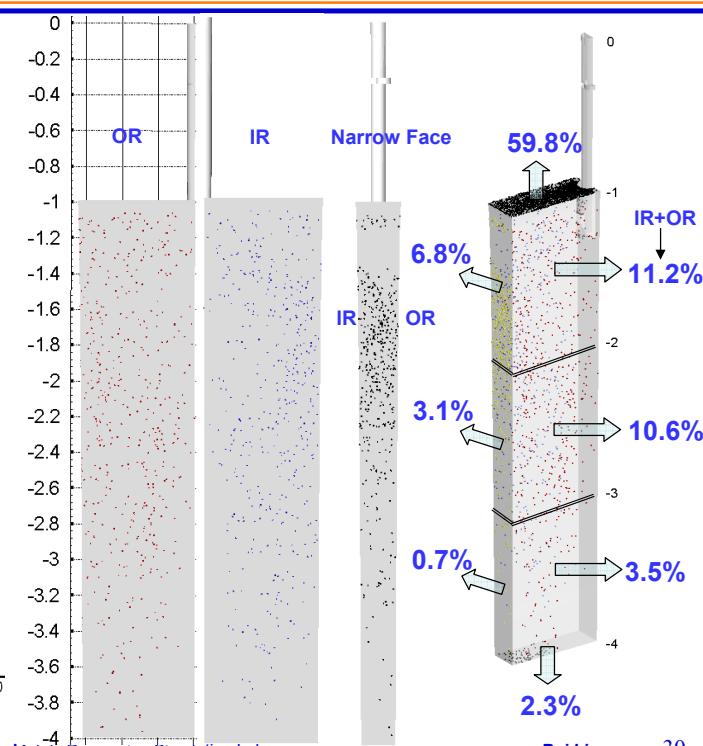
Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	12.4%
Shell (wide face OR)	12.8%
Shell (narrow face)	10.6%
Outer SEN walls	2.0%
Free Surface	59.8%



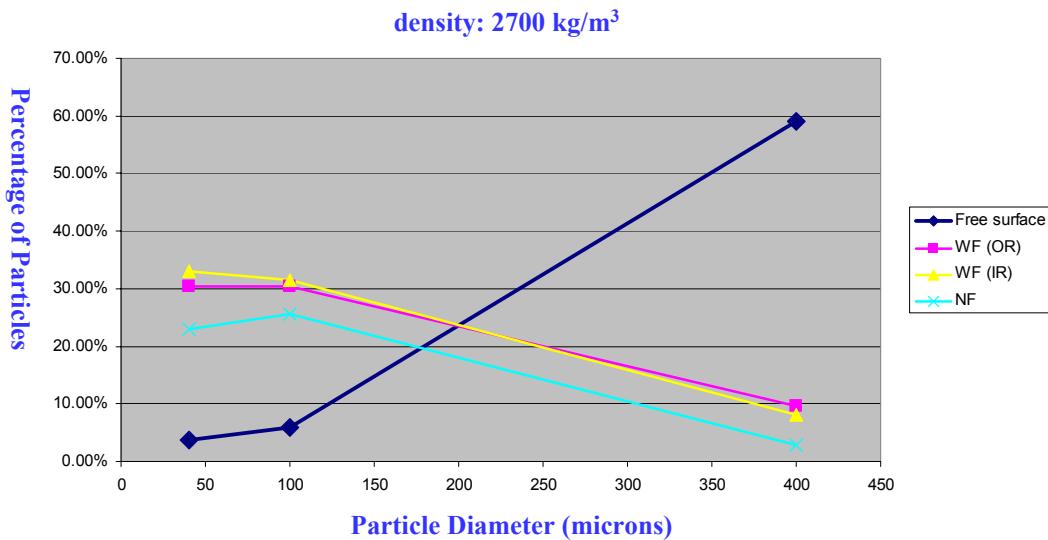
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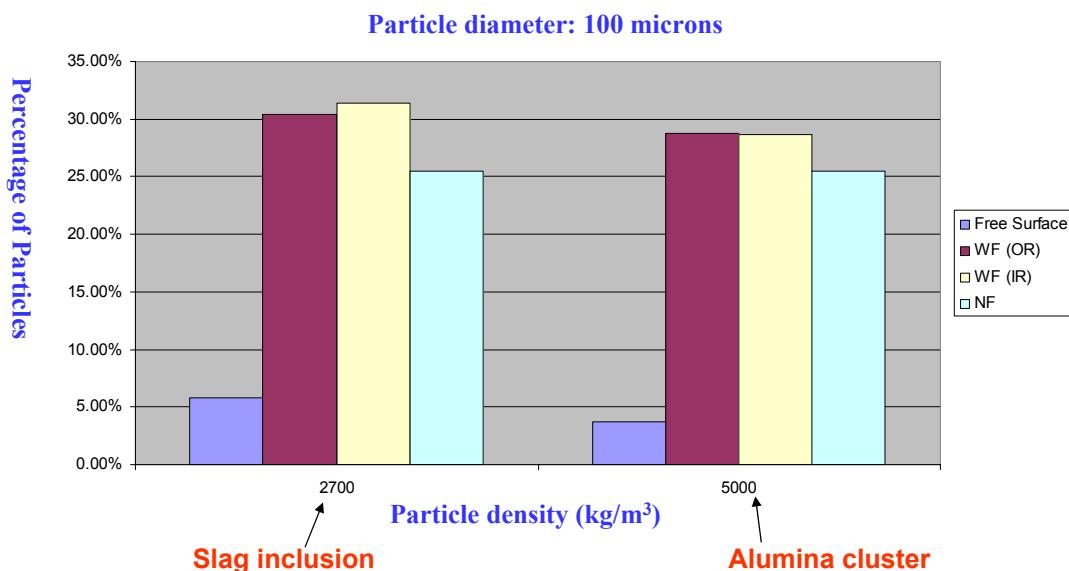
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Particle size effect on Slag particle distribution– CASE 3



- Around 60% of the large particles (400 microns diameter) are removed from top surface.
- Particles are trapped preferentially on the NF (considering its only 1/7 area, 5%/m² for NF vs. 2%/m² for WF for 400 microns diameter). No obvious preference in capturing the particles is found between OR and IR.

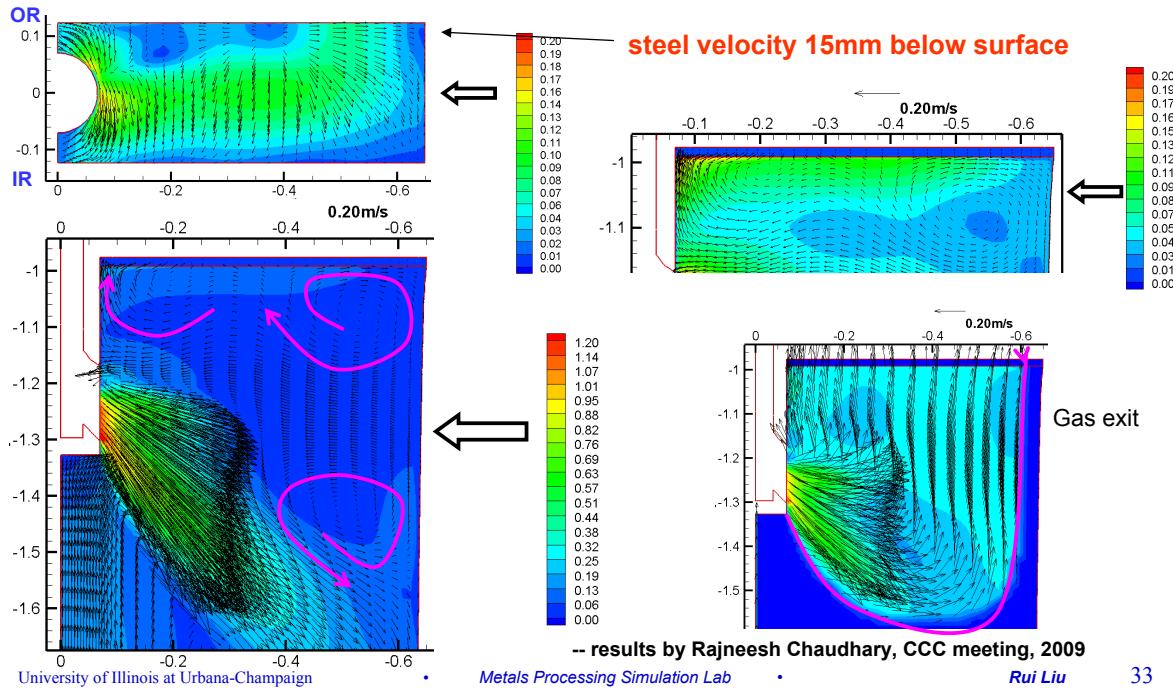
Effect of density on particle distributions – CASE 3



- Denser particles are slightly less removed from the top surface than lighter ones (3.8 vs. 5.7%).

Case 4 – Fluid Flow in the mold

Case 4: Multiphase Flow Model WITH MHD (30LPM, 2.4 mm bubble, U:300A,L:300A)



Case 4–1: 100 microns Slag particle

Computation Model:

multiphase flow, with MHD

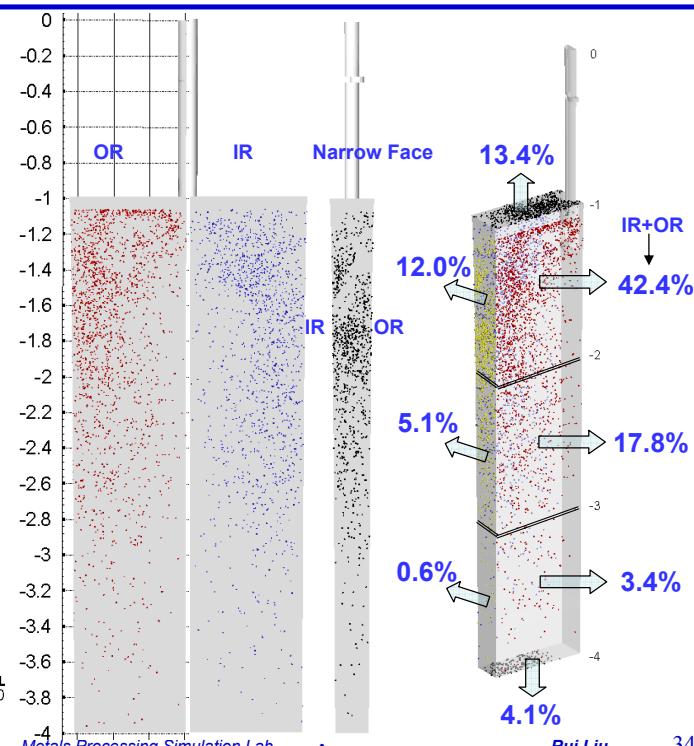
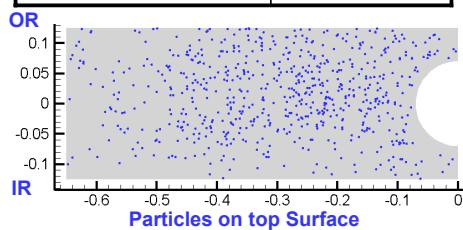
Particle density: 2700 kg/m³

Diameter: 100 microns

Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	28.2%
Shell (wide face OR)	35.4%
Shell (narrow face)	17.7%
Outer SEN walls	1.5%
Free Surface	13.4%



Case 4–2: 400 microns Slag particle

Computation Model:

multiphase flow, with MHD

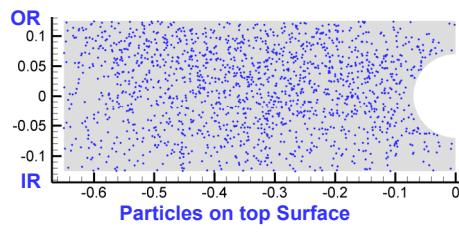
Particle density: **2700 kg/m³**

Diameter: **400 microns**

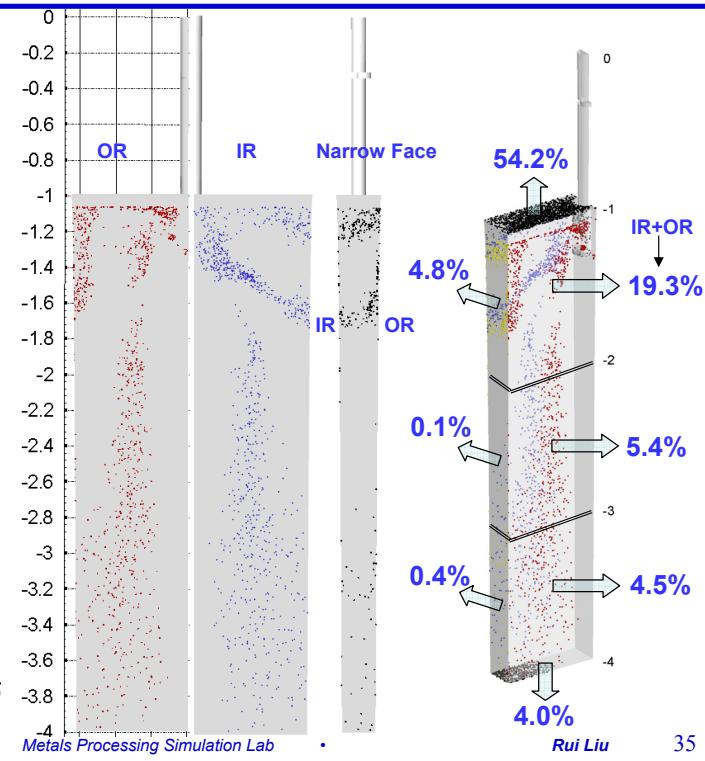
Length unit: **m**

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	14.9%
Shell (wide face OR)	14.4%
Shell (narrow face)	5.3%
Outer SEN walls	7.1%
Free Surface	54.2%



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Case 4–3: 100 microns Alumina cluster

Computation Model:

multiphase flow, with MHD

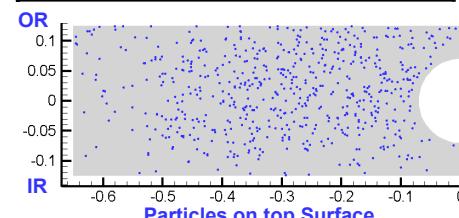
Particle density: **5000 kg/m³**

Diameter: **100 microns**

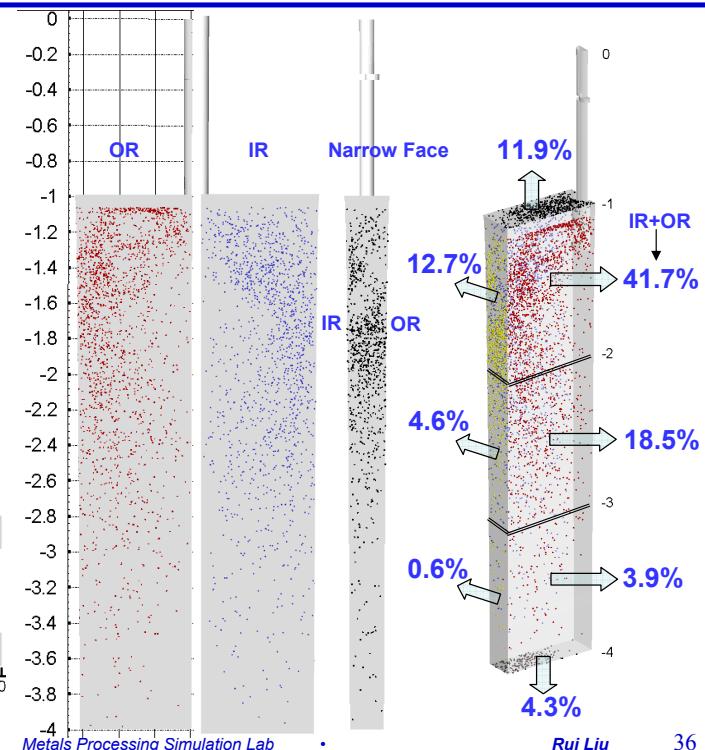
Length unit: **m**

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	28.1%
Shell (wide face OR)	36.0%
Shell (narrow face)	17.9%
Outer SEN walls	1.6%
Free Surface	11.9%



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Case 4-4: Argon bubble

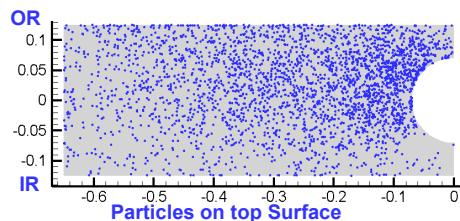
Computation Model:

multiphase flow, with MHD

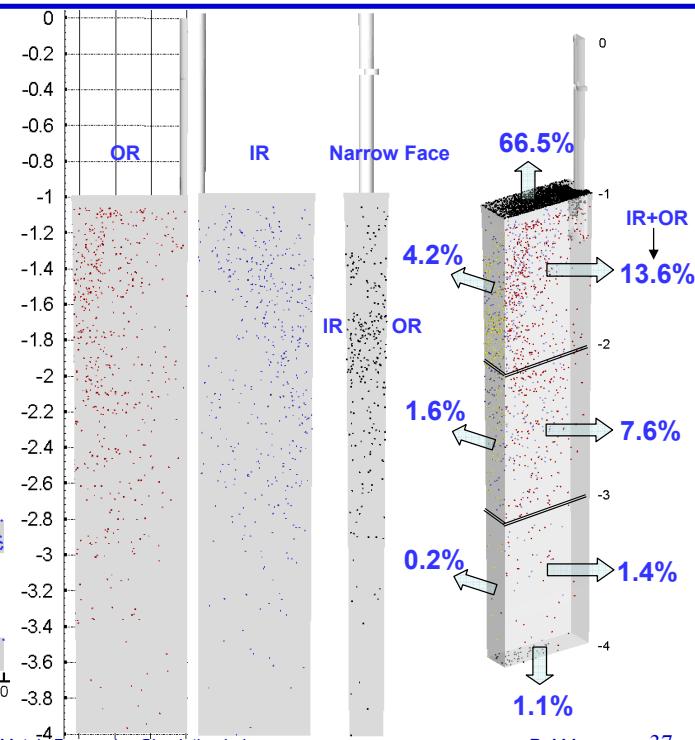
Length unit: m

Percentage = # on the boundary/total #

Boundaries	Percentage
Shell (wide face IR)	10.7%
Shell (wide face OR)	11.9%
Shell (narrow face)	6.0%
Outer SEN walls	3.8%
Free Surface	66.5%



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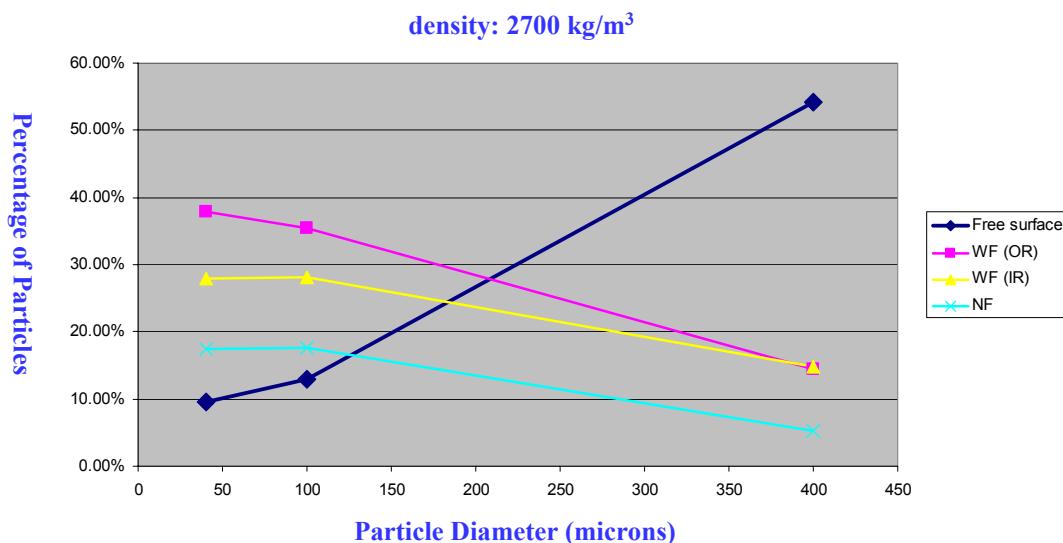


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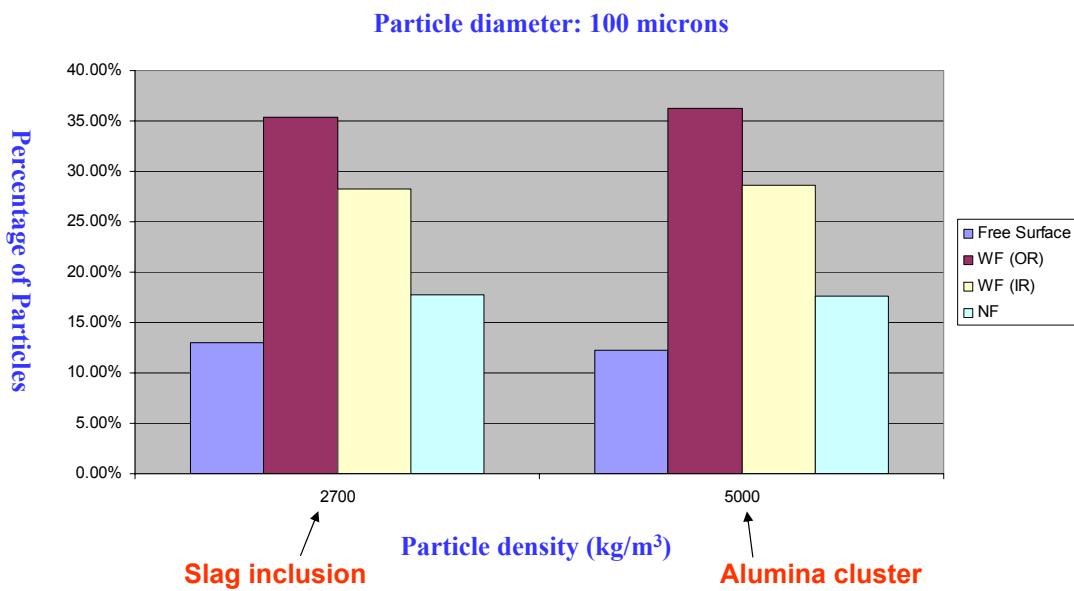
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Particle size effect on Slag particle distribution– CASE 4



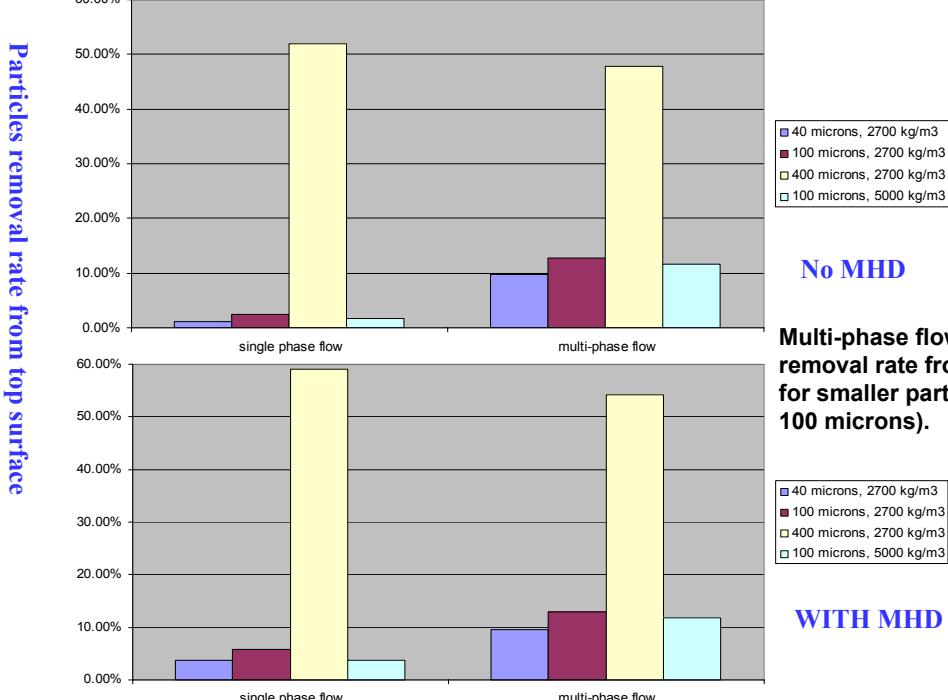
- More smaller particles (40 and 100 microns) are trapped at OR than IR on the wide face, while no preference between OR and IR is found for large particles (400 microns) to be trapped in.

Effect of density on particle distributions – CASE 4



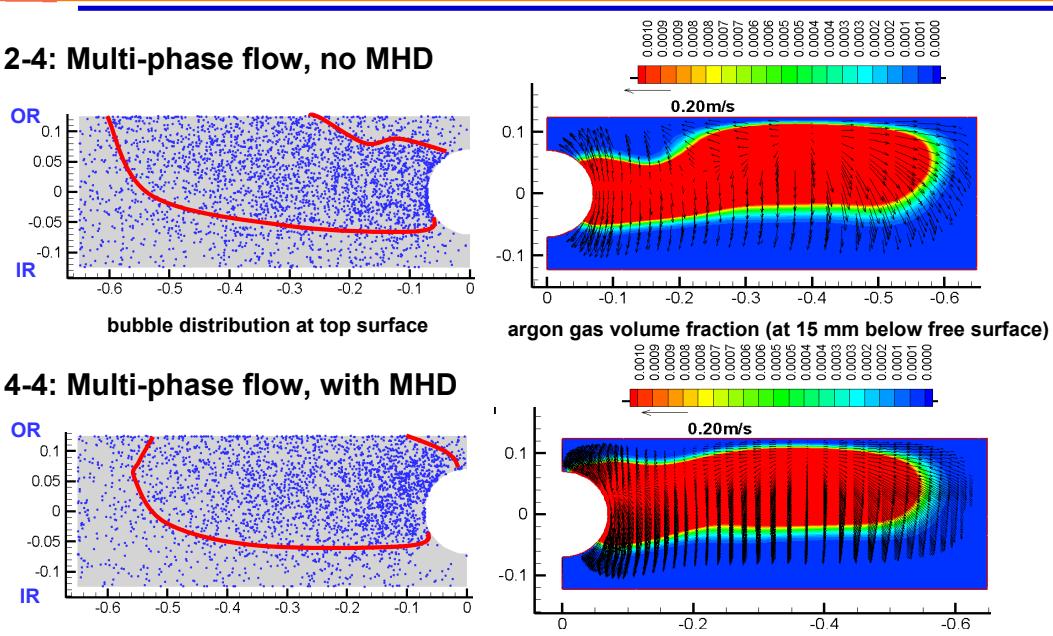
- Only slight increase (1.5%) of percentage for top surface is found from density of 5000 kg/m³ to 2700 kg/m³.

Multi-phase flow effect on particle removal from top surface

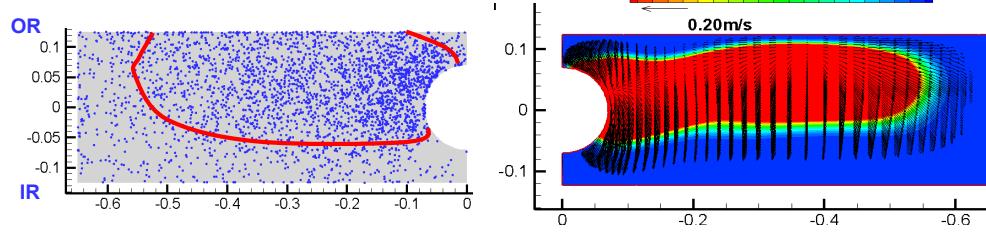


Multi-phase flow effect on bubble removal from top surface

CASE 2-4: Multi-phase flow, no MHD



CASE 4-4: Multi-phase flow, with MHD



- Bubbles gather densely at top surface in regions where the gas fraction is high.
(the bubble removal rates at top surface are 66% in both cases)

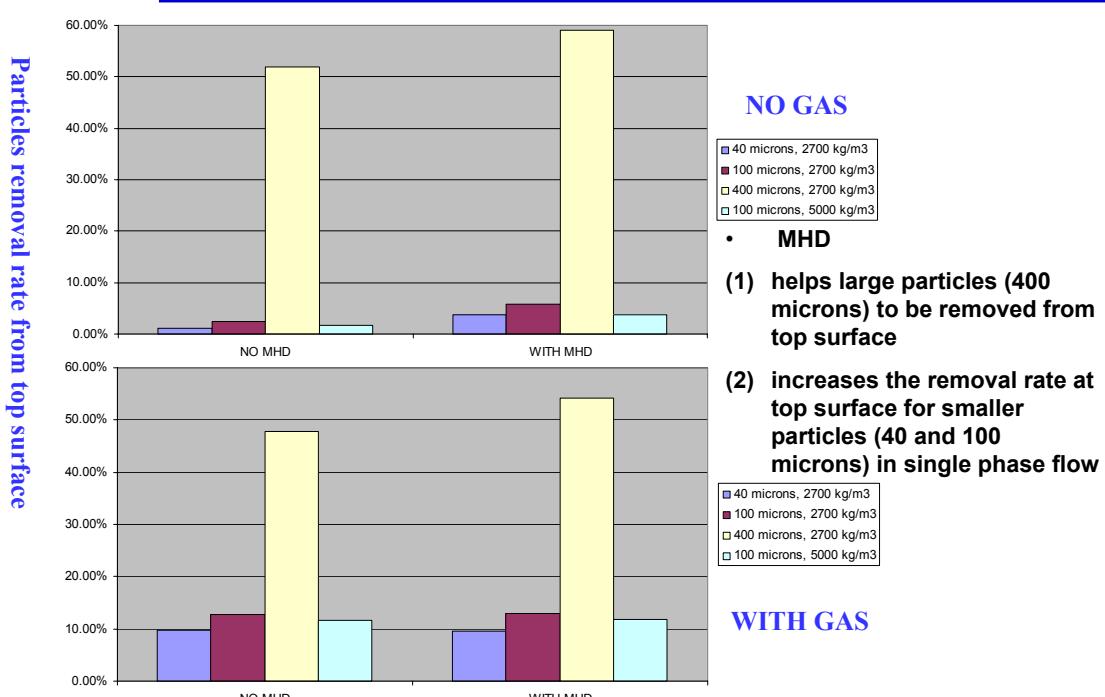
-- argon gas volume fraction results from Rajneesh Chaudhary, CCC meeting, 2009

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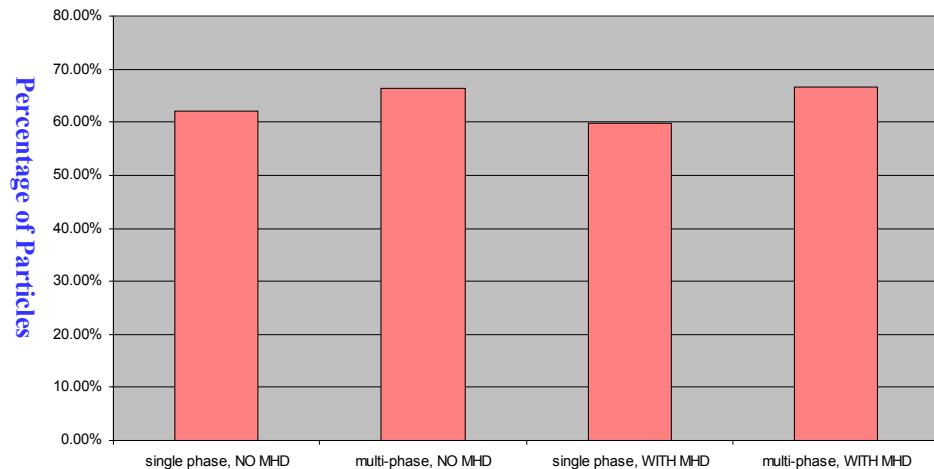
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MHD effect on particle removal from top surface



Bubble removal from top surface in different cases

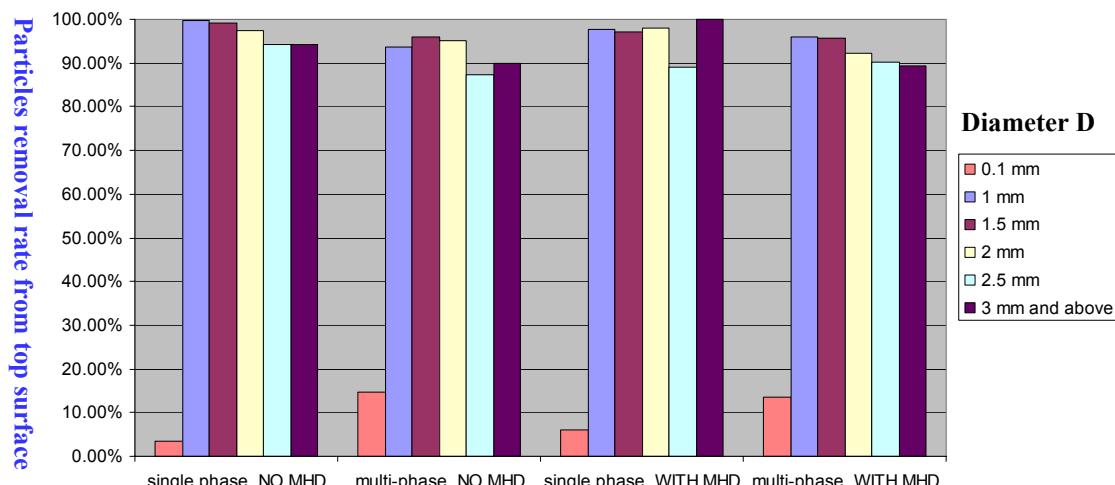
percentage calculated by: # of bubbles removed by top surface/# of bubbles entering the mold
 bubbles escaping from top surface



- Single phase flows always have fewer bubbles removed from the top surface than the multi-phase flows

Percentage removed from top surface for different bubble sizes

Calculated by: # of particles removed from top surface with diameter D/total # of particles with diameter D



- Only few 0.1 mm diameter bubbles are removed from the top surface for single phase flows (6.0% and 3.4% for single phase flows with/without MHD)
- Smaller bubbles (0.1 mm) are more removed by top surface in multiphase flows (with a factor of 2~3 compared with the cases in single phase flows)

Conclusions

- In each case, with/without MHD, single/multi-phase flow,
 - percentage of particles removed by top surface increases greatly with particle size increasing due to the decrease in entrapment likelihood at the dendritic interface
 - increasing the particle density (from 2700 kg/m³ to 5000 kg/m³) has a slight influence on decreasing the number of particles removed by the top surface (1% to 2% decrease)
 - particles are trapped preferentially at NF (by percentage/m²)
- Injecting argon into the mold greatly helps particles to escape from the top surface
 - especially for smaller particles (40 and 100 microns) (2.5% single phase vs. 12.7% with gas)
 - with little effect on large particles (400 microns)

Conclusions

- Using EMBR
 - helps larger particles (400 microns) to escape from top surface (52% vs. 59% in single phase flow, 48% vs. 54% in multi-phase flow)
 - increases the removal rate at top surface for smaller particles (40 and 100 microns) in single phase flow (1% vs. 4% for 40 microns diameter, 2% vs. 6% for 100 microns diameter)
- For gas bubbles entrapment:
 - small bubbles (0.1 mm) are more likely to be removed from top surface in multi-phase flows (4% in single phase flow vs. 15% in multi-phase flow)
 - bubbles gather more densely at top surface in the regions where the argon gas fraction is higher
 - generally, about 90% of the bubbles with diameter of 1mm and above are removed from the top surface, while only around 10% of the 0.1 mm diameter bubbles are removed from top surface

Future Work

- Further improve the particle transport model taking into account the mold curvature to provide better predictions for particle entrapment at OR and IR.

- Parametric study using the model under different casting conditions, including:
 - casting speed
 - argon flow rate
 - mold width
 - nozzle geometry and port angle

Acknowledgements

- Continuous Casting Consortium Members
(POSCO, ABB, Arcelor-Mittal, Baosteel, Corus, Delavan/Goodrich, LWB Refractories, Nucor, Nippon Steel, Postech, Steel Dynamics, ANSYS-Fluent)

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