Inclusion Nucleation, Growth, Removal and Entrapment in Molten Steel and Continuous Casting

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Acknowledgements

- Accumold
- AK Steel
- Columbus Stainless Steel
- Hatch Associates
- Fluent Inc.
- National Science Foundation
- National Center for Supercomputing Applications

Outline

1. Overview of Steel Cleanliness;
2. Inclusion nucleation, growth and removal in steel;
3. Interaction between Inclusion and Bubble in Liquid Steel;
4. Inclusion removal in continuous casting mold.

1. Overview of Steel Cleanliness

Direct Evaluation Methods for Measuring Steel Cleanliness

Inclusion evaluation: amount, size distribution, morphology, composition

1. Inclusion Evaluation of Solid Steel Sections

1) Metallographic Microscope Observation
2) Image Analysis
3) Sulfur Print
4) Scanning Electron Microscopy
5) Optical Emission Spectrometry with Pulse Discrimination Analysis
6) Laser Microprobe Mass Spectrometry
7) X-ray Photoelectron Spectroscopy
8) Auger Electron Spectroscopy
9) Fractional Thermal Decomposition

2. Inclusion Evaluation of Solid Steel Volumes

1) Conventional Ultrasonic Scanning
2) Mannesmann Inclusion Detection by Analysis Surfboards
3) Scanning Acoustic Microscope
4) X-ray Detection
5) Slime (Electrolysis)
6) Electron Beam melting
7) Cold Crucible melting

3. Inclusion Size Distribution After Inclusion Extraction

1) Coulter Counter Analysis
2) Photo Scattering Method
3) Laser-Diffraction Particle Size Analyzer

4. Inclusion Evaluation of Liquid

1) Ultrasonic Techniques for Liquid System
2) Liquid Metal Cleanliness Analyzer
3) Confocal Scanning Laser Microscope

Cost, Time requirements, Different aspects measured

Indirect Evaluation Methods of Steel Cleanliness

Total Oxygen (T.O.) Measurement

Nitrogen Pick-up Measurement

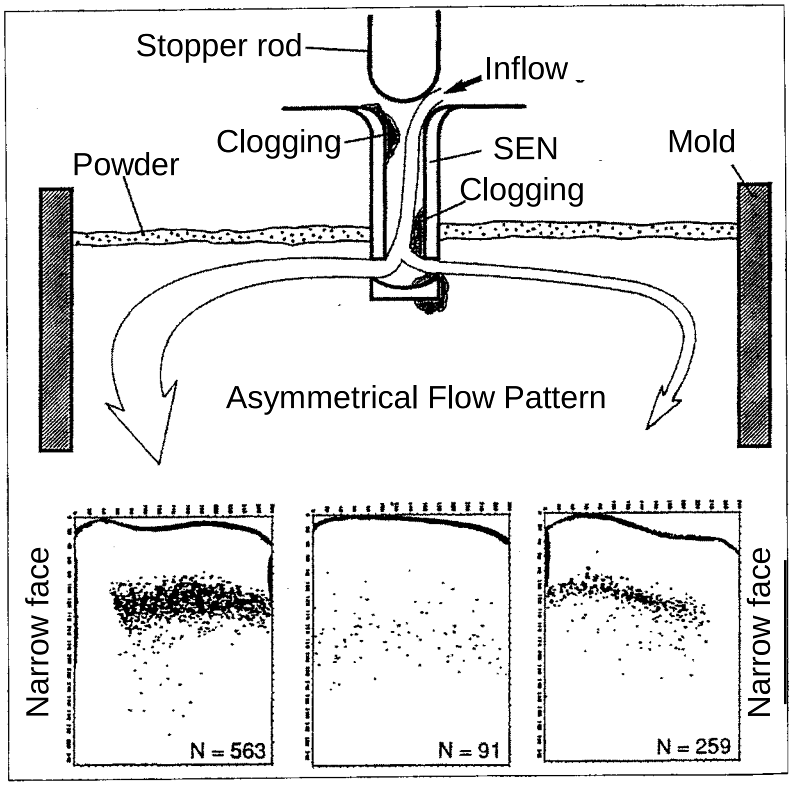
Dissolved aluminum loss and silicon change measurement

Slag composition measurement

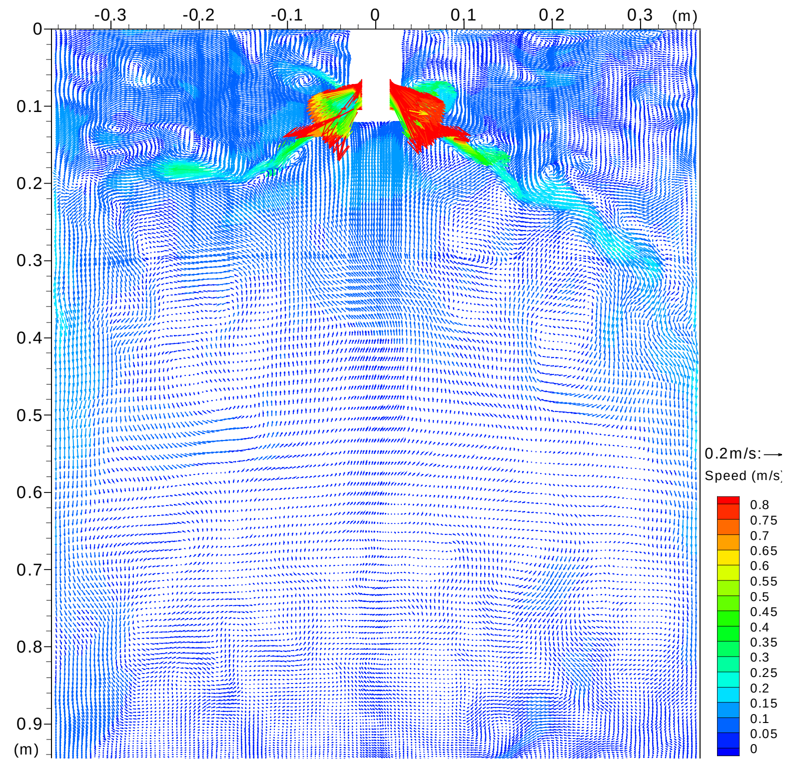
Asymmetrical Mold Flow Pattern Lowers Steel Cleanliness

Asymmetrical Mold flow pattern caused by:

1) Nozzle clogging
2) Turbulence



From the SEN clogging (N—inclusion number index by the methods of MIDAS)

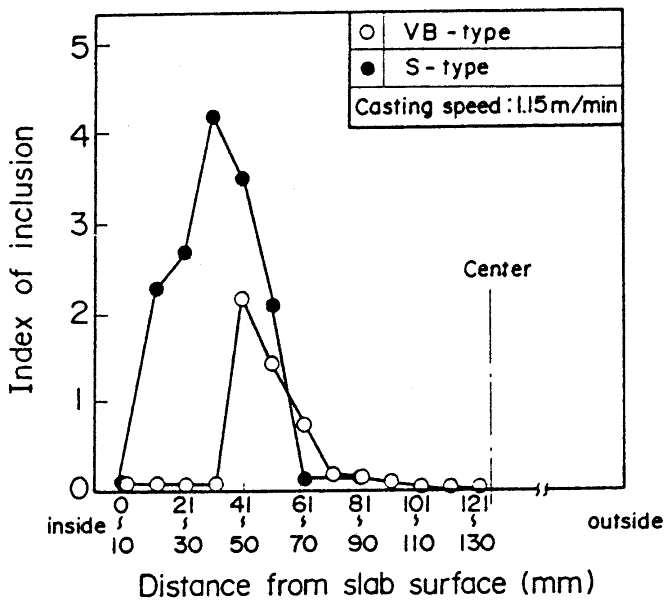


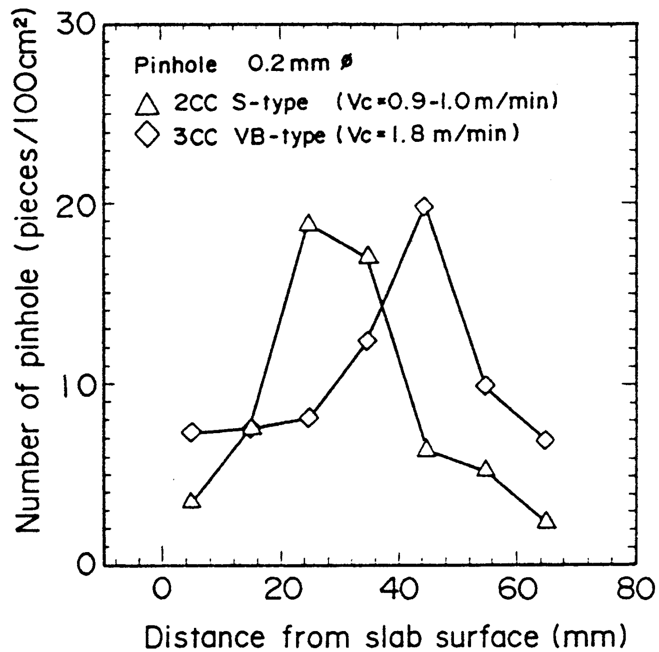
From transient behavior of fluid flow

Ref.: 1) H. Jacobi, Stahl und Eisen, Vol. 118 (11), 1998, 87-94. 2) Q. Yuan and B.G.Thomas, CCC report, 2001

Effect of Caster Type on Steel Cleanliness

Curved mold (S-Type) machines
Vertical-bending) mold caster (VB-type)



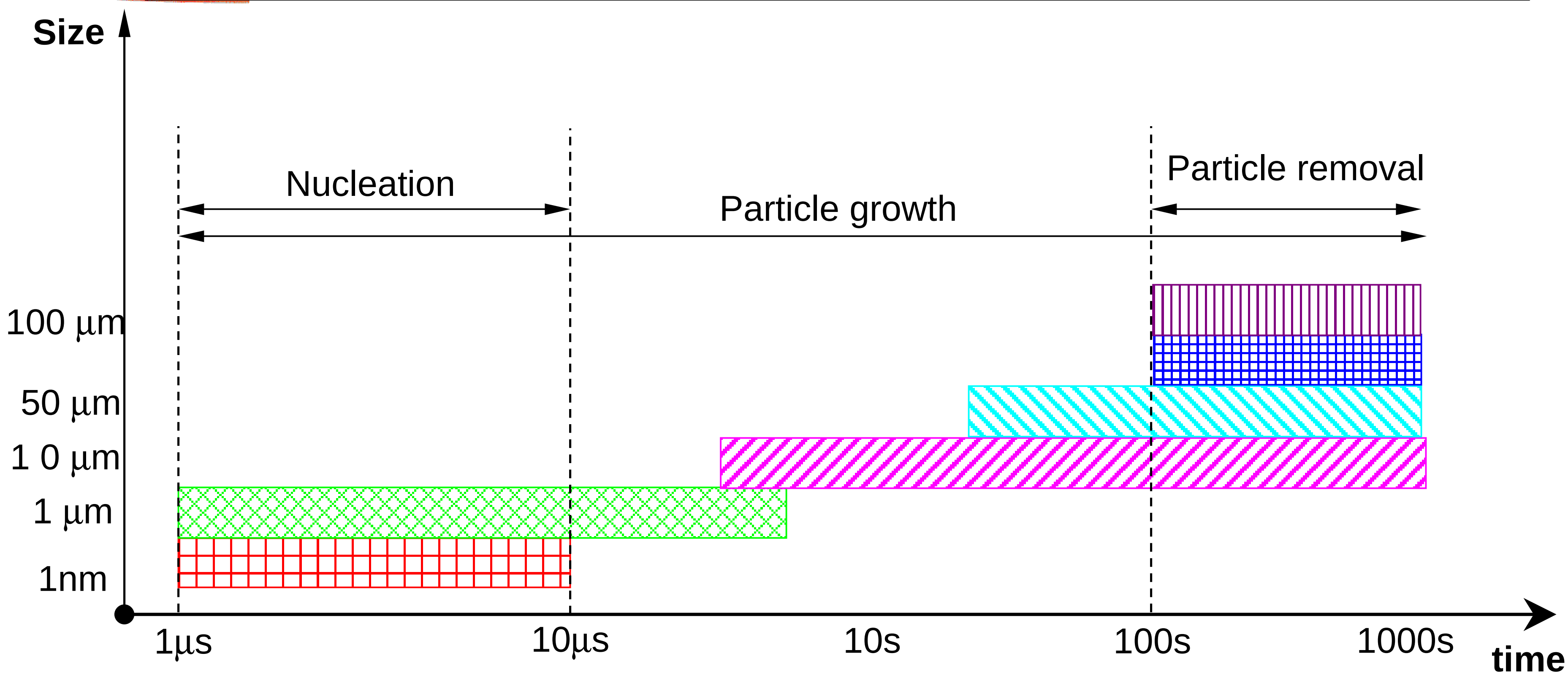


The inclusions amount (left) by VB-type is lower and the peak of the inclusions and pinholes (right) is deeper than S-type.

Ref. Y. Sirota, in Nishiyama Memorial Seminar, Vol. 143/144,, (ISIJ Tokyo), 1992, 167-191.

2. Inclusion Nucleation, Growth and Removal in Steel

Mechanisms of Inclusion Evolution

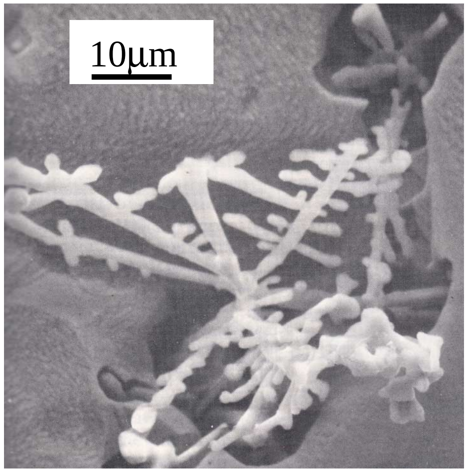


Phenomena

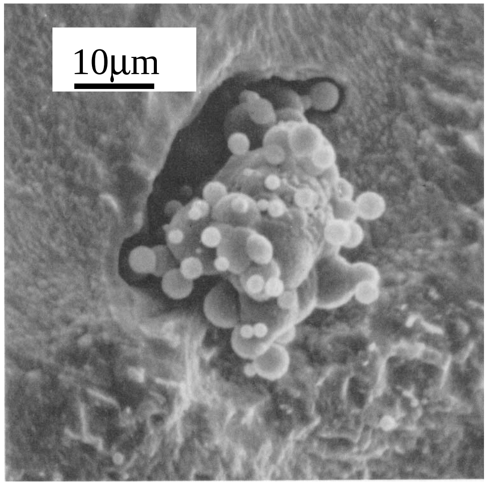
- **Brownian collision**
- **Ostwald-Ripening (Elements Diffusion)**
- **Stokes collision and buoyancy rising**
- **Turbulent collision**
- **Interface reaction**
- **Flow transport**

Inclusion Morphologies and Sources

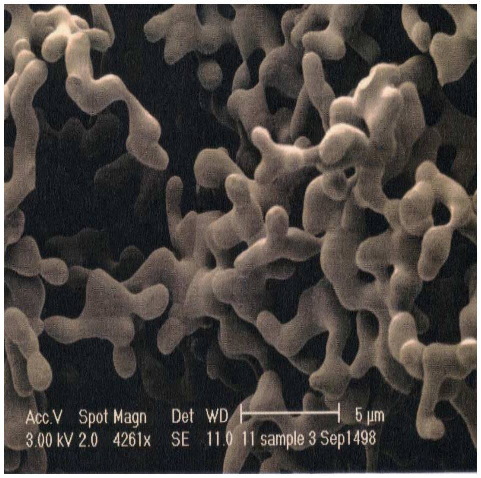
Dendritic alumina



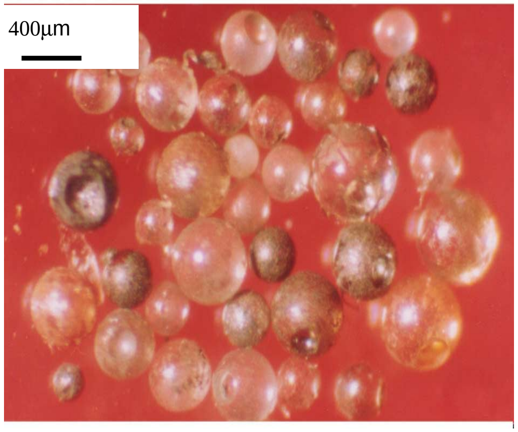
Alumina cluster



Coral structure alumina



Slag inclusions

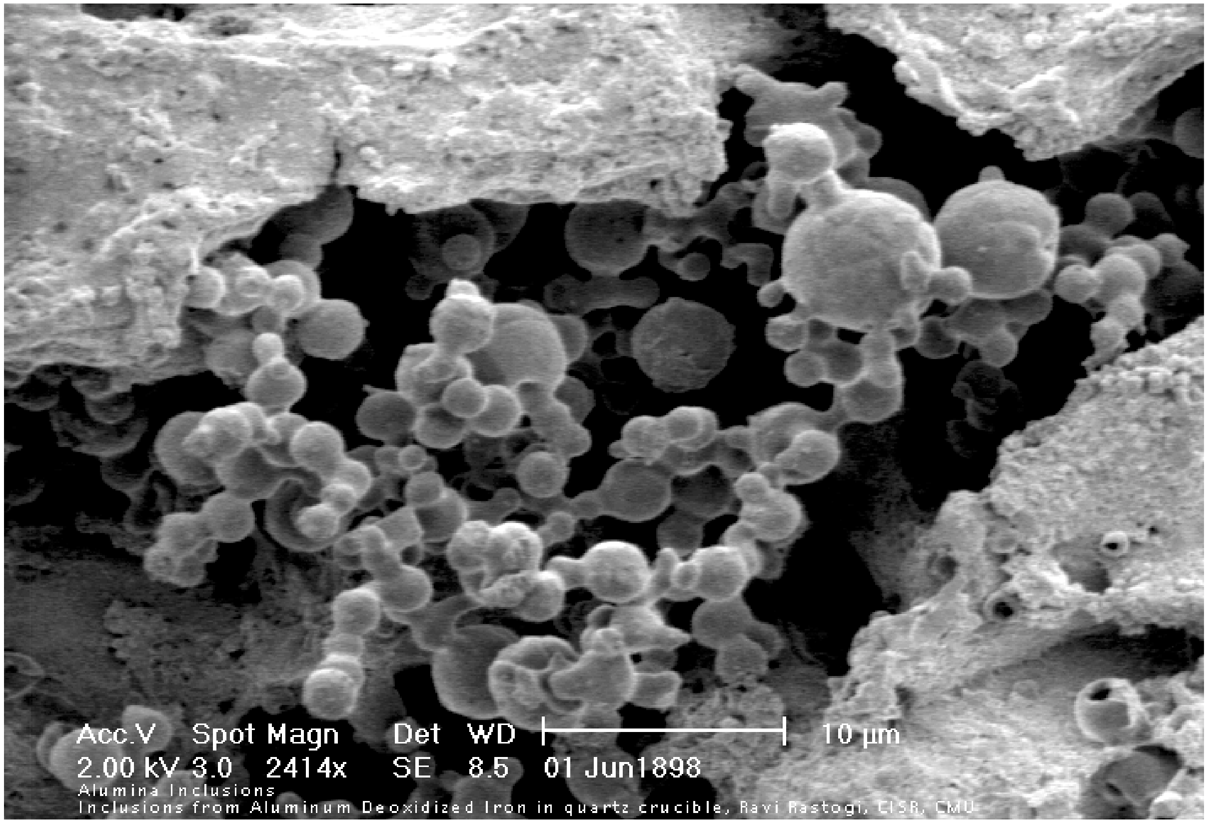


Inclusion Sources

1) Deoxidation products;
2) Reoxidation products (oxidized by slag or by air);
3) Slag entrapment;
4) Exogenous inclusions from other sources, such as, broken refractory brickwork and ceramic lining particles;
5) Chemical reactions, such as dissolution of refractory walls

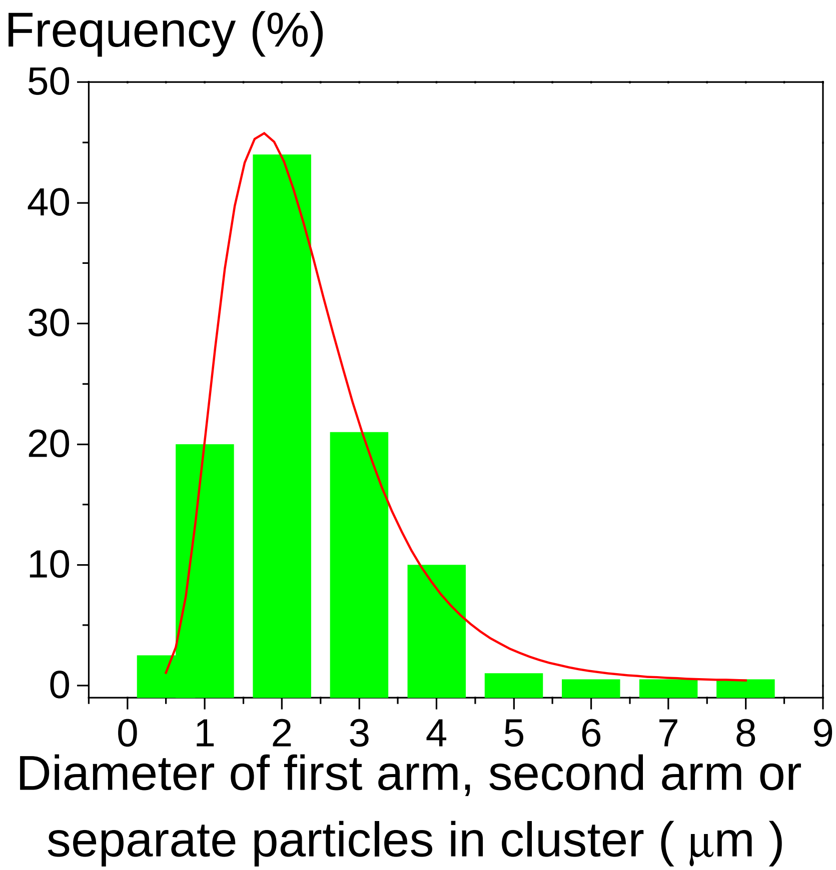
Refs:
L. Zhang, B. Thomas. ISIJ 2002, in Press

Alumina Cluster from Deoxidation



Ref.: Ravi Rastogi and Alan Cramb, Personal communication, 2002,

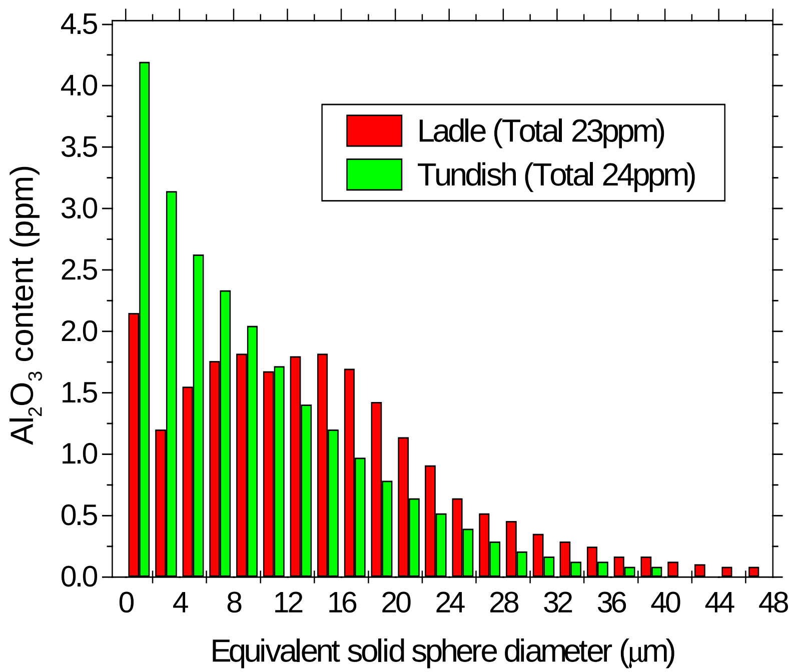
Characteristic of Inclusion Features



Alumina inclusion features have consistent 1~4 μm size

- **Central globules**
- **Secondary dendrite arms**
- **Separate spheres in clusters**

Inclusion Size Distribution Evolution



Inclusion evaluation:

1) amount
2) size distribution
3) morphology
4) composition

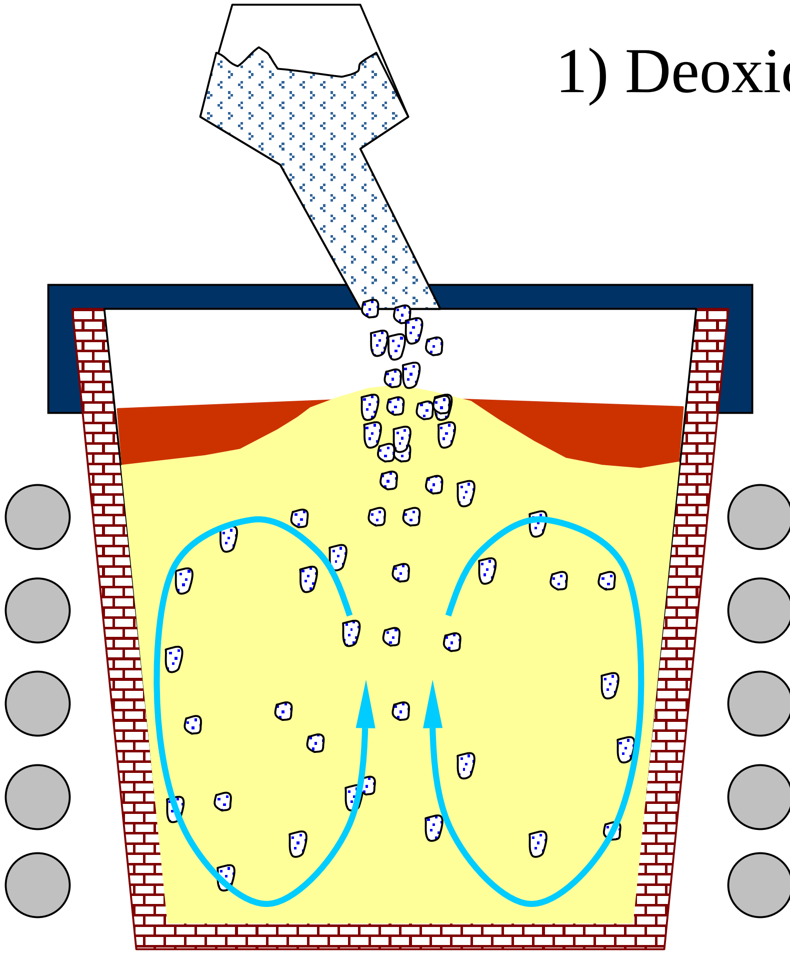
How does inclusion size distribution start, and how does it evolve with time?

Desire to model inclusion size distribution evolution

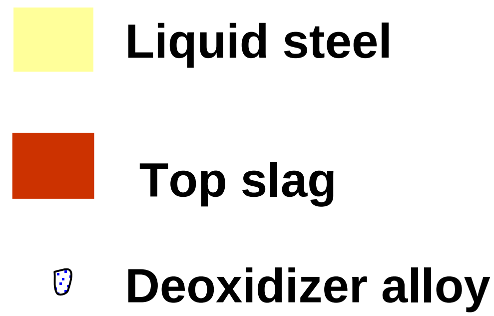
Previous models assume initial size distribution from measurements

Ref: Y. Miki and B.G. Thomas, " CAMP-Iron and Steel Inst. of Japan, Vol. 11 (4), 1998, 807.

Steps of Inclusion Nucleation and Growth during Deoxidation

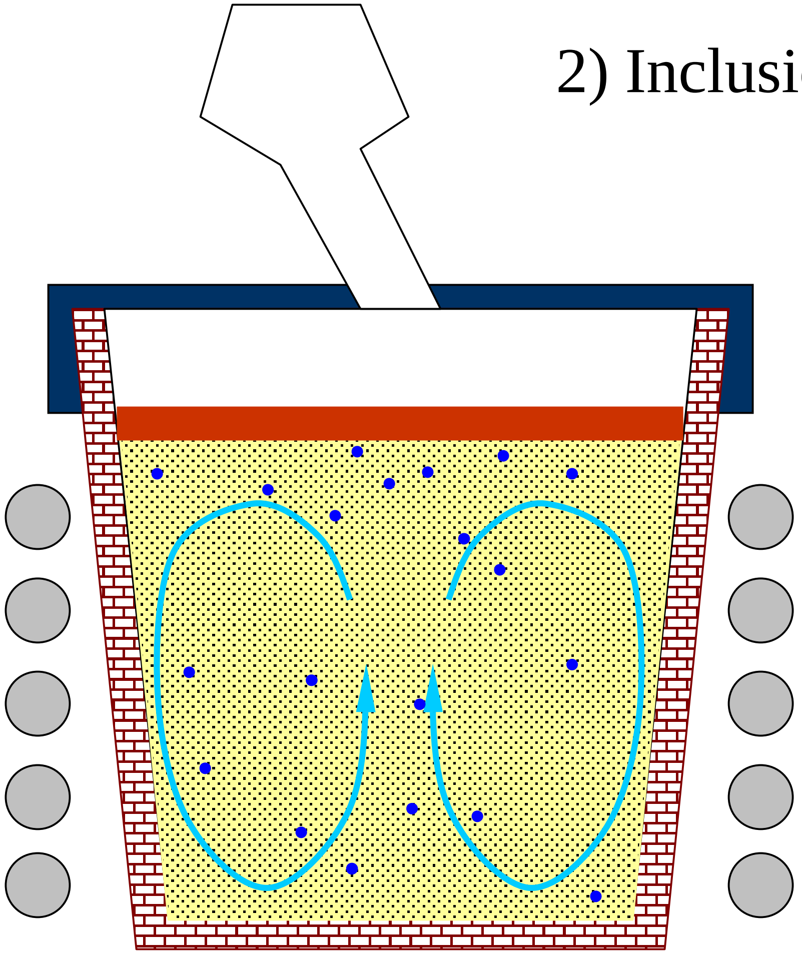


1) Deoxidizer addition



Steps of Inclusion Nucleation and Growth during Deoxidation

2) Inclusion nucleation



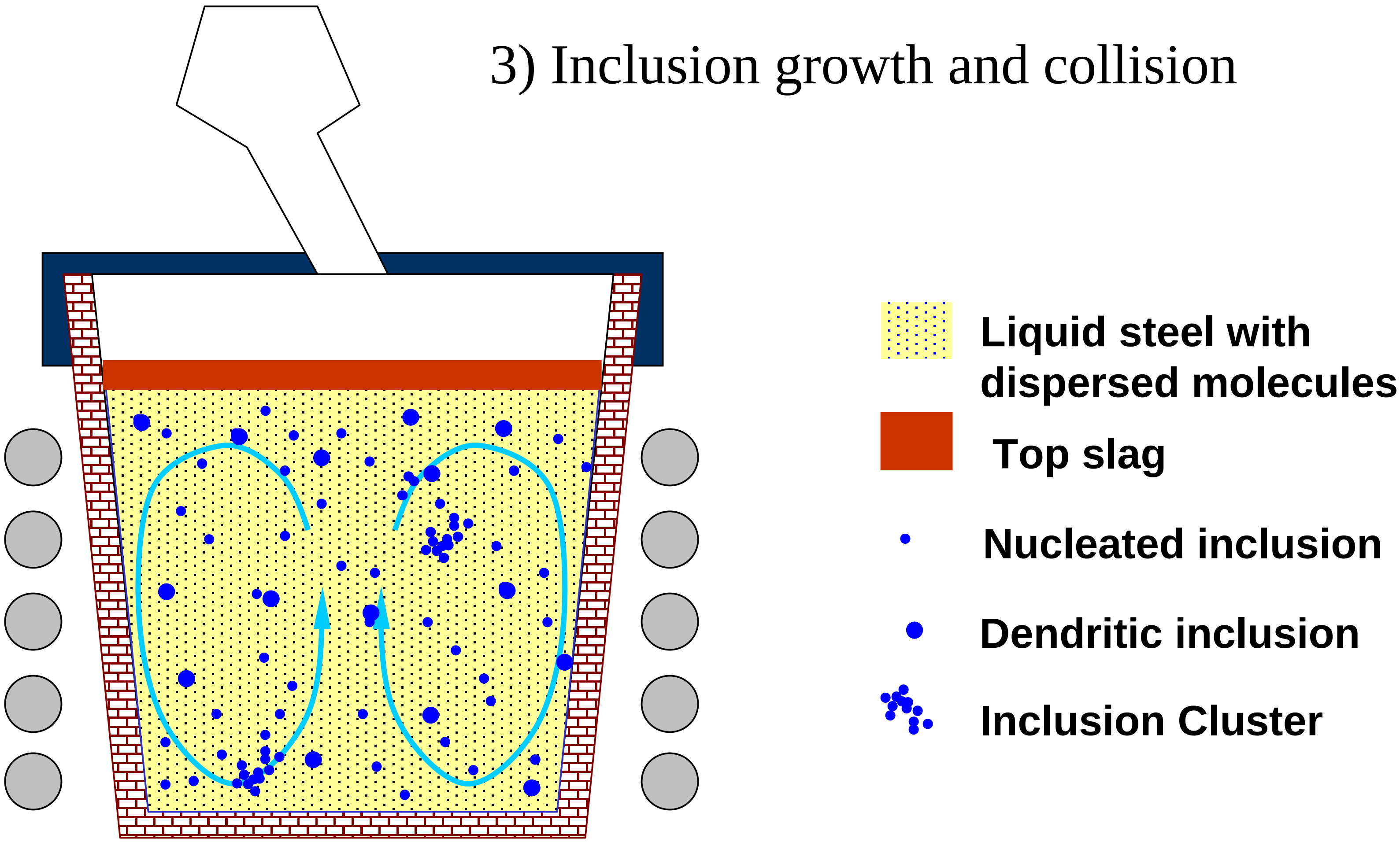
Liquid steel with dispersed molecules

Top slag

Nucleated inclusion

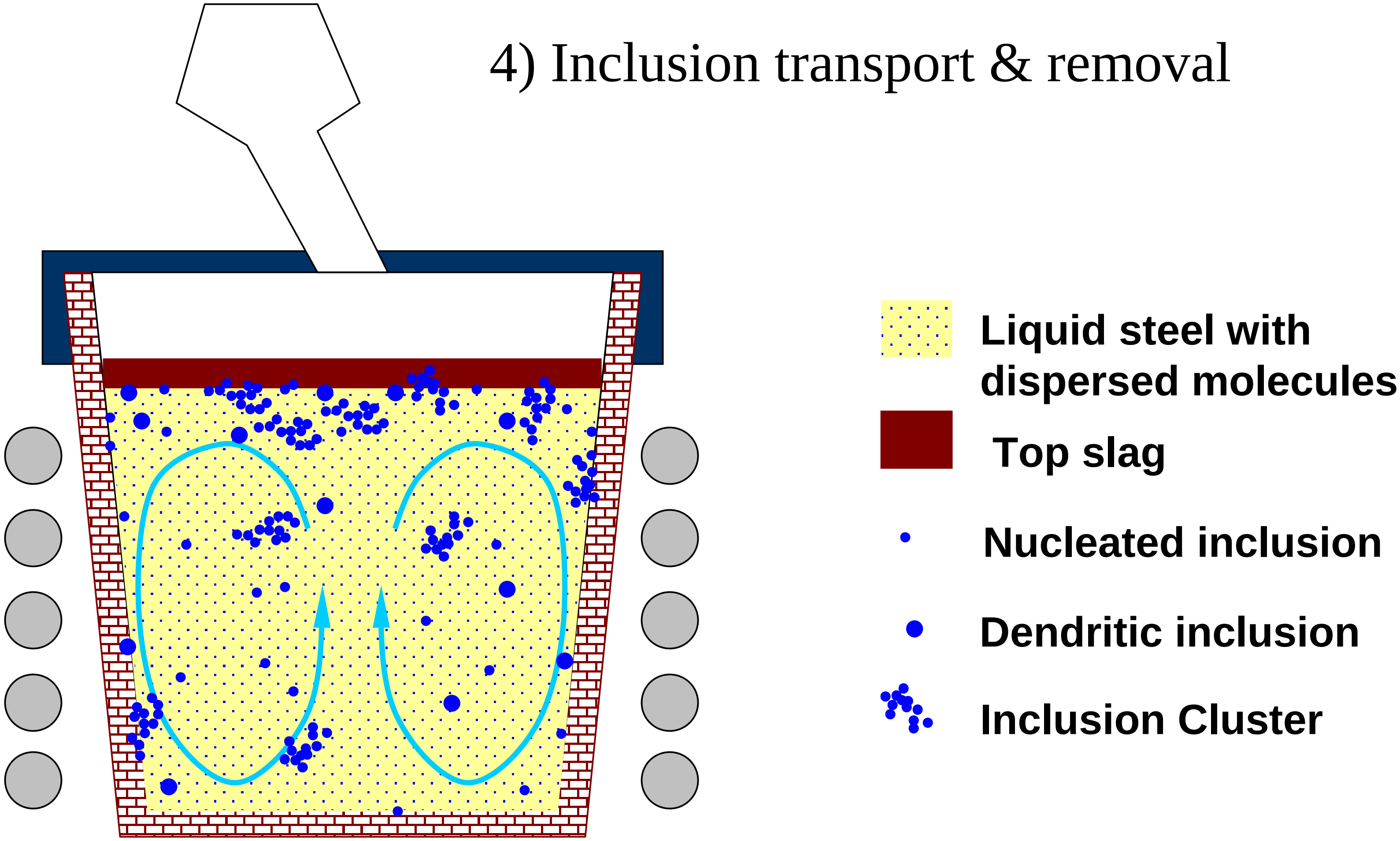
Steps of Inclusion Nucleation and Growth during Deoxidation

3) Inclusion growth and collision



Steps of Inclusion Nucleation and Growth during Deoxidation

4) Inclusion transport & removal



Model of Nucleation and Growth of Inclusions in Liquid Steel

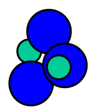
1) Numerically simulate homogeneous nucleation and growth of inclusions from a solute of "pseudo-molecules" of deoxidizing element (Al) and oxygen atoms;

2) Predict inclusion concentration & size distribution;

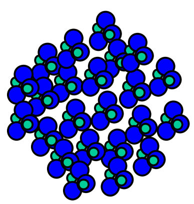
3) Quantitatively evaluate the contribution of Ostwald-ripening, Brownian collision, turbulent collision, and surface tension to inclusion nucleation and growth;

4) Explain the morphology of alumina clusters.

Thermodynamic Fundamentals of Homogeneous Nucleation



Al_2O_3
pseudo-molecule



Random group of pseudo-molecules

$$r_C = r_1 i_c^{1/3} = \frac{2\sigma V_m}{RT \ln \Pi}$$

1) If a random group of “pseudo-molecules” is larger than this critical size:
   - nucleation occurs,
   - particle is stable and will grow.

2) Critical nucleus size decreases with:
   - increasing supersaturaion
   - decreasing surface tension.

Supersaturation of "Pseudo-molecules" of Al_2O_3

$$n[Me]+m[O]\rightarrow(Me_nO_m)$$

$$\Pi\equiv\frac{N_1}{N_{1,eq}}=N_1^*=N_s^*-\sum_{i=2}^{\infty}N_i^*\cdot i$$

$$N_s^*(t^*)=N_{s,eq}^*\left[1.0-\exp(-0.1t^*)\right]$$

N^*_S = Number concentration of Al_2O_3 molecules (including those in nucleated particles)

$N_{1,eq}$ = 2.634×10^{23} m^{-3} (corresponds to 3ppm dissolved oxygen)

$N^*_{s,eq}$ = 100 (corresponds to 300ppm initial oxygen content before Al addition).

Ref: L. Kampmann and M. Kahlweit, Berichte der Bunsen-Gesellschaft physikalische Chemie, Vol. 74 (5), 1970, 456-462.

Population Balance Equations

$2 \le i < i_C$ **(Before nucleation)**

$$\frac{dN_i}{dt} = \overbrace{-\beta_{D,i} N_1 N_i + \beta_{D,i-1} N_1 N_{i-1}}^{\text{“Molecule” diffusion}} \overbrace{-\alpha_i A_i N_i + \alpha_{i+1} A_{i+1} N_{i+1}}^{\text{“particle” dissolution}}$$

Diffusion

Generation of “particle” *i*

Loss of “particle” *i*

Continuous Casting Consortium

Population Balance Equations

$i_C \le i < 10^{15}$ **(after formation of stable inclusion particles)**

Diffusion

$$\frac{dN_i}{dt} = \underbrace{-\beta_{D,i}N_1N_i + \beta_{D,i-1}N_1N_{i-1}}_{\text{"Molecule" diffusion}} \underbrace{-\alpha_i A_i N_i + \alpha_{i+1}A_{i+1}N_{i+1}}_{\text{"particle" dissolution}}$$

Loss of "particle" *i*

Generation of "particle" *i*

Collision

$$-\phi N_i \sum_{j=1}^{\infty}\left(\beta_{B,ij} + \beta_{T,ij}\right)N_j + \frac{1}{2}\phi\sum_{j=1}^{i-1}\left(\beta_{B,j,i-j} + \beta_{T,j,i-j}\right)N_jN_{i-j}$$

Loss of "particle" *i*

Generation of "particle" *i*

Example Liquid Steel Ladle System

Aluminum deoxidation of low carbon steel during ASEA-SKF

Ladle: 50 tonne, 2.3m diameter and 1.7m depth

Turbulent energy dissipation rate 0.01224 m2/s3

T.O before deoxidation: 300ppm

Free oxygen at equilibrium: 3ppm

Comparison of Inclusion Growth Constants

Diffusion:

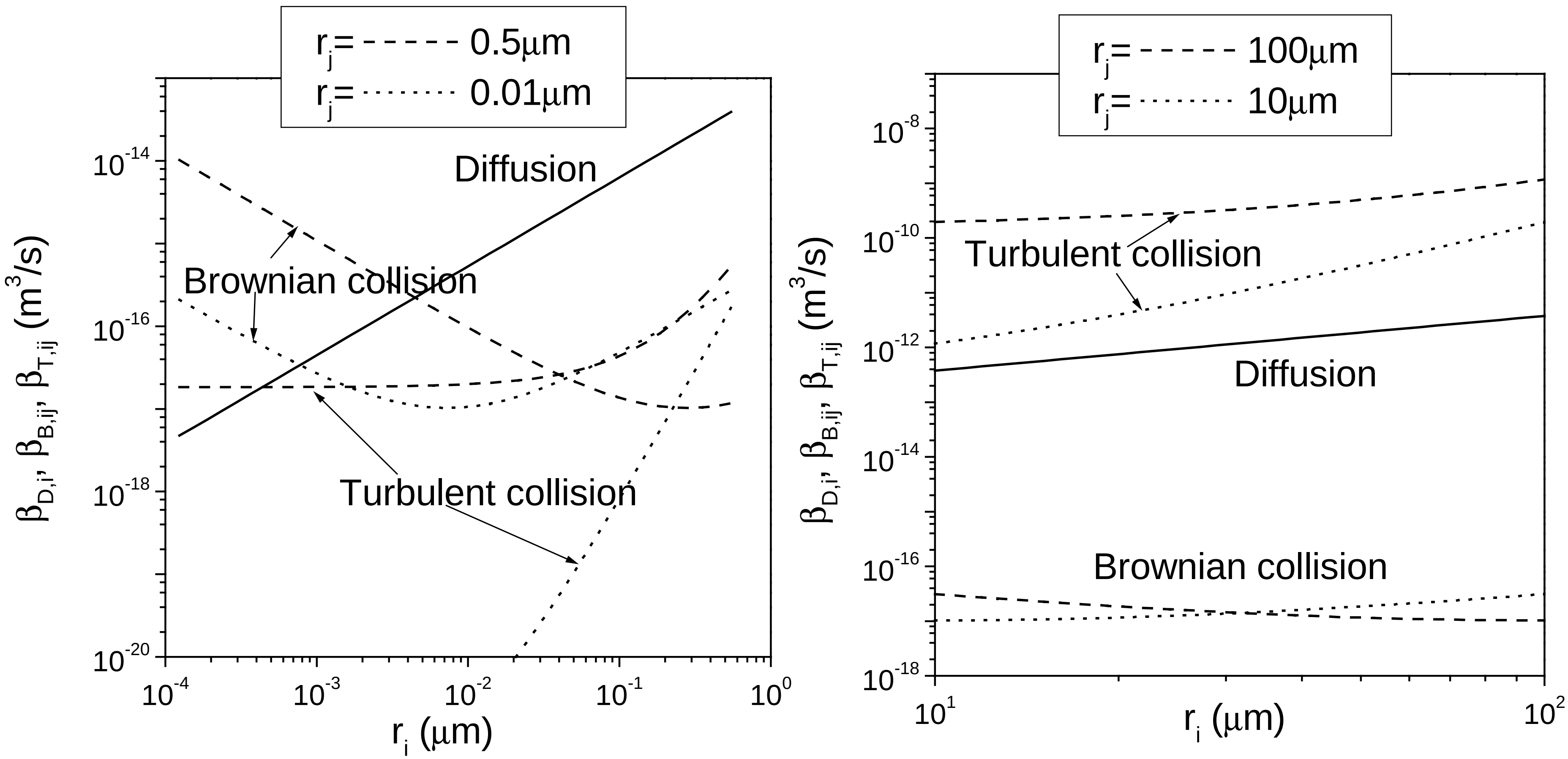
$$\beta_{D,i} = 4\pi D_1 r_i$$

Brownian collision:

$$\beta_{B,ij} = \frac{2kT}{3\mu}\left(1/r_i + 1/r_j\right)\left(r_i + r_j\right)$$

Turbulent collision:

$$\beta_{D,ij} = 1.3\left(r_i + r_j\right)^3 \left(\varepsilon/\nu\right)^{1/2}$$

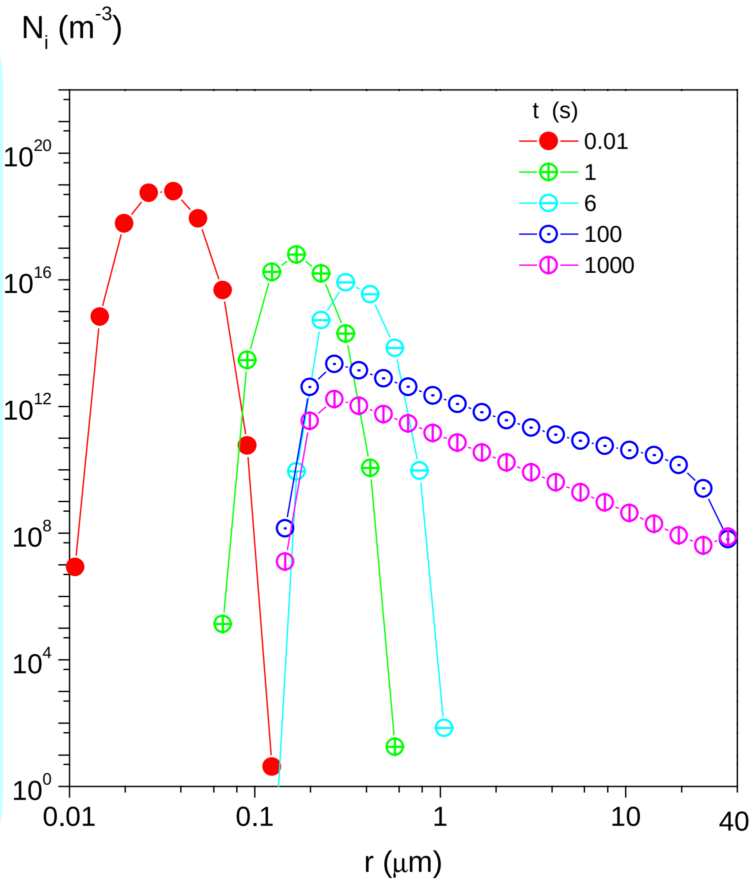


Inclusion Growth Mechanism and Its Length Scale

- Brownian scale (L_B<1μm)
- Turbulent scale (L_T>2 μm ~L_e)

Inclusion Size Distribution Evolution with Time

1) First particles appear: 0.53μs
   Particle size range is:
   0.1~1μm at 6s,
   0.1~36μm at 100s.
2) With increasing time:
   - smaller inclusions decrease in number concentration
   - larger inclusions increase
3) After t=6s, the largest inclusion is ~ 2 μm diameter,

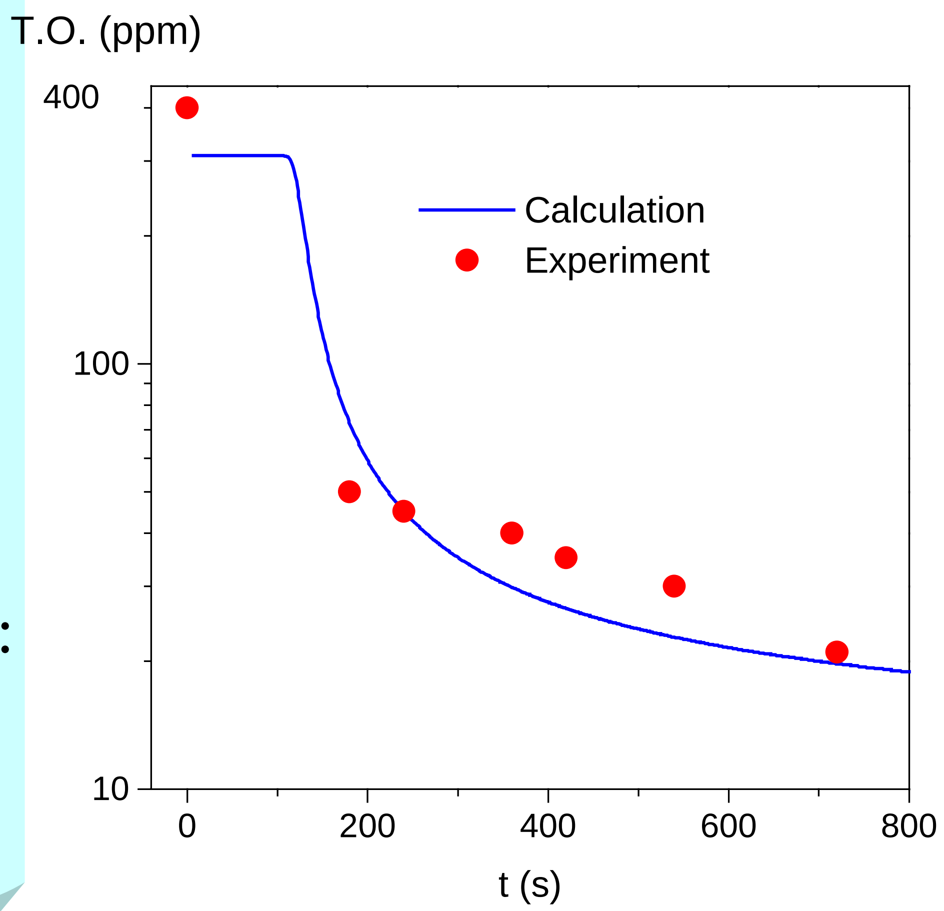


Comparison between Calculation and Experiment

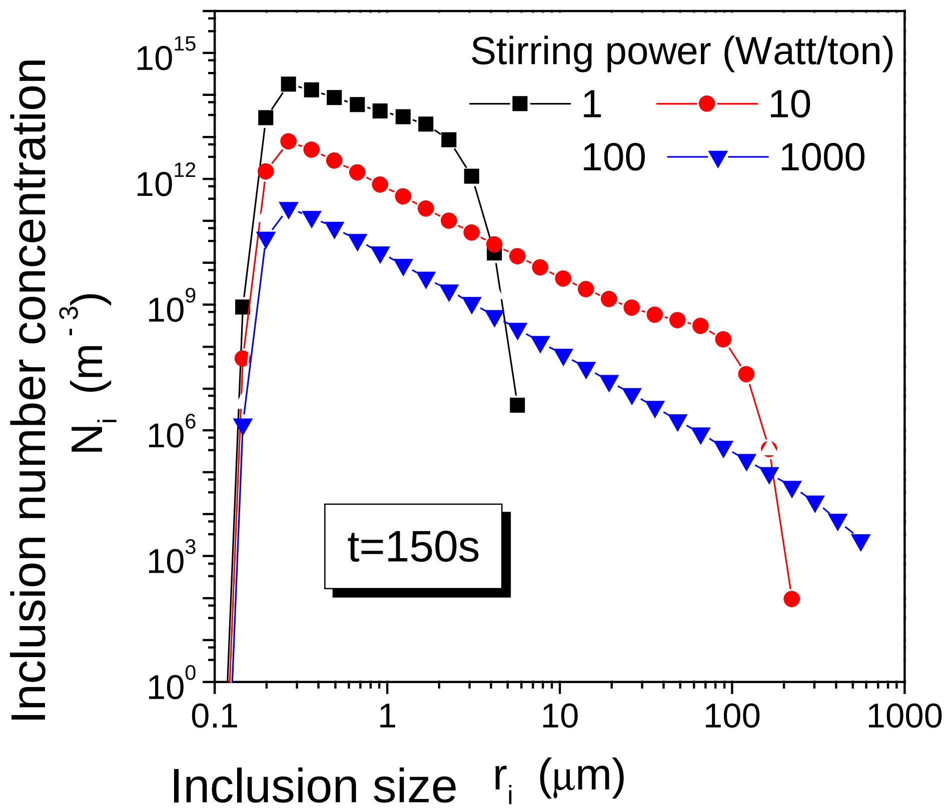
1) Reasonable agreement between calculation and experiment

2) After 720 s (12min), total oxygen drops to ~ 20 ppm.

<ins>Simple inclusion removal model</ins>: assume all inclusions larger than 36μm radius are instantly removed;

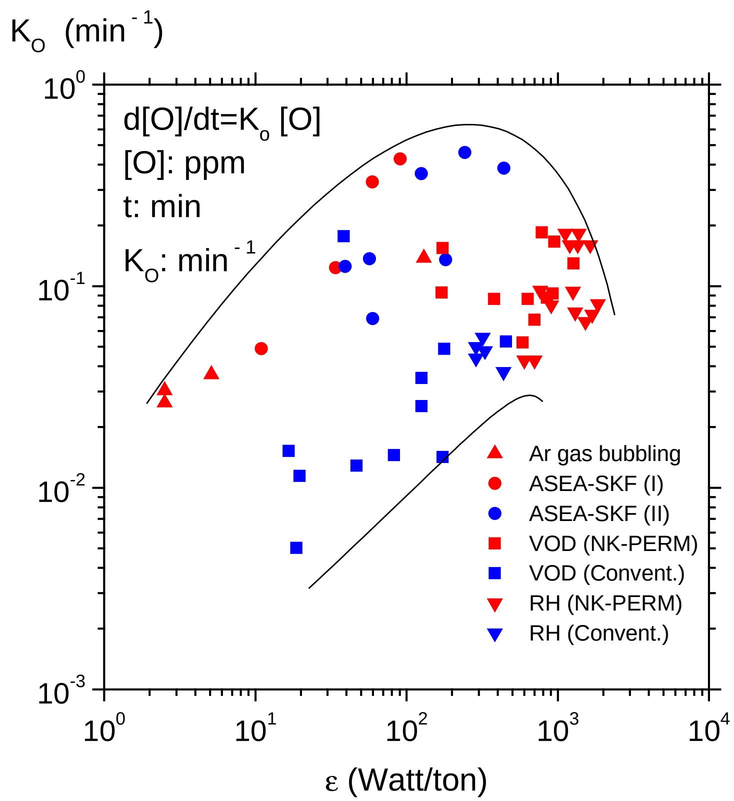


Effect of Stirring Power on Inclusion Size Distribution



- The inclusion size distribution evolves to form larger inclusions with increasing stirring power.
- Actual steel refining processes have a range of different stirring powers.

Effect of Stirring Power on Steel Cleanliness



Stirring helps to lower T.O. if

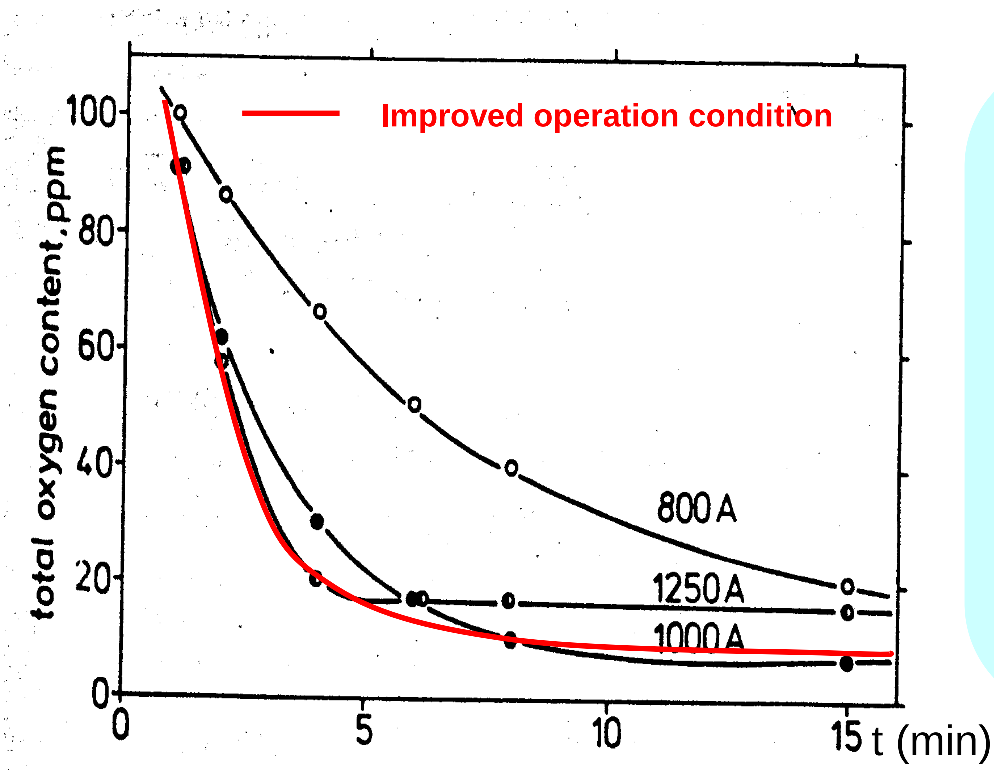
1) Sufficient high stirring power
- helps collisions
- helps transport to interfaces

2) Not too vigorous or long
- avoid reoxidation (eyes)
- avoid ladle erosion
- avoid detrimental collisions

and formation of large clusters at end of refining

Refs: 1) K. Ogawa, in Nishiyama Memorial Seminar, Vol. 143/144, ISIJ, 1992, 137-166. 2) M. Matsuno et al., I & Smaker, Vol. 20 (7), 1993, 35-38.

Effect of Stirring Power on Steel Cleanliness



Recommendation:

1) first stir vigorously to encourage the collision of small inclusions into large ones,

2) "final stir" slowly recirculates the steel to facilitate their removal into the slag while minimizing the generation of more large inclusions via collisions.

Ref: K. Schwerdtfeger, Arch. Eisenhutten, Vol. 54, 1983, 87-98.

Conclusions

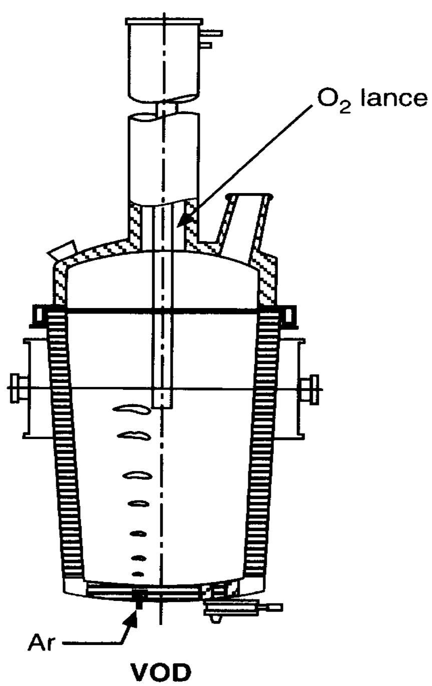
1. Homogeneous nucleation takes 1μs - 10 μs.

- Initial growth via Ostwald ripening and Brownian collision: spherical inclusions < 1μm.
- Inclusions > 2μm grow by turbulent collisions: large clusters, which retain minimum feature sizes of 1~2μm.
- For optimal inclusion removal, a suitable stirring process should be chosen.

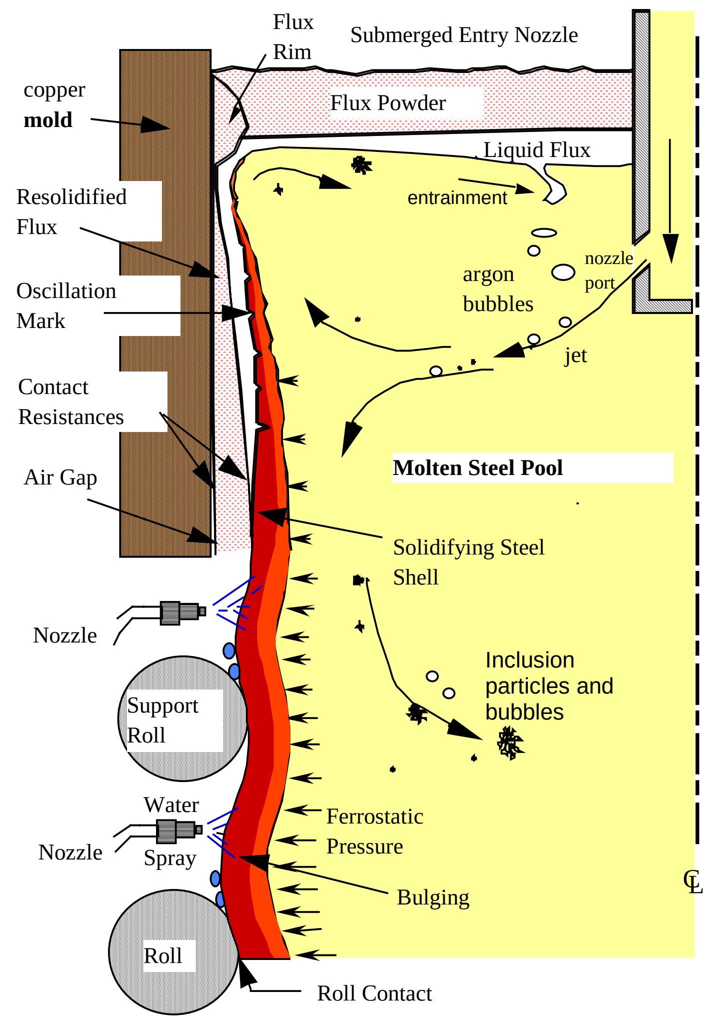
3. Interaction Between Inclusion and Bubble in Liquid Steel

Functions of Gas Injection into Liquid Steel

1) to achieve homogeneity in the temperature and metal composition
2) to assist in the removal of second phases and dissolved impurities (inclusions) from molten steel.

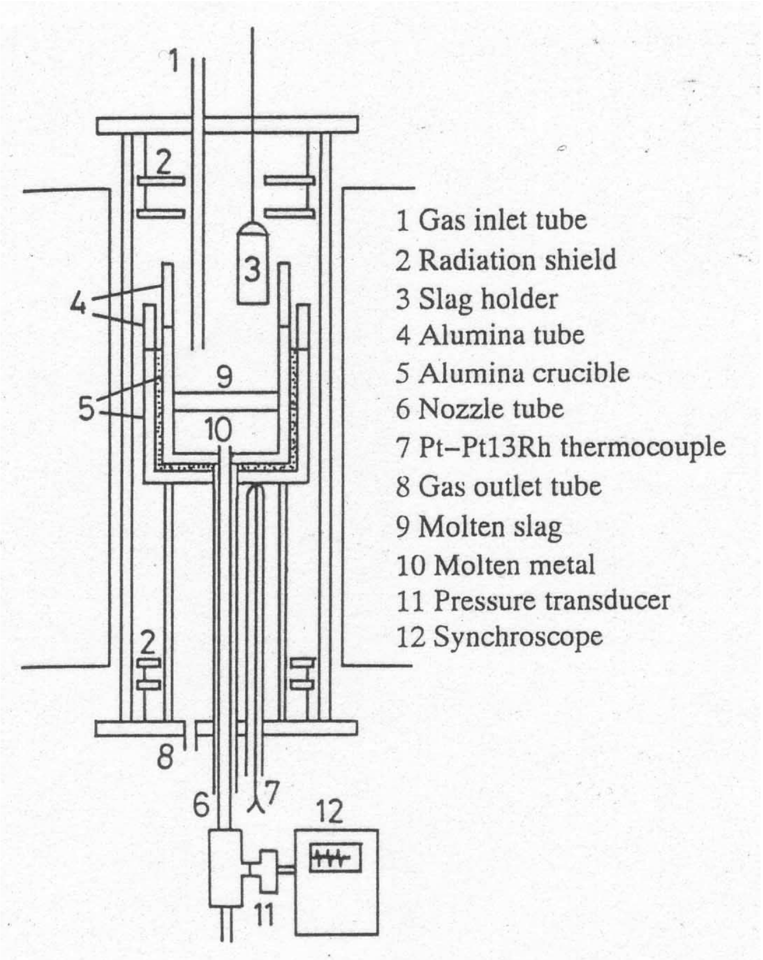


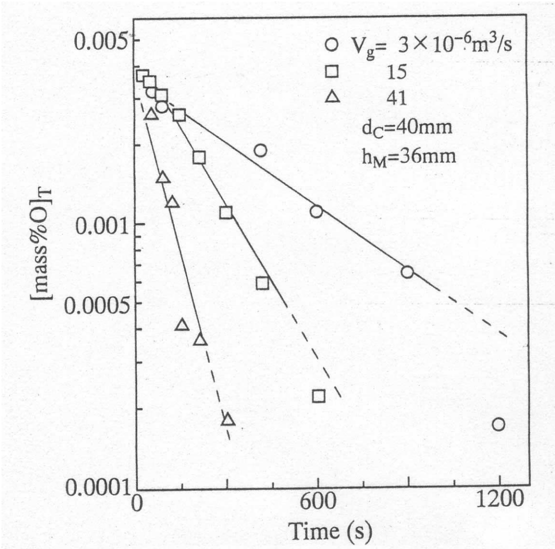
VOD ladle treatment

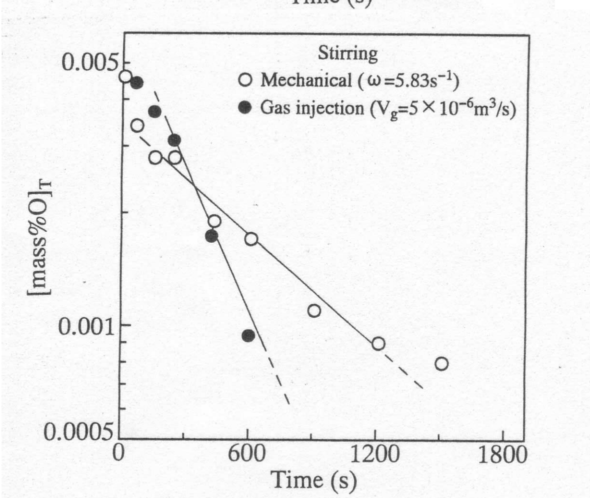


Continuous Casting Mold

Example: Rate of SiO2 Inclusion Removal from Molten Copper to Slag Under Gas Injection Stirring Condition



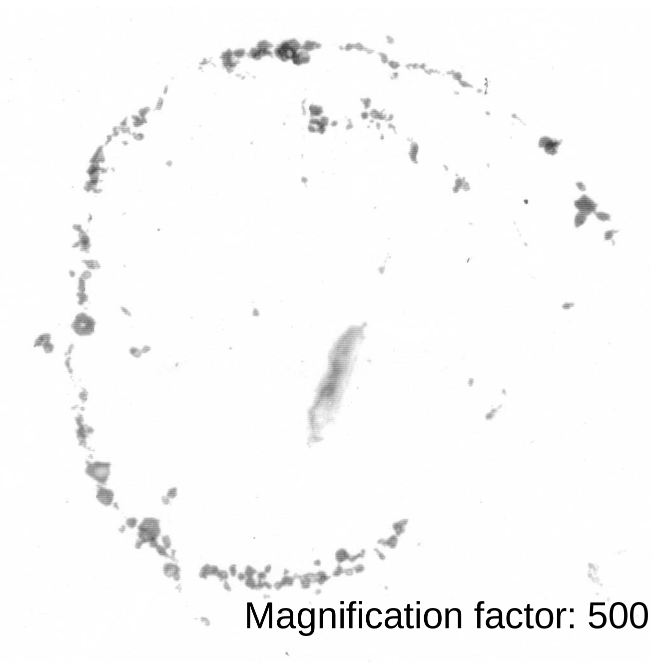




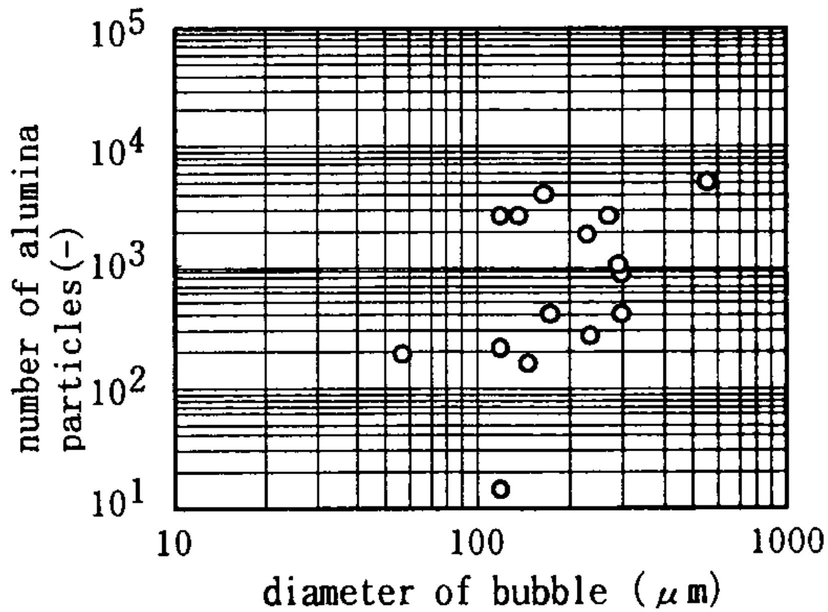
Okumura, K., M. Kitazawa, et al. (1995). "Rate of SiO2 Inclusion Removal from Molten Copper to Slag Under Gas Injection Stirring Condition." ISIJ Inter. **35**(7): 832-837.

Example of Inclusion Capture by Bubbles in Slab

- ➢ Good for inclusion removal of bubbles float out;
- ➢ Bad for steel cleanliness is bubbles entrapped by the solidifying shell.



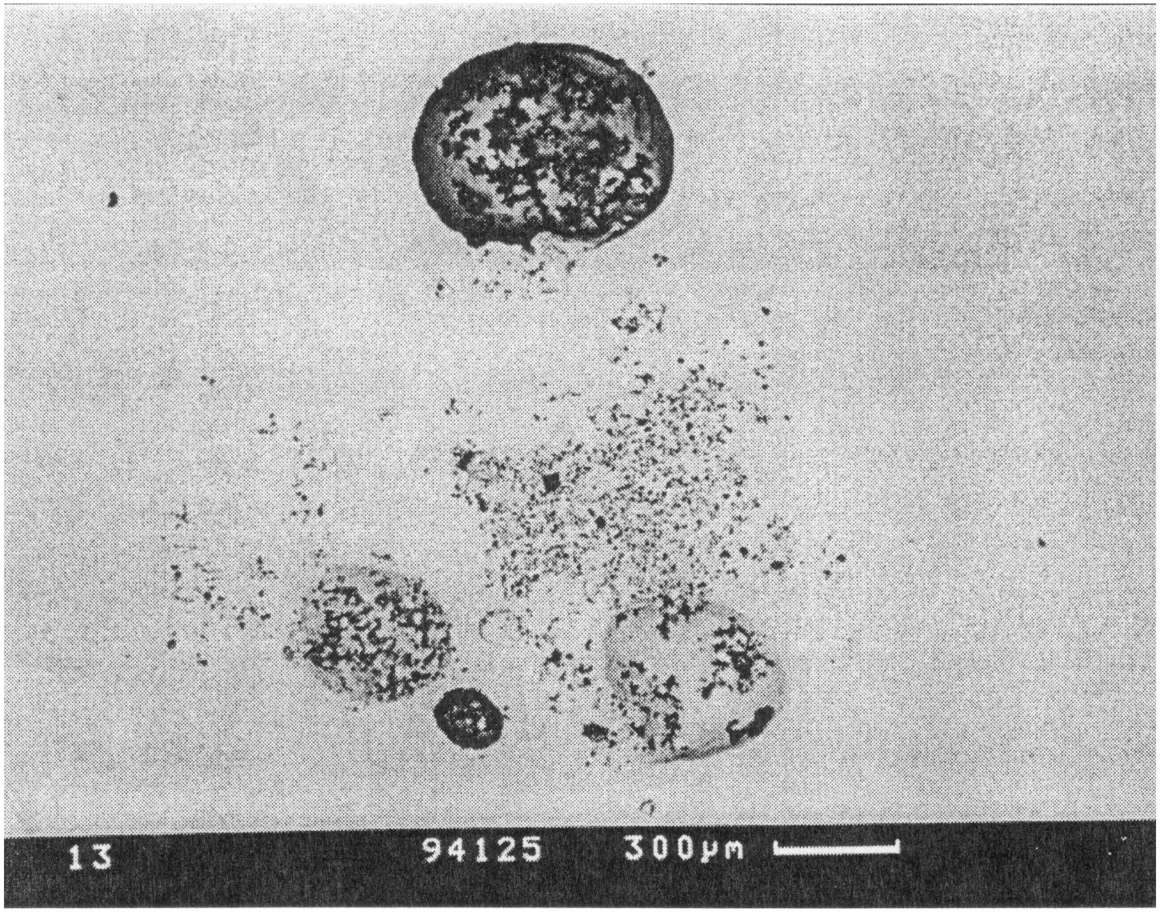
Magnification factor: 500



Observed inclusions number attached to different size bubbles for LCAK steel slab

Ref.: L. Kiriha et al., CAMP-ISIJ, Vol. 13, 2000, 120.

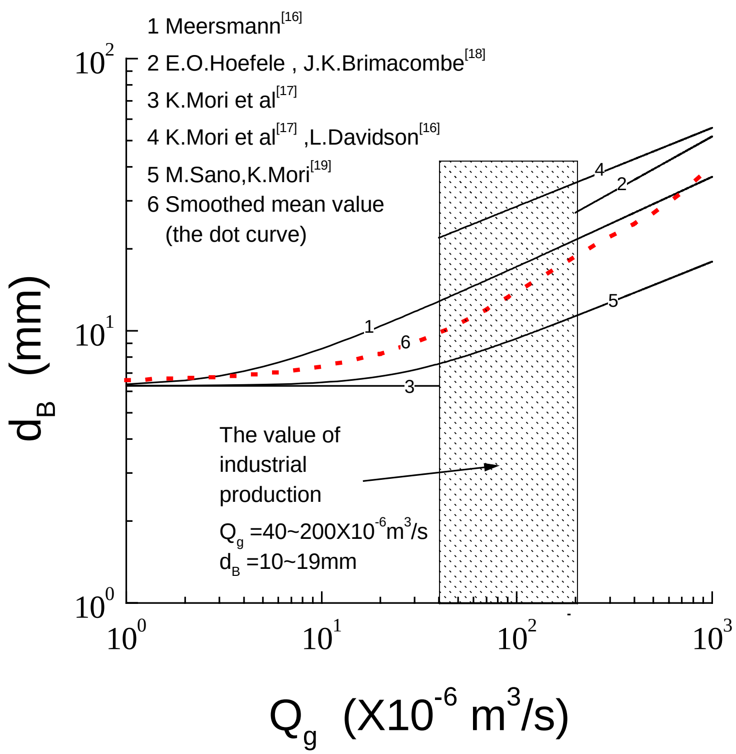
Argon Bubbles and Clusters in the Wake of a Larger Bubble

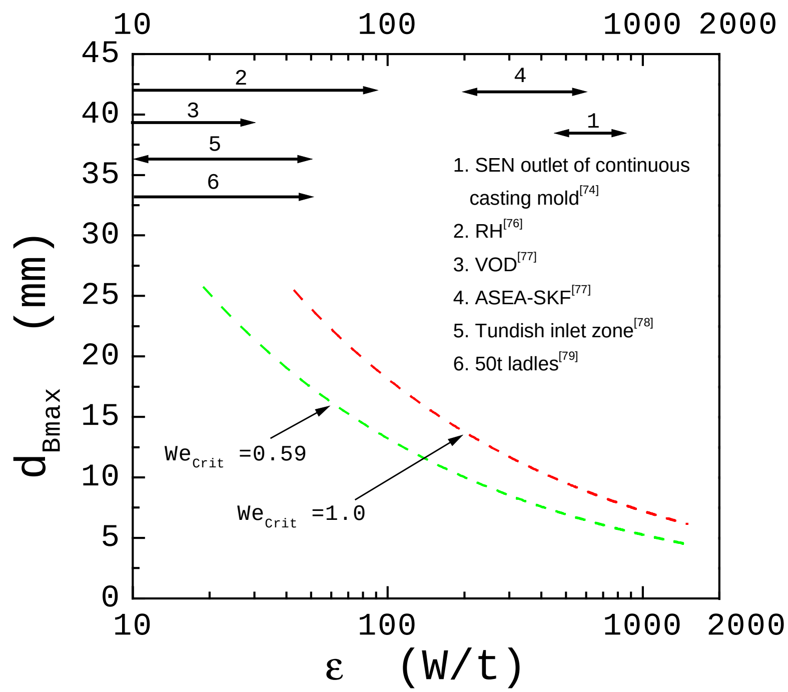


Damen, W., G. Abbel, et al. (1996). "The Influence of the Mould Process on Argon Bubbles in Slabs.".

Abbel, G., W. Damen, et al. (1996). "Argon Bubbles in Slabs." ISIJ **36**: S219-S222.

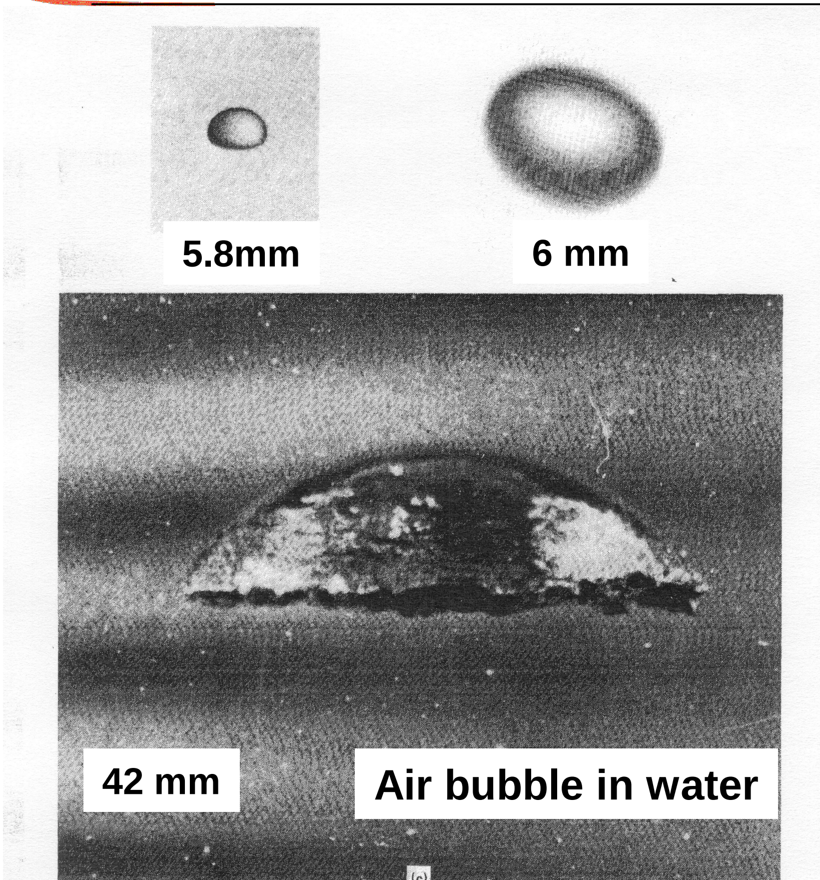
Bubble Size as Function of Gas Flow Rate and Bulk Stirring Power





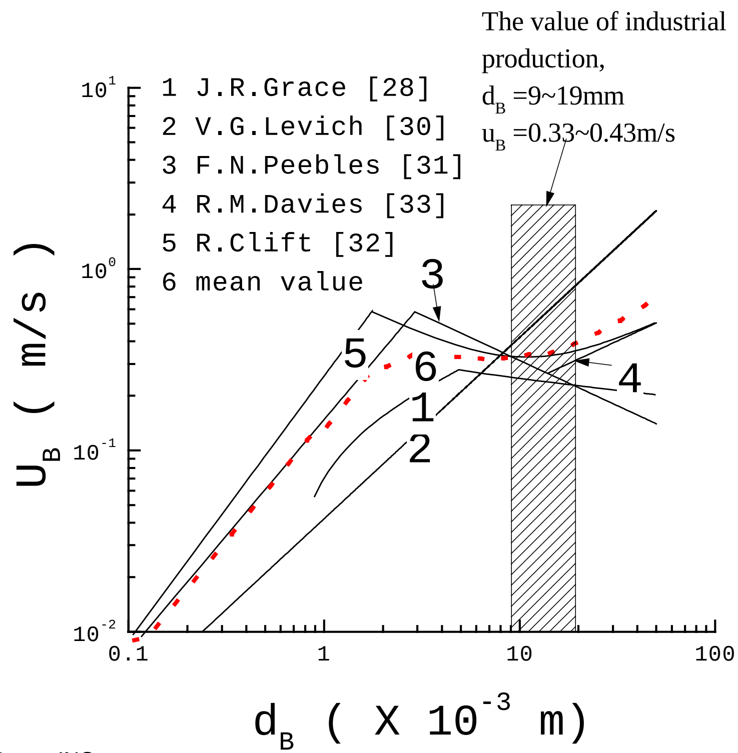
Ar bubble in liquid steel

Bubble Shape and Terminal Velocity



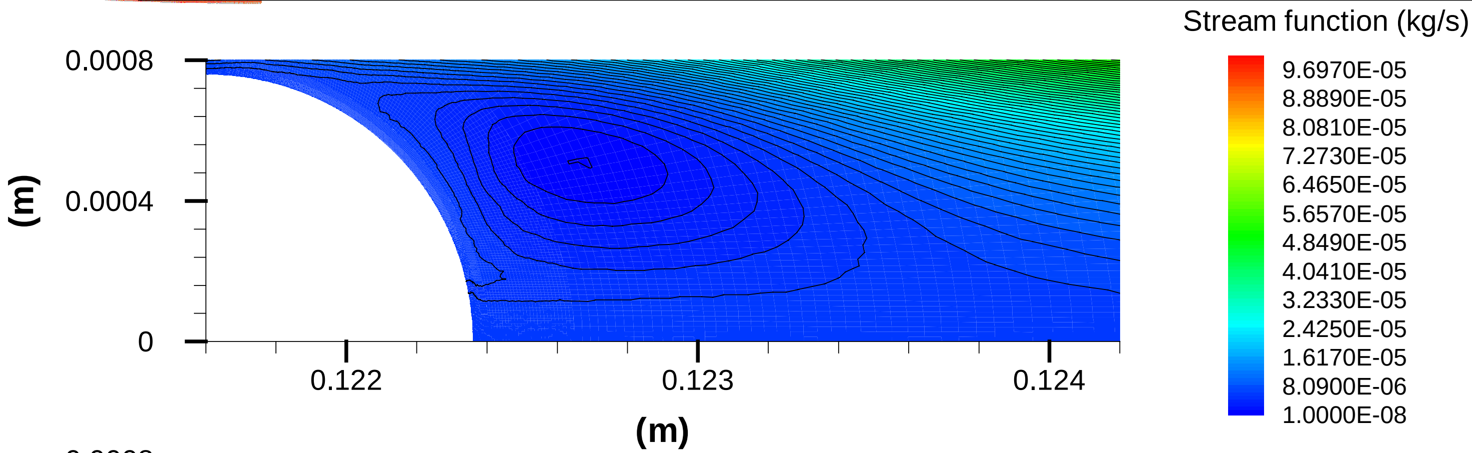
Clift, R., J. R. Grace, et al. (1978). Bubbles, Drops and Particles. New York, Academics Press, INC.

Ar bubble Terminal Velocity in Liquid Steel

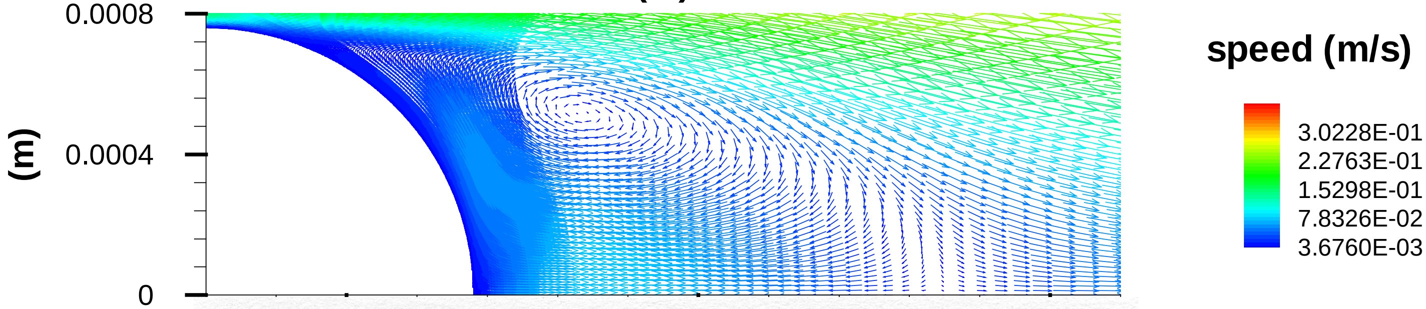


1) A peak of terminal velocity at a bubble diameter of 3 mm exists.
2) The terminal velocity and shape of bubble depend on the bubble size and bubble Reynolds number.

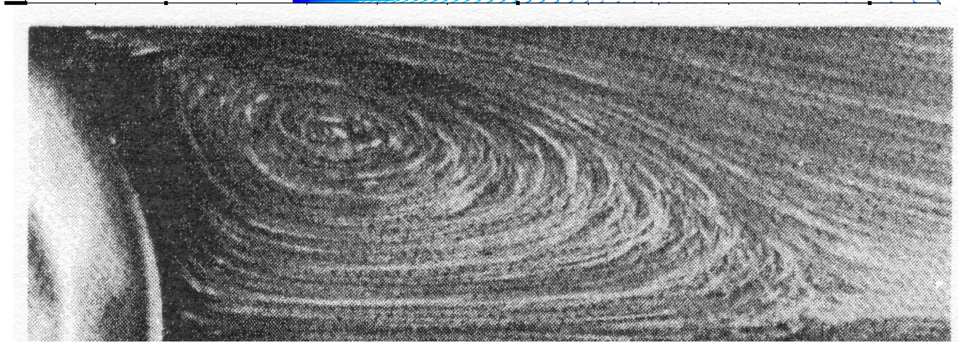
Fluid Flow around a Rigid Sphere (Water)



Simulation of fluid flow behind a rigid sphere



Re=480

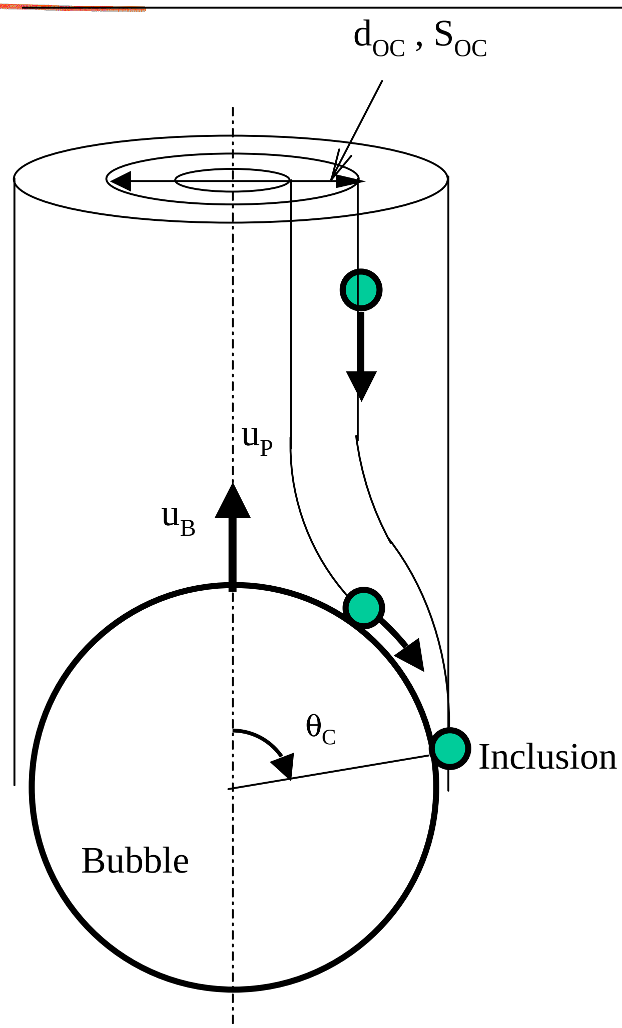


Experiments of fluid flow behind a rigid sphere.

Clift, R., J. R. Grace, et al. (1978). Bubbles, Drops and Particles. New York, Academics Press, INC.

Re=133

Attachment Probability of Particle to Bubble Surface



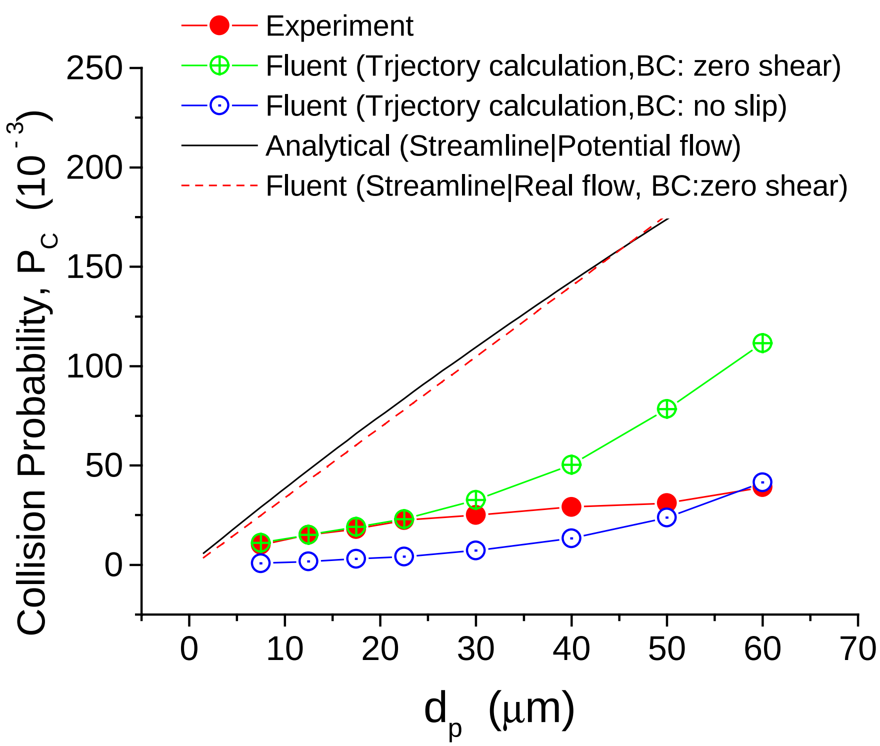
Collision probability, P_C

$$P_C = \left(\frac{d_{oc}}{d_B + d_{oc}} \right)^2$$

Assumption: Inclusion will be attached to bubble surface if the distance between the center of inclusion and bubble surface is the inclusion radius. Then the value of d_{oc} can be obtained by streamline calculation or particle trajectory calculation.

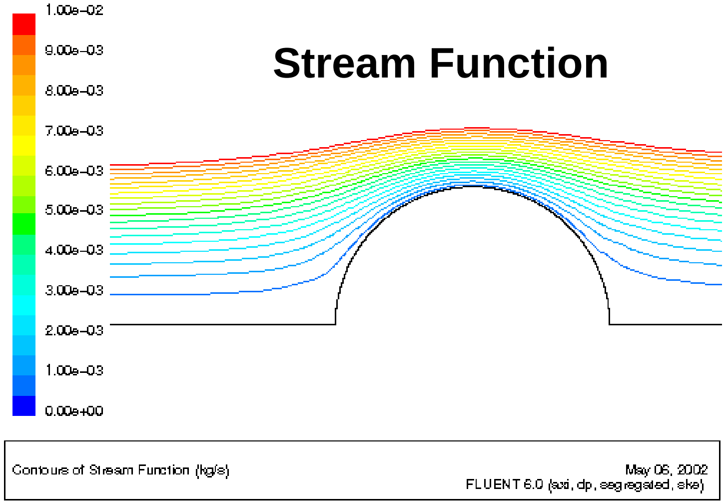
Collision Probability by Different Models

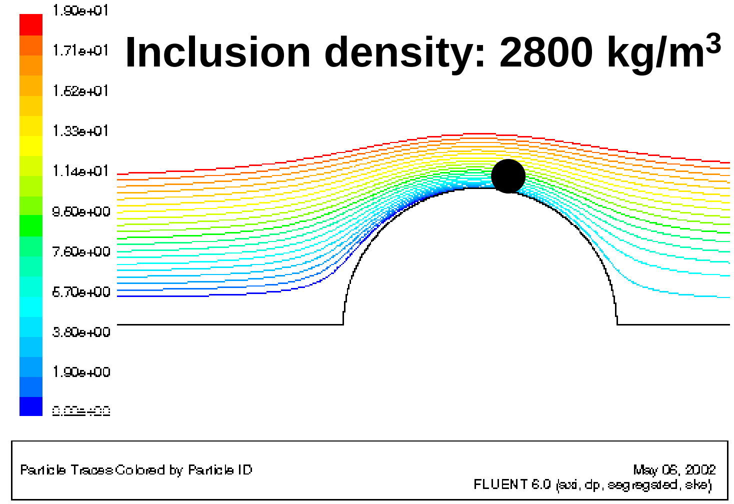
SiO_2 particles attachment to a bubble (1.52mm diameter and 0.316m/s rising velocity) in water



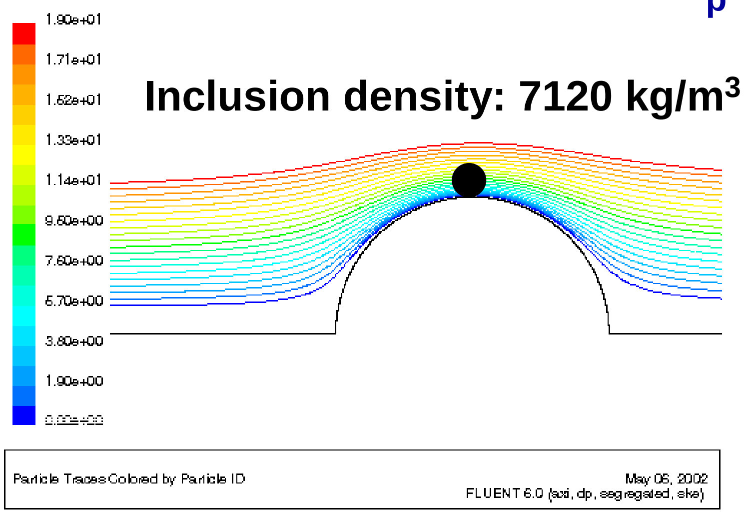
Conclusion: the trajectory model with a bubble boundary condition of zero shear stress has a best agreement with the experiments.

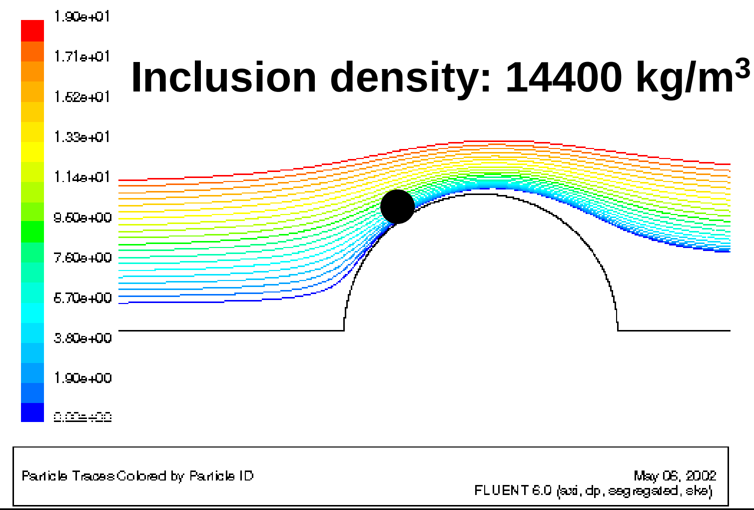
Stream Function and Inclusion Trajectory in Liquid Steel (Density: 7120 kg/m3)





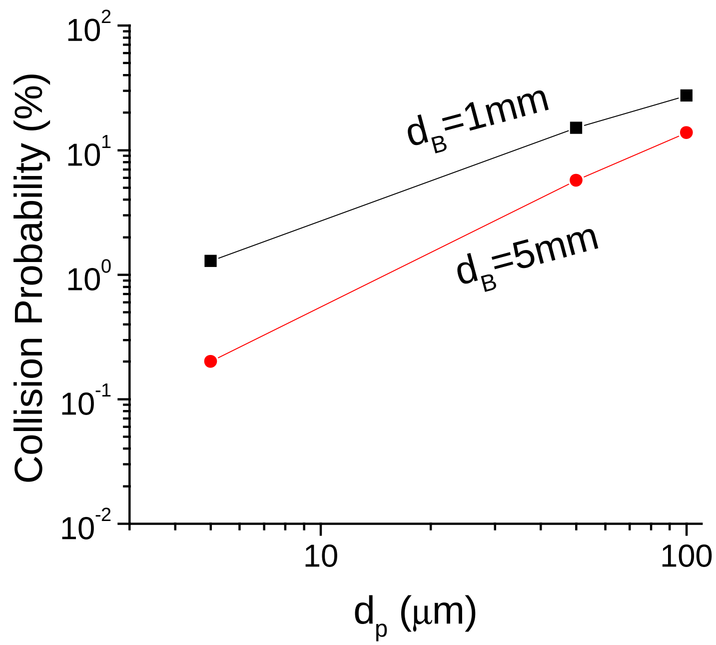
d_p=100µm





Collision Probability by Trajectory Calculation

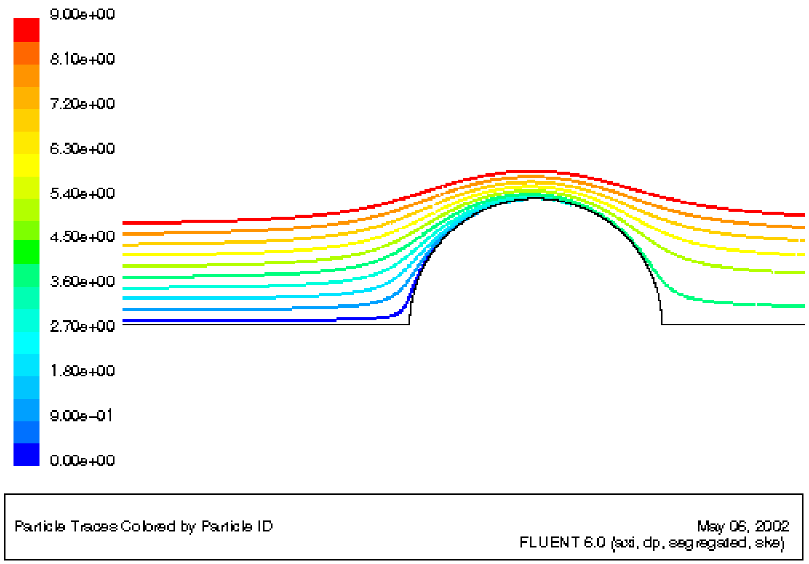
Silica inclusions attachment to a bubble in Liquid steel



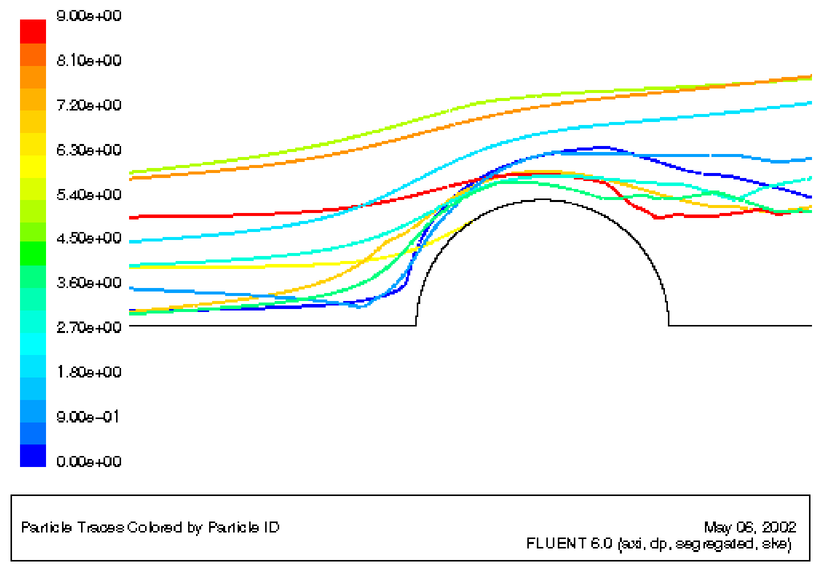
Conclusion: The attachment probabilities between the smaller bubbles and larger inclusions are larger that between larger bubbles and smaller inclusions.

Effect of Turbulence Fluctuations on Inclusion Trajectory

100μm Silica inclusions moving towards a 5mm bubble in Liquid steel



Streamline model



Random-walk model

The Optimum Bubble Size for Inclusion Removal by Bubble Flotation

One important conclusion: Small bubbles favor inclusion removal by bubble flotation compared to the large bubbles with the same gas fraction.

Shortcomings of very small bubbles:
1).Smaller bubbles require longer rising time. In practice, shorter treatment times will significantly reduce operational costs by reducing the temperature loss and refractory consumption.
2). Small bubbles (<1mm) are much more easily trapped in the recirculation zone of the bulk or re-entrained into bulk from the interface between liquid steel and slag and some of then finally are captured in the solidified front.

The optimum bubble size:
High inclusion removal efficiencies, and short refining times → 1~5mm bubbles.

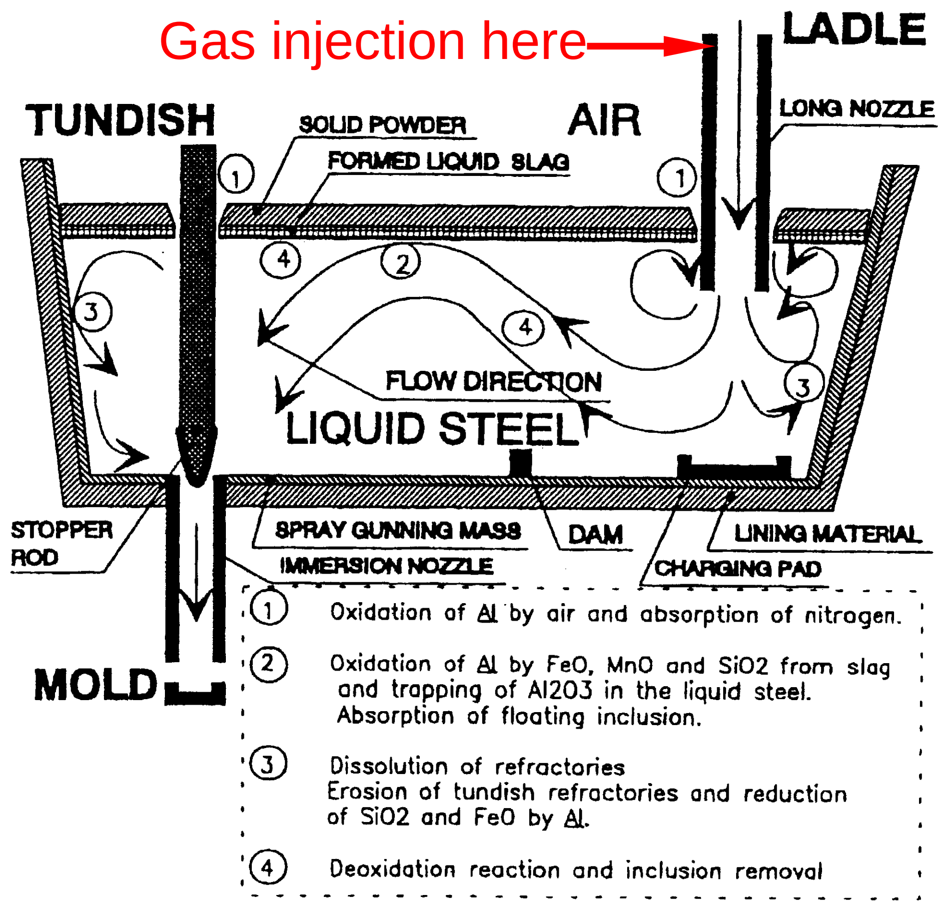
Possible Application Place of of Inclusion Removal by Bubble Flotation

The shroud from ladle to continuous casting tundish.

Merits:

1). Good mixing and high turbulence, small bubbles can be obtained;

2). Better than SEN because bubbles have enough time to float out but not captured by solidified front of the steel.



Summary

1. The optimum bubble size for inclusion removal by bubble flotation is 1~5mm.

2. The shroud from ladle to continuous casting tundish is a good place to inject gas to remove inclusion by bubble flotation.

4. Inclusion Removal in Continuous Casting Mold

SEN Simulation Parameters

Turbulence	k-ε two equation, Fluent
Inclusion motion model	Random-Walk, 0.1s time step, 15000 particles each size

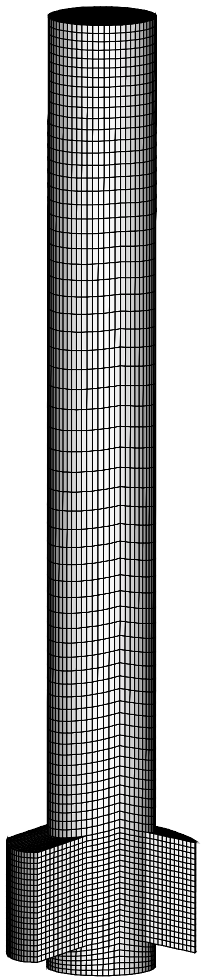
Parameters	Value
SEN bore diameter (mm)	80
SEN length (mm)	717
SEN submergence depth (mm)	300
Port width× port height (mm × mm)	65 × 80
Port thickness (mm)	30
Port angle (down)	15 deg
Bottom well depth (mm)	10
Liquid steel flow rate (m^3/s)	0.0065
Casting speed (m/s)	0.02
Fluid density (kg/m^3)	7020
Fluid kinetic viscosity (m^2/s)	9.54×10^{-7}
Particle size (diameter) (mm)	10, 20, 48, 90, 200,300
Particle density (kg/m^3)	5000
Inlet condition	Uniform

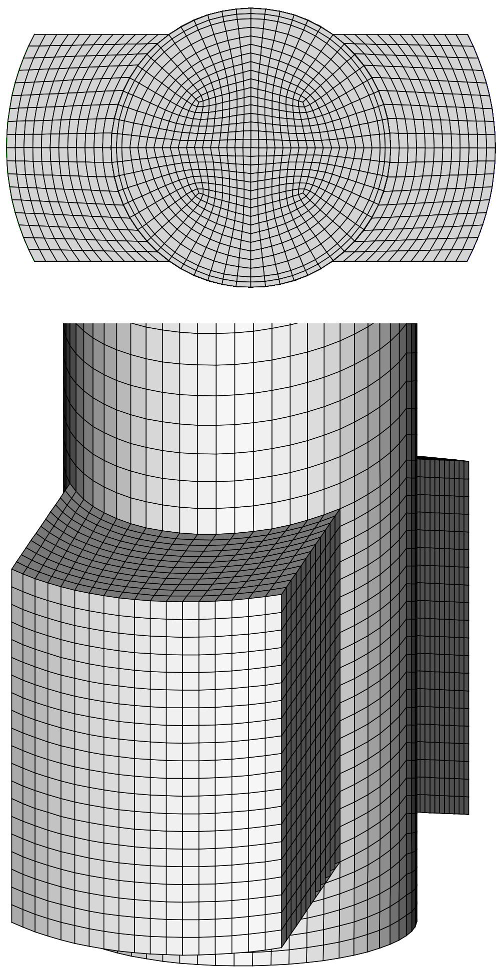
Parameters for Mold

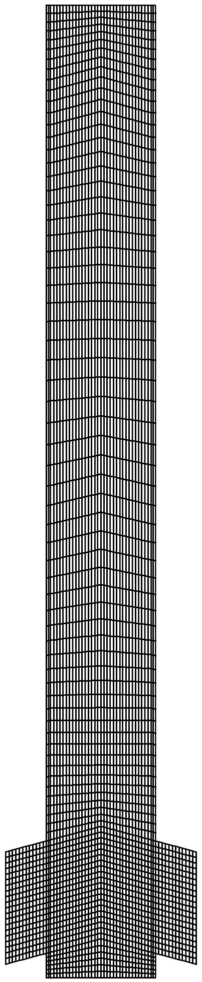
Turbulence model	*k-ε*, by Fluent
Inclusion motion model	Random walk model , 0.1s time step ,by Fluent
Boundary condition for inclusions	Escape from top surface and open bottom, trapped at narrow and wide face walls

Parameters	Values
Inlet port size (width× height) (m × m)	0.065×0.080
Nozzle angle	15^{o} (down)
Inlet jet angle	26^{o} (down)
Submergence depth (m)	0.3
Domain height/width/thickness (m)	2.55/1.3/0.25
Average inlet flow rate (half mold) (m^3/s)	0.00325
Casting speed (m/min)	1.2
Fluid density (kg/m^3)	7020
Fluid kinetic viscosity (m^2/s)	0.954×10^{-6}
Particle size (diameter) (μm)	0.5-300
Particle density (kg/m^3)	5000
Inlet condition	Nozzle simulation result
Gas flow rate	None

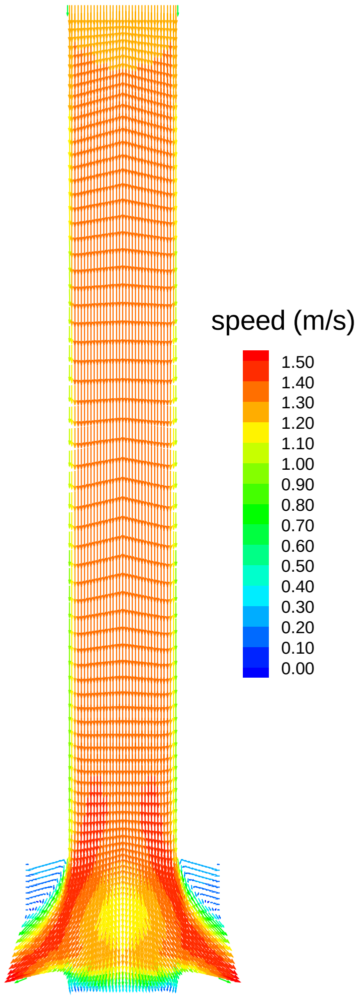
Nozzle Mesh



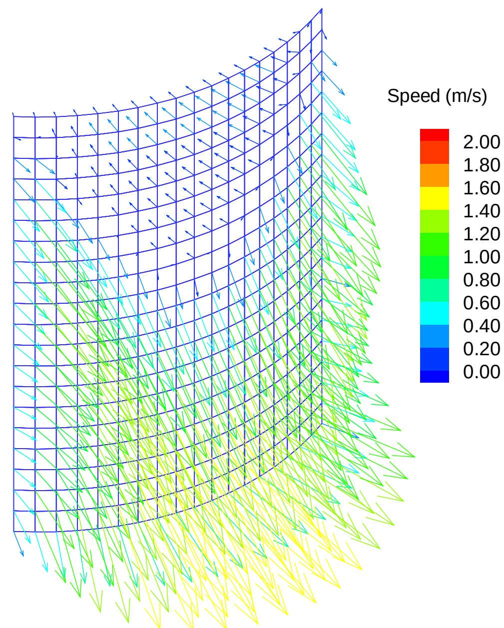




Velocity Distribution in SEN

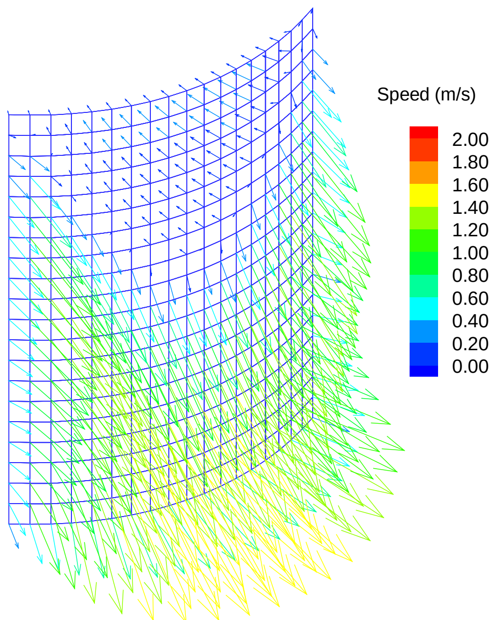


Vertical Section

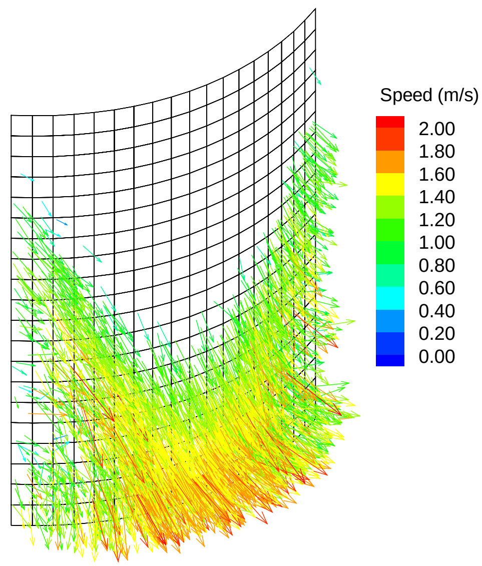


Outlet port

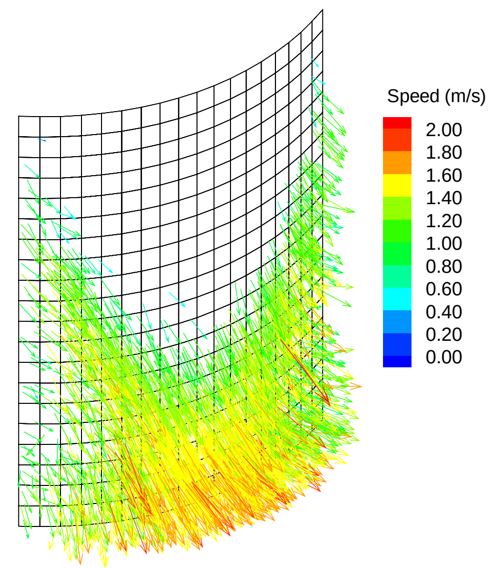
Fluid flow and Inclusion Velocity at SEN Outlet Port



Fluid flow



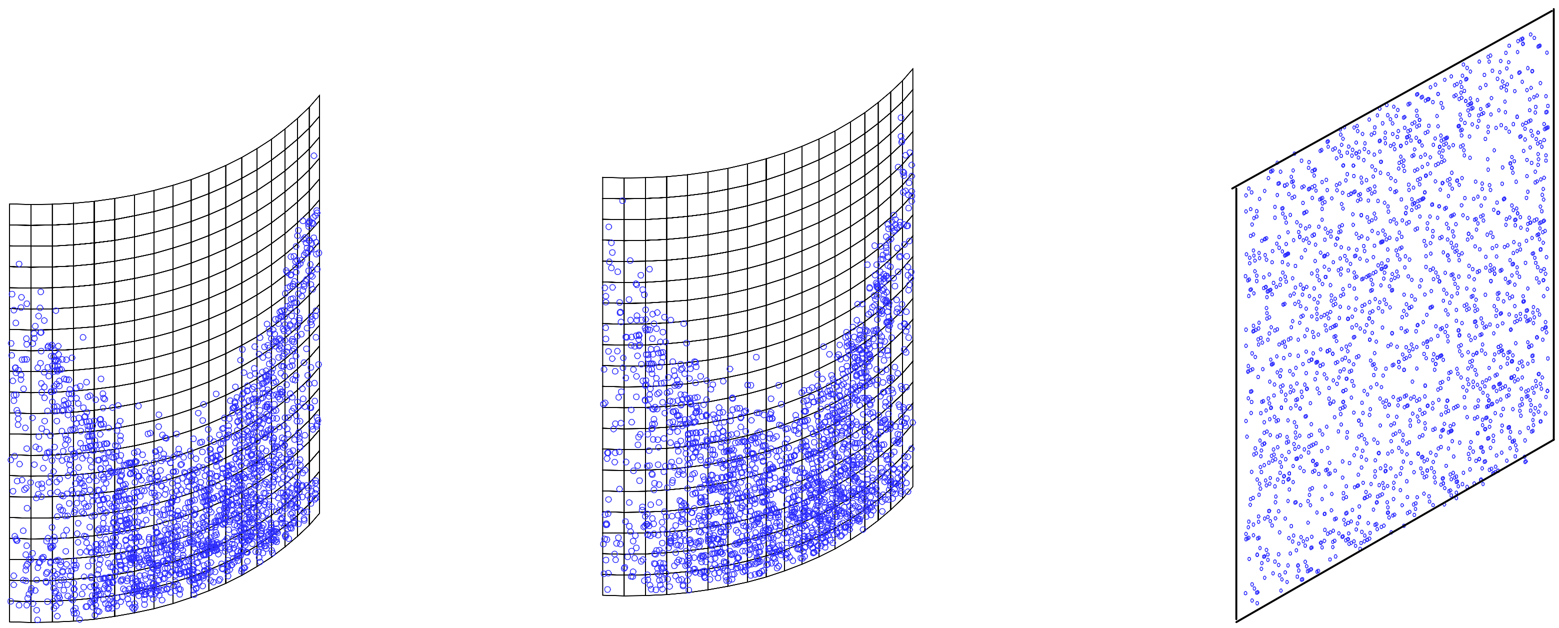
50μm inclusion



225μm inclusion

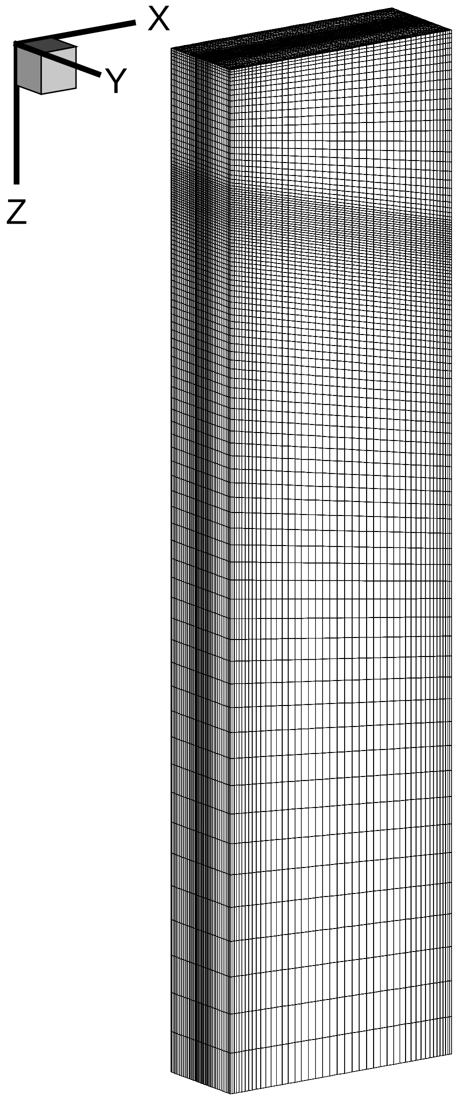
Conclusion: Inclusion travel virtually at fluid velocity.

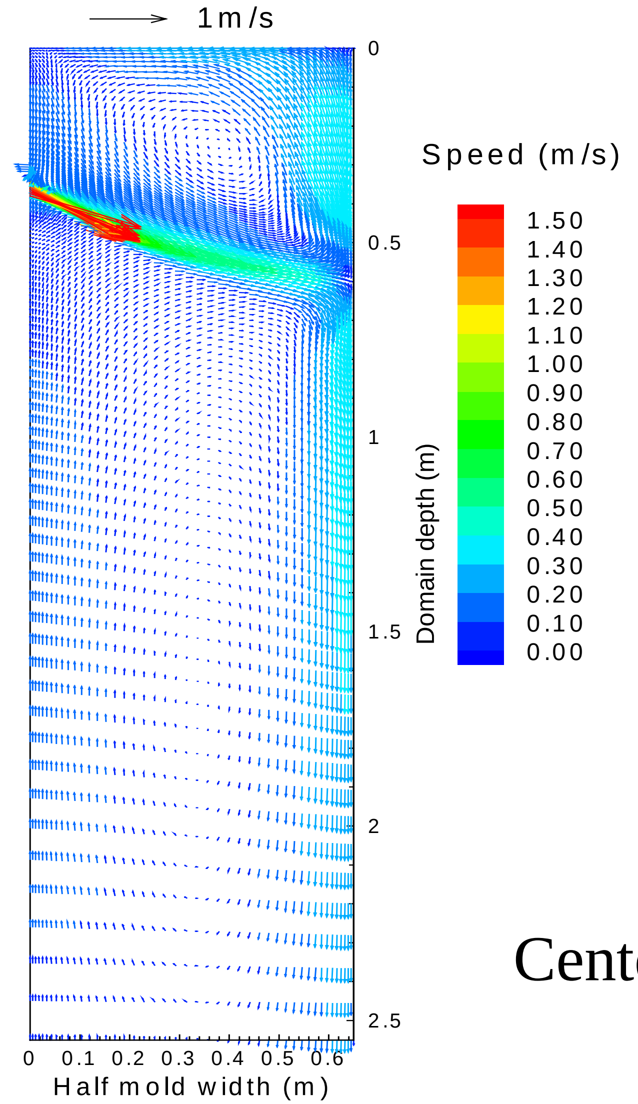
Inclusion Positions Entering Mold from SEN Outlet Port



50μm inclusion (2018) 225μm inclusion (2044) 2000 random positions

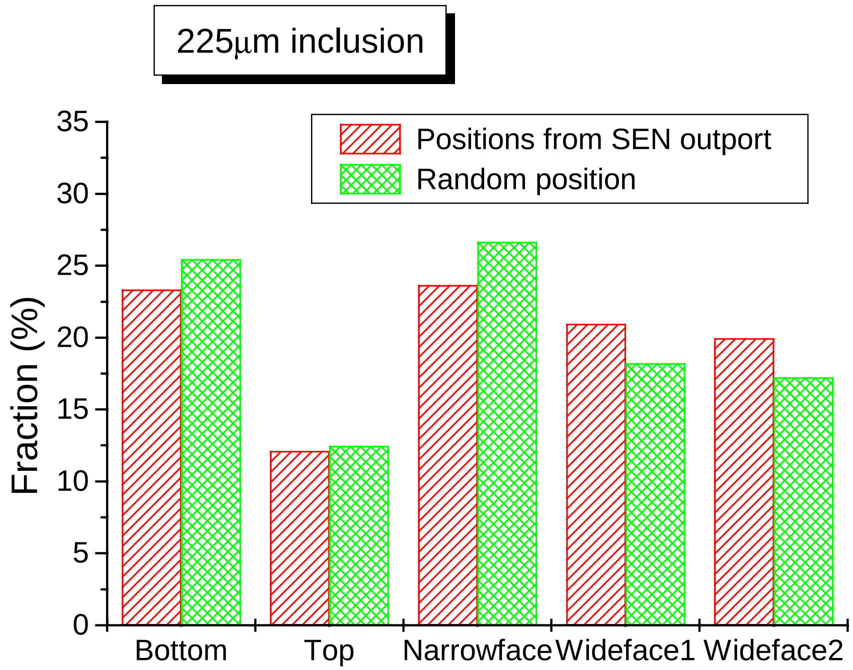
Mesh and Velocity Vector Distribution in Mold

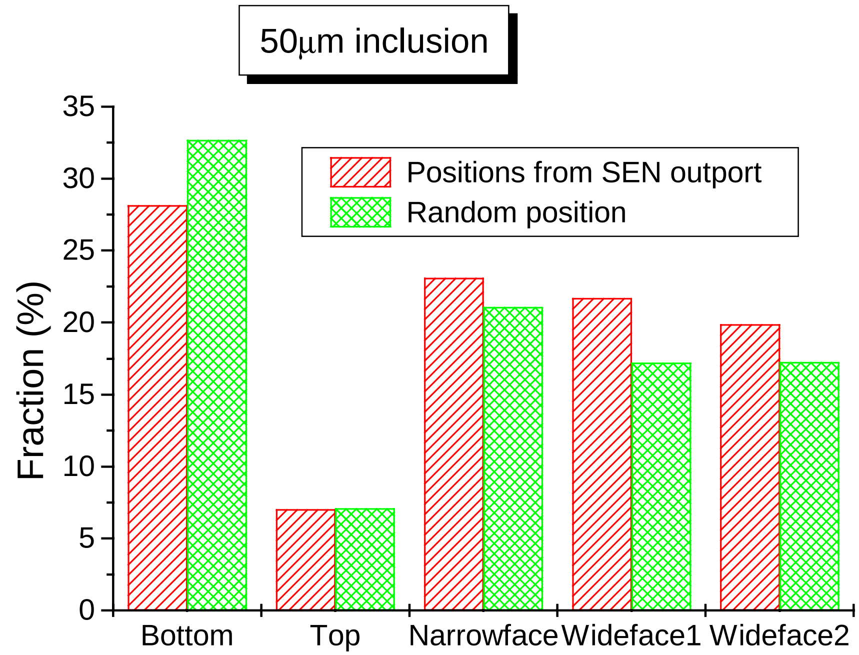




Center face

Inclusion Destinations (10000 Inclusions Per Case)





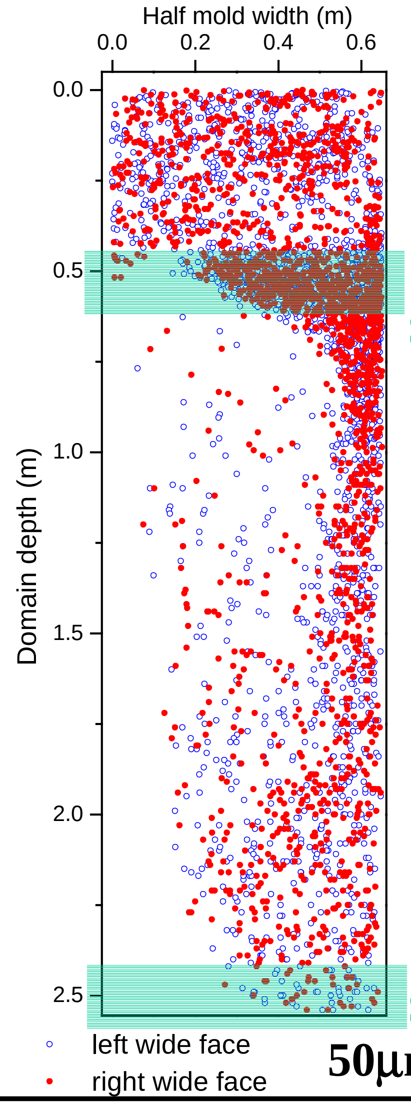
1. Effect of injection location: very small
2. Effect of inclusion size: 12% large inclusions escape *vs* 7% small inclusions.

Inclusion Destinations (10000 Inclusions Per Case)

Inclusion size	Wide face		Narrow face		28-125mm	Top
	0-15mm	15-28mm	0-15mm	15-28mm		
50μm	27%	15%	13%	10%	28%	7%
225μm	29%	12%	14%	10%	23%	12%

1. Around 27-29% inclusion are entrapped at 0-15mm surface thickness, and 12-15% at 15-28mm of wide face; Around 13-14% inclusion are entrapped at 0-15mm surface thickness, and 10% at 15-28mm at narrow face.
2. If the entrapment criteria are the same for small and large inclusions, their entrapment to walls are very similar at 0-28mm slab surface thickness.

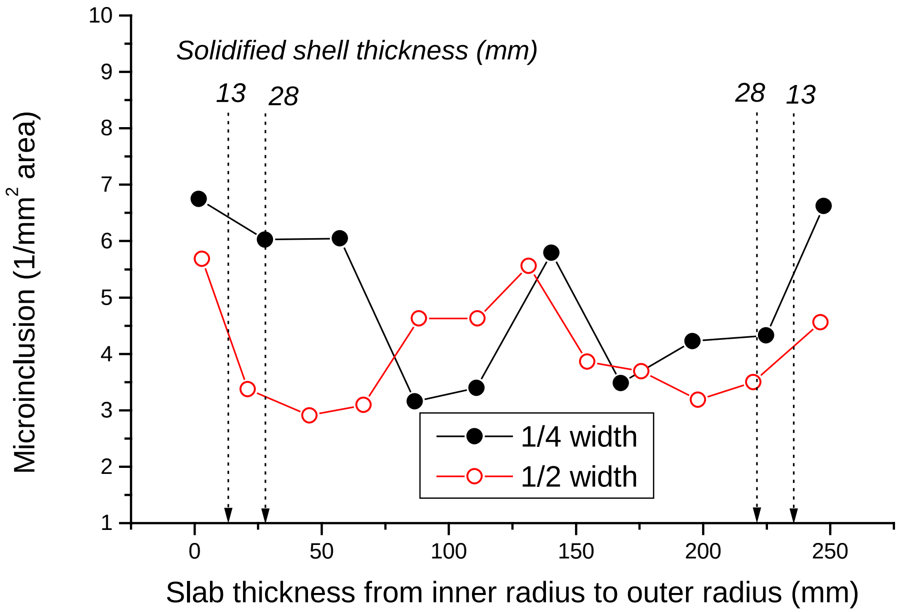
Inclusions Entrapped on Wide Faces (10000 Inclusions Injection from SEN outlet port)

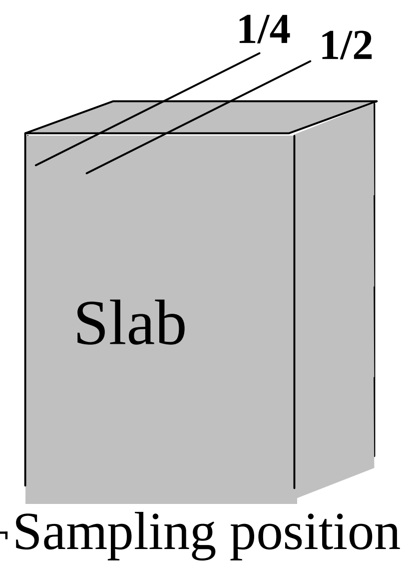


Solidified shell thickness (mm), $S=2.5\ t^{0.5}=2.5\ (L/V_c)^{0.5}$

L: casting length in m (domain depth); V_c: casting speed in m/s.

$L=0.55m \rightarrow S=13mm$; $L=2.55m \rightarrow S=28mm$;

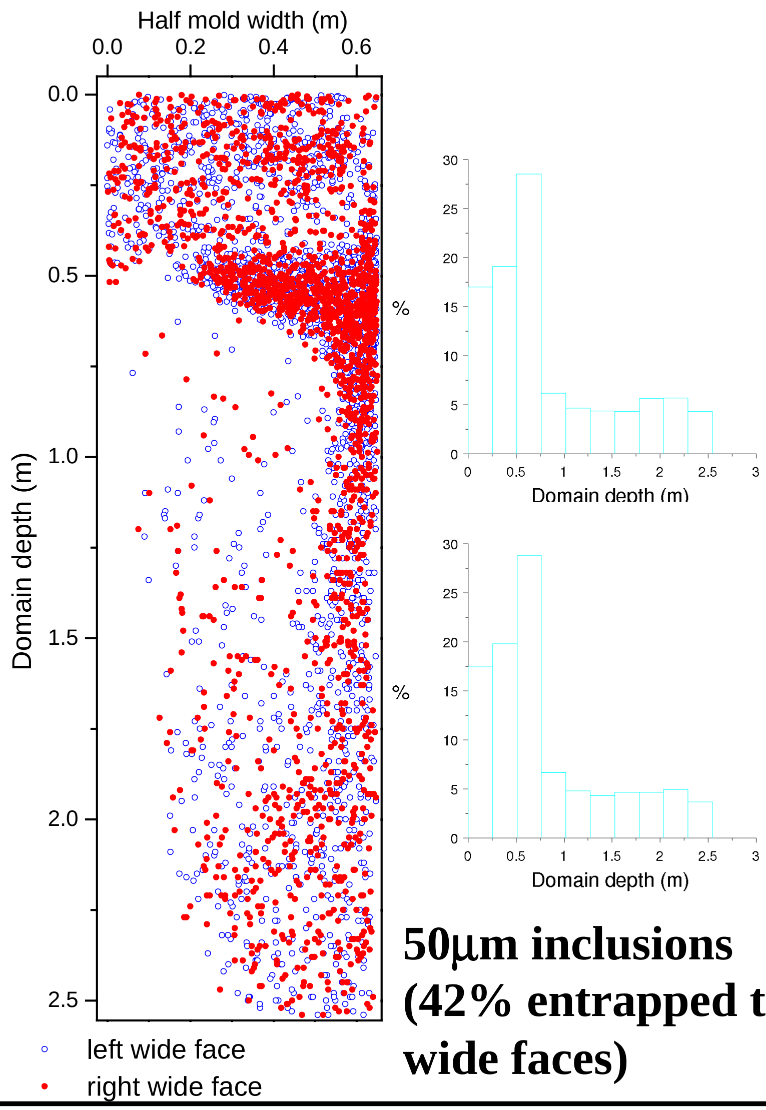




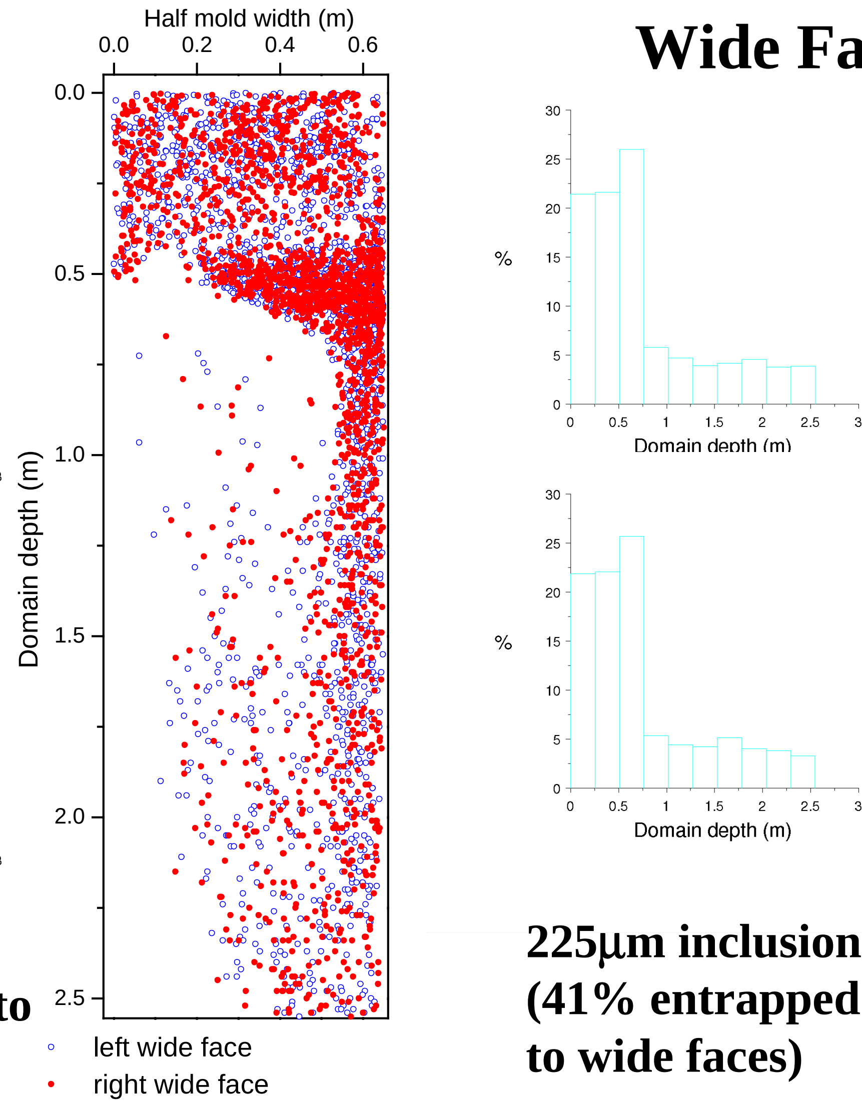
50μm inclusions (42% trapped to wide faces)

Particle Transport Is the Same for Large and Small Inclusions

Wide Faces



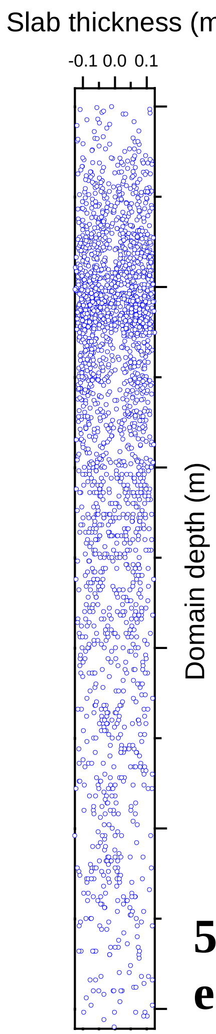
50µm inclusions (42% entrapped to wide faces)

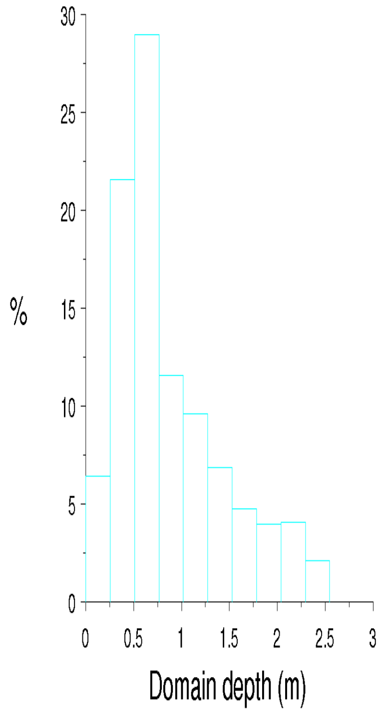


225µm inclusions (41% entrapped to wide faces)

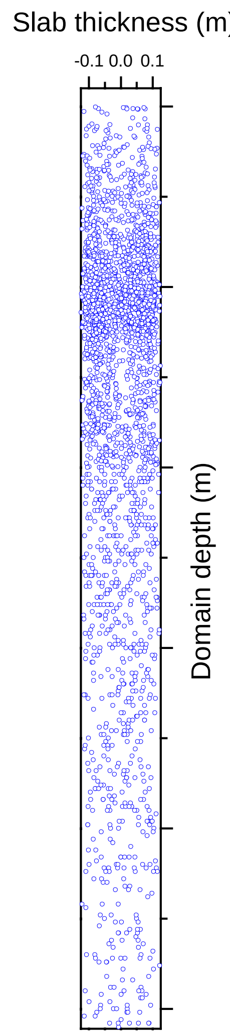
Inclusions Entrapment Locations (10000 Inclusions Injection from SEN outlet port)

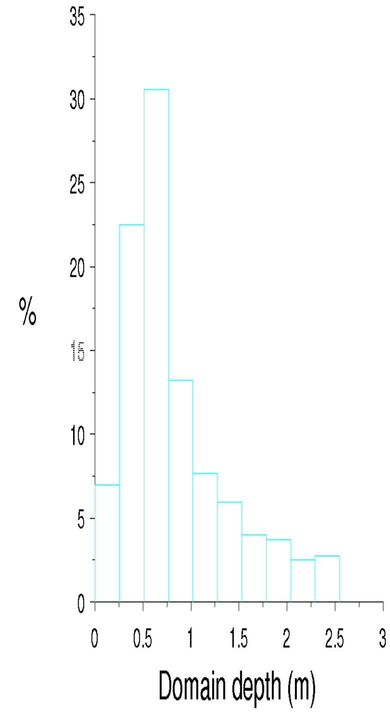
Narrow Faces





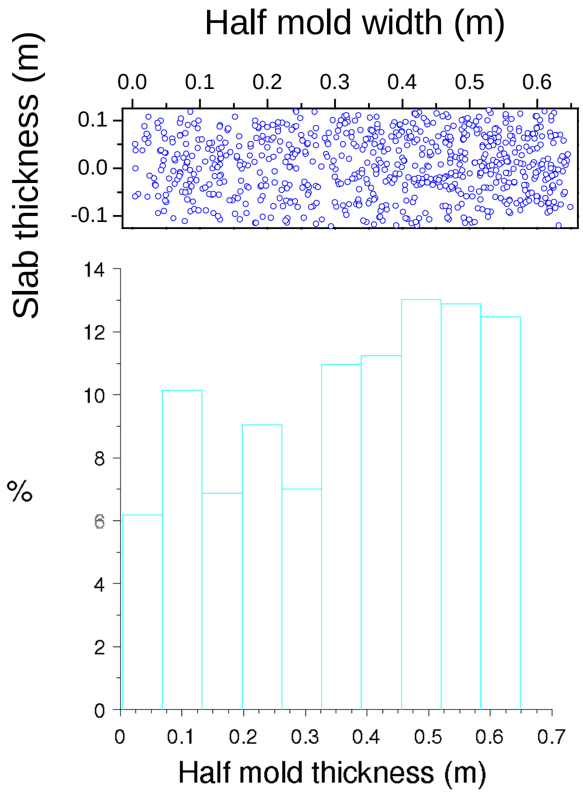
50µm inclusions (23% entrapped to narrow face)



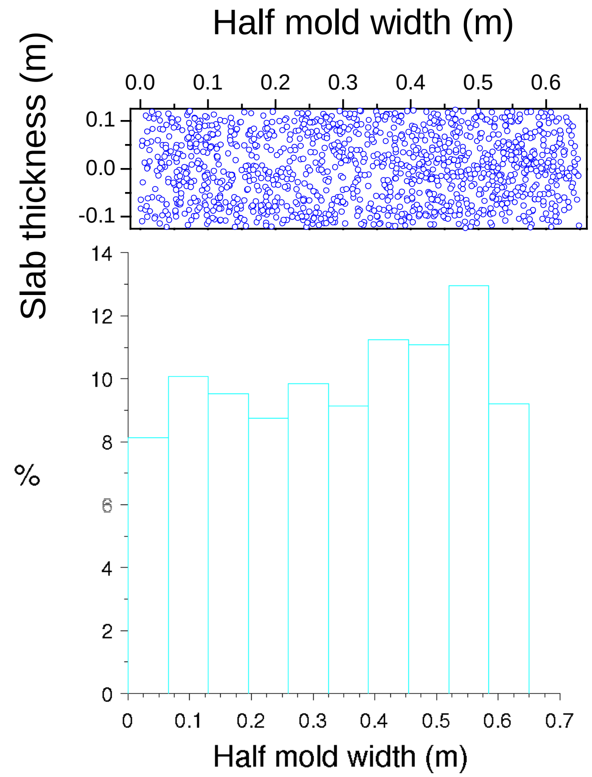


225µm inclusions (24% entrapped to narrow face)

Inclusions Removed to Top Surface (10000 Inclusions Injection from SEN outlet port)



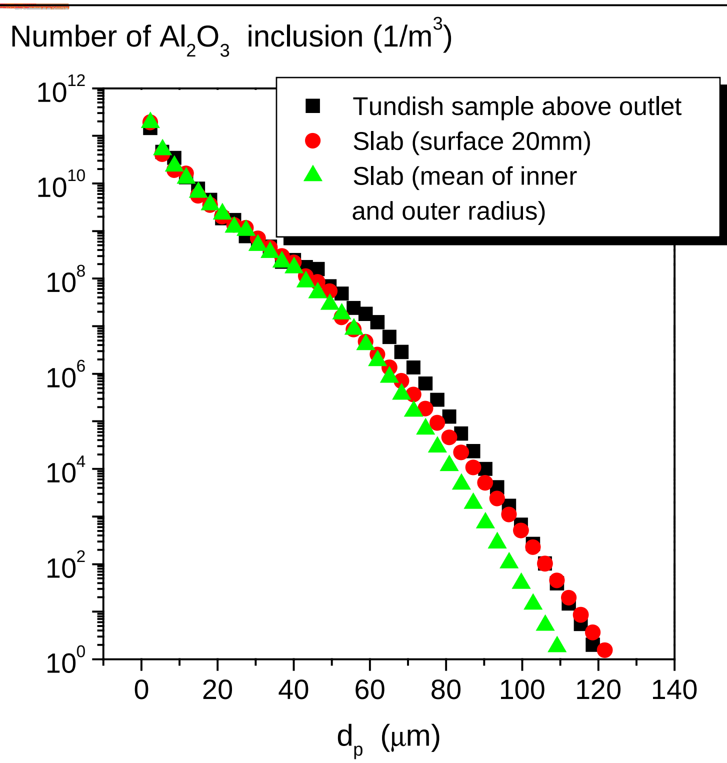
50µm inclusions
(7.5% removed to top surface)



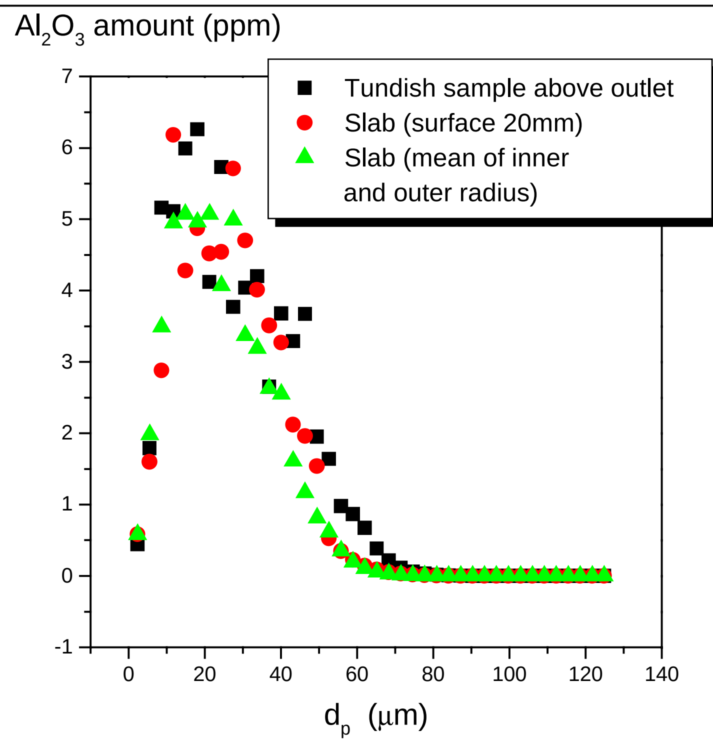
225µm inclusions
(12% removed to top surface)

Small inclusions tend to accumulate towards the narrow edge of the top surface; large inclusions distribute more uniform on top surface.

Inclusion Size Distribution Measurement



Number density distribution



Mass fraction size distribution

1) Total oxygen content: Inlet 31.4ppm, Slab surface 27.2ppm, Slab other places: 24.4ppm

2) The inclusion size distribution of tundish sample above outlet is used as the mold inlet inclusion size distribution.

Inclusion Fraction to Different Destinations

	Simulation		Experiment
	T.O	Fractions	Fractions
Top surface	**1.8**	**6%**	**20%**
Narrow Face	**8.4**	**28%**	
Wide Face	**6.6**	**22%**	
Remaining in domain	**13.2**	**44%**	

The current entrapment model underpredicts the inclusion removal in mold.

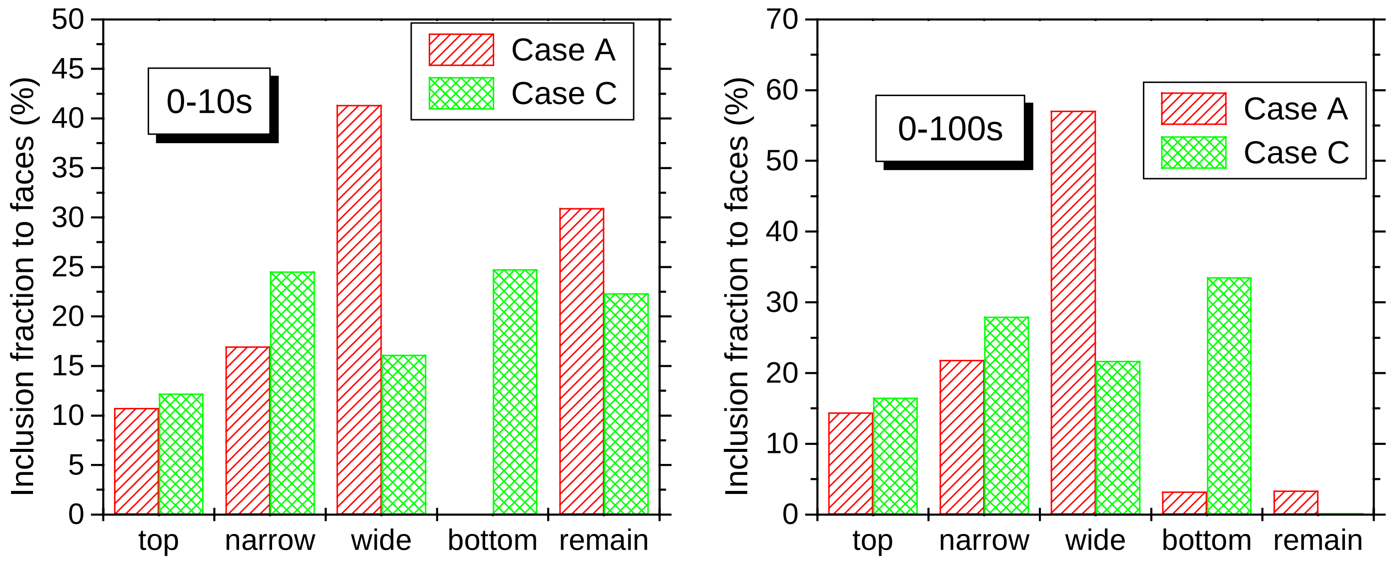
Inclusion Removal for Two Cases

Turbulence model	*k-ε*, by Fluent
Inclusions number injected	15000
Inclusion motion model	Random walk model, 0.1s time step, by Fluent
Boundary condition for inclusions	Escape from top surface and open bottom, trapped at narrow and wide face walls

Parameters	Case A	Case C
Inlet port size (width× height) (m × m)	**0.051×0.056**	**0.065×0.080**
Nozzle angle	25° (down)	15° (down)
Inlet jet angle	25° (down)	26° (down)
Submergence depth (m)	**0.15**	**0.3**
Domain height/width/thickness (m)	**4.0/1.83/0.238**	**2.55/1.3/0.25**
Average inlet flow rate (half mold) (m^3/s)	0.00344	0.00325
Casting speed (m/s)	0.0152	0.02
Fluid density (kg/m^3)	7020	7020
Fluid kinetic viscosity (m^2/s)	0.954×10^{-6}	0.954×10^{-6}
Particle size (diameter) (μm)	300	300
Particle density (kg/m^3)	**2700/5000**	**5000**
Inlet condition	LES simulation of nozzle	Nozzle simulation result

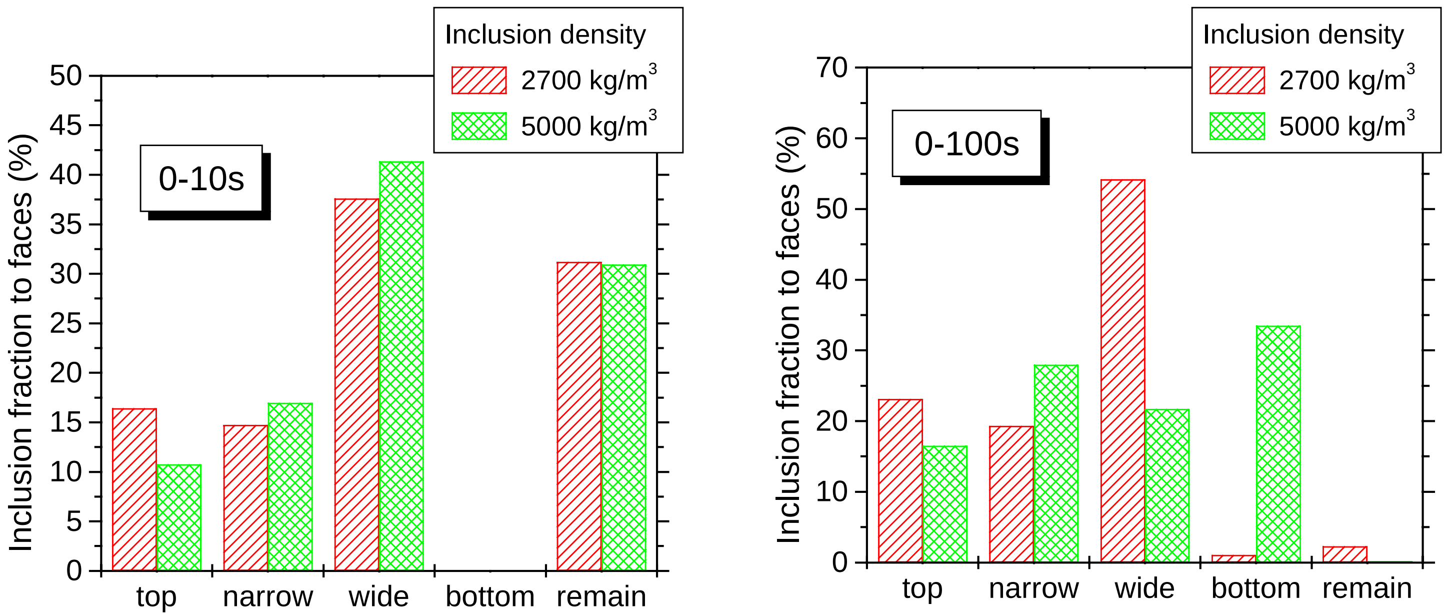
Inclusion Removal for Two Cases

Inclusions density: 5000 kg/m^3



Because case C has a shorter domain height and larger submergence depth, thus inclusions fraction to outlet (bottom) is higher than case A. The inclusion fraction entrapped to wide face is much lower than case A. Thus, the real difference might not be so large.

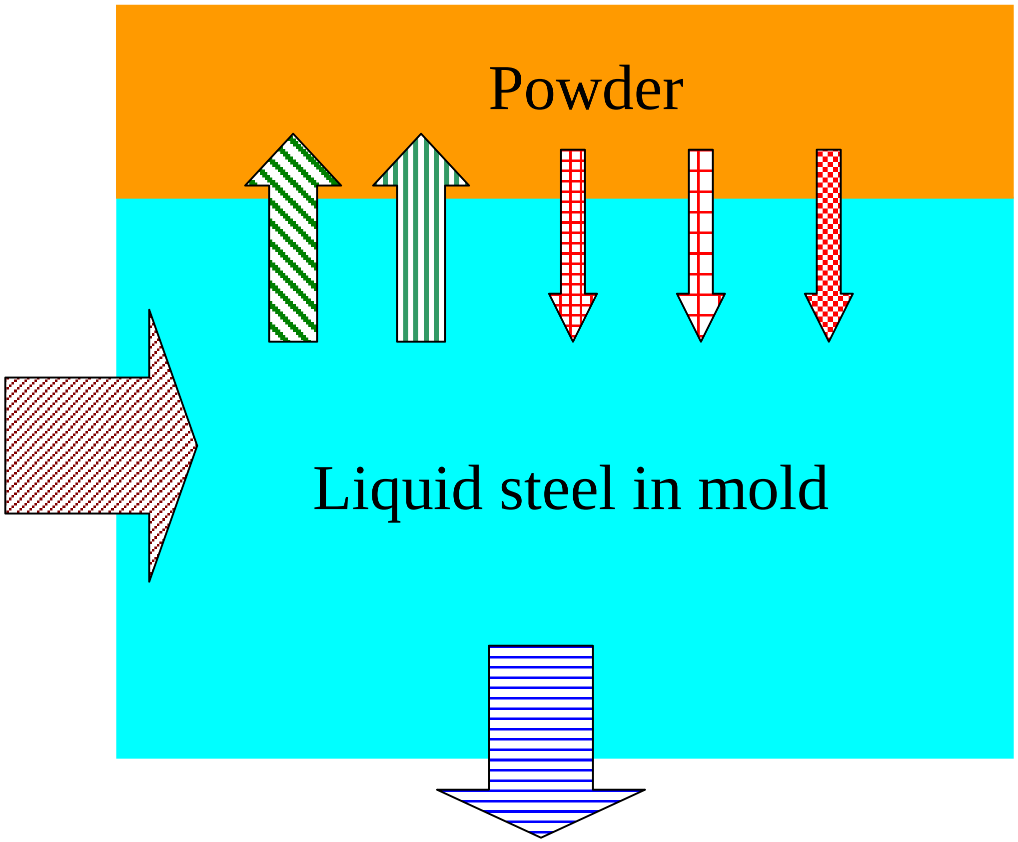
Effect of Inclusion Density on Its Removal



Case A

Smaller density inclusions more easily float out to the top surface, larger density inclusion more easily escape from bottom (outlet).

Inclusion Mass Balance Model



Inflowing flux from SEN (Measurement)

Removed to top surface by it own motion (Trajectory calculation)

Removed by bubble flotation (interaction between inclusion and bubble, trajectory calculation)

Generation by reaction with SiO_2 in powder (measurement of [Si] and (SiO_2))

Reoxidation by air absorption (measurement of [N])

Entrainment from powder (Theoretical prediction)

Final inclusion in slab (Measurement and Theoretical prediction)

Others phenomena:

1. Slag composition change;
2. Inclusion size distribution by their collision.

Conclusions

1. For the inclusions smaller than 50 μm, the fraction to the top surface is independent of inclusion size, and this fraction is around 7%. For the inclusions larger than 50 μm, their removal to top surface increases with increasing size.

2. Inclusion fraction captured by the wide and narrow face is independent of inclusion size. Around 24% of inclusions are captured by 28mm outer thickness of the top 2.55m of the narrow face, and 42% are captured by 28mm outer thickness of the top 2.55m of wide face.

3. Smaller density inclusions more easily float out to the top surface, larger density inclusion more easily escape from bottom (outlet).

4. The current entrapment model at the walls underpredicts inclusion removal due to neglect of argon bubbles.

Further Investigations

1. The transient fluid flow simulation for the steel caster mold;
2. The suitable entrapment model of inclusion to the solidified shell;
3. The inclusions collision and coagulation simulation and its contribution to inclusion size growth and removal;
4. The interaction between inclusions and bubbles and its contribution to inclusion motion (removal) from mold;
5. Inclusion mass balance calculation.