Inclusion Removal from Steel Caster

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Objectives

- Fluid flow and inclusion clogging simulation in SEN
- Fluid flow and inclusion removal from continuous casting mold (trajectory calculation model, lumped collision model)
- Similarity criteria for particle motion in water and in liquid steel

Background—Review on Steel Cleanliness and Inclusions

Direct Evaluation Methods of Steel Cleanliness

Direct Methods

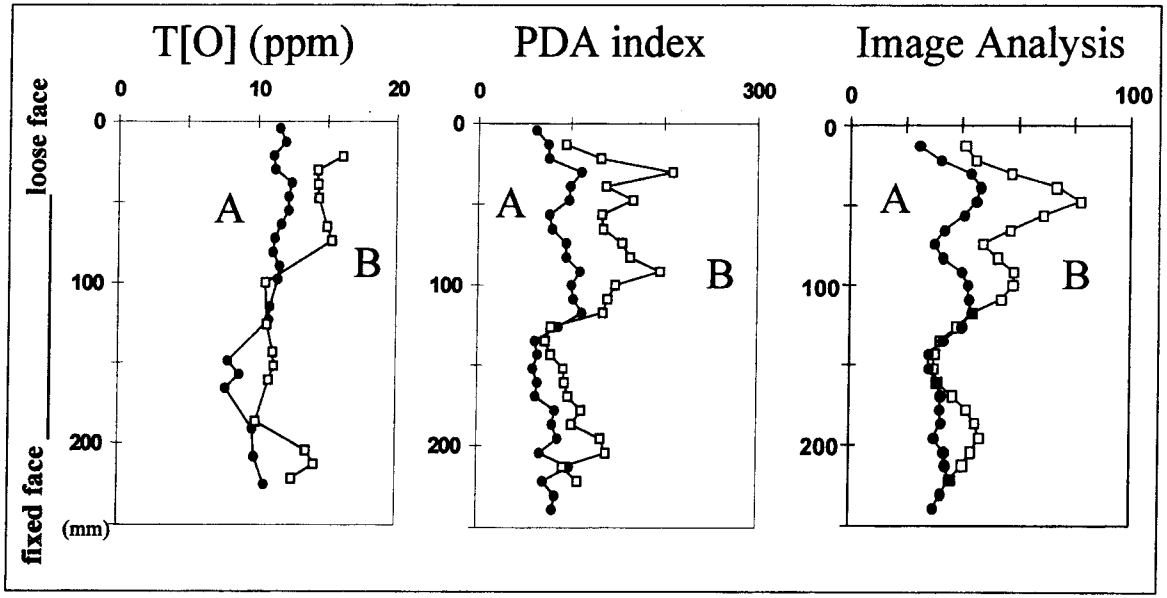
Metallographical Microscope Observation (MMO);
Image Analysis (IA);
Sulfur Print;
Slime (Electrolysis);
Electron Beam melting (EB);
Cold Crucible (CC) melting;
Scanning Electron Microscopy (SEM);
Electron Probe Micro Analyzer (EPMA)
Optical Emission Spectrometry (OES-PDA)
Mannesmann Inclusion Detection (MIDAS)
Laser-Diffraction Particle Size Analyzer (LDPSA)
Conventional Ultrasonic Scanning (CUS)
Cone Sample Scanning
Fractional Thermal Decomposition (FTD)
Laser Microprobe Mass Spectrometry (LAMMS)
X-ray Photoelectron Spectroscopy (XPS)
Auger Electron Spectroscopy (AES)
Photo Scattering Method
Coulter Counter Analysis
Liquid Metal Cleanliness Analyzer (LIMCA)
Ultrasonic Techniques for Liquid System

Indirect Methods

Total oxygen measurement
Nitrogen pick-up
Dissolved aluminum loss measurement
Slag composition measurement
Submerged entry nozzle (SEN) clogging

Steel Cleanliness Evaluation

- **No single ideal method can evaluate steel cleanliness.**
- **Several methods should be coupled together**

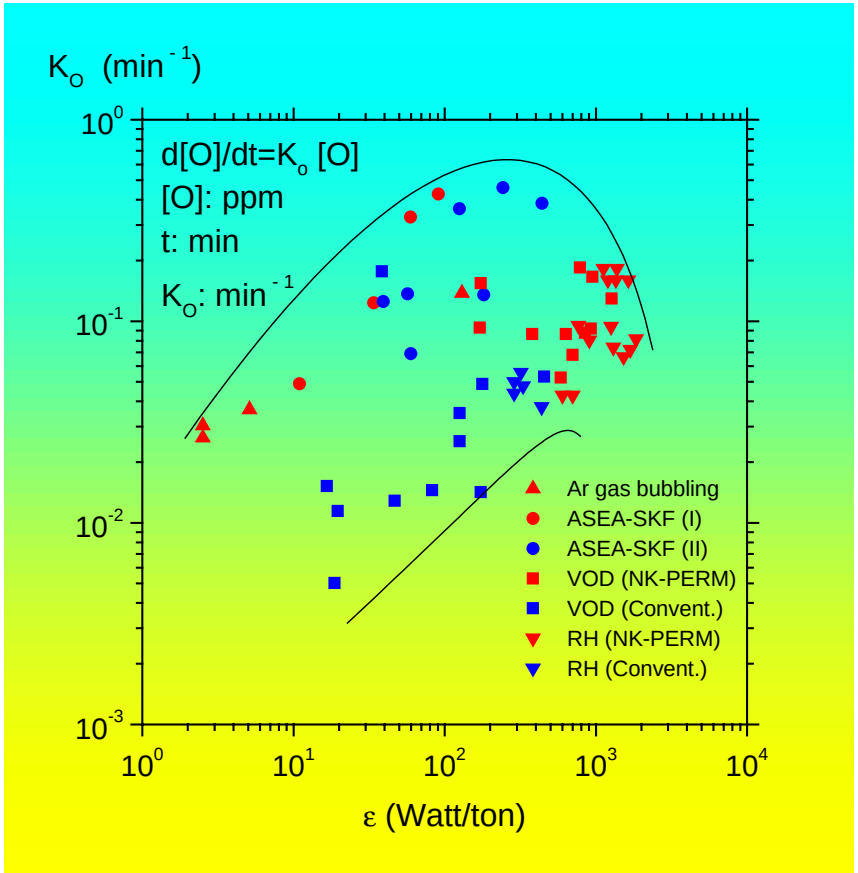


1) **<u>Nippon Steel Co.:</u>** T.O measurement and EB melting for small inclusions, Slime method and EB-EV for large inclusions;

2) **<u>Usinor</u>**: T.O measurement with FTD, OES-PDA, IA and SEM for small inclusions, Electrolysis and MIDAS for large inclusions.

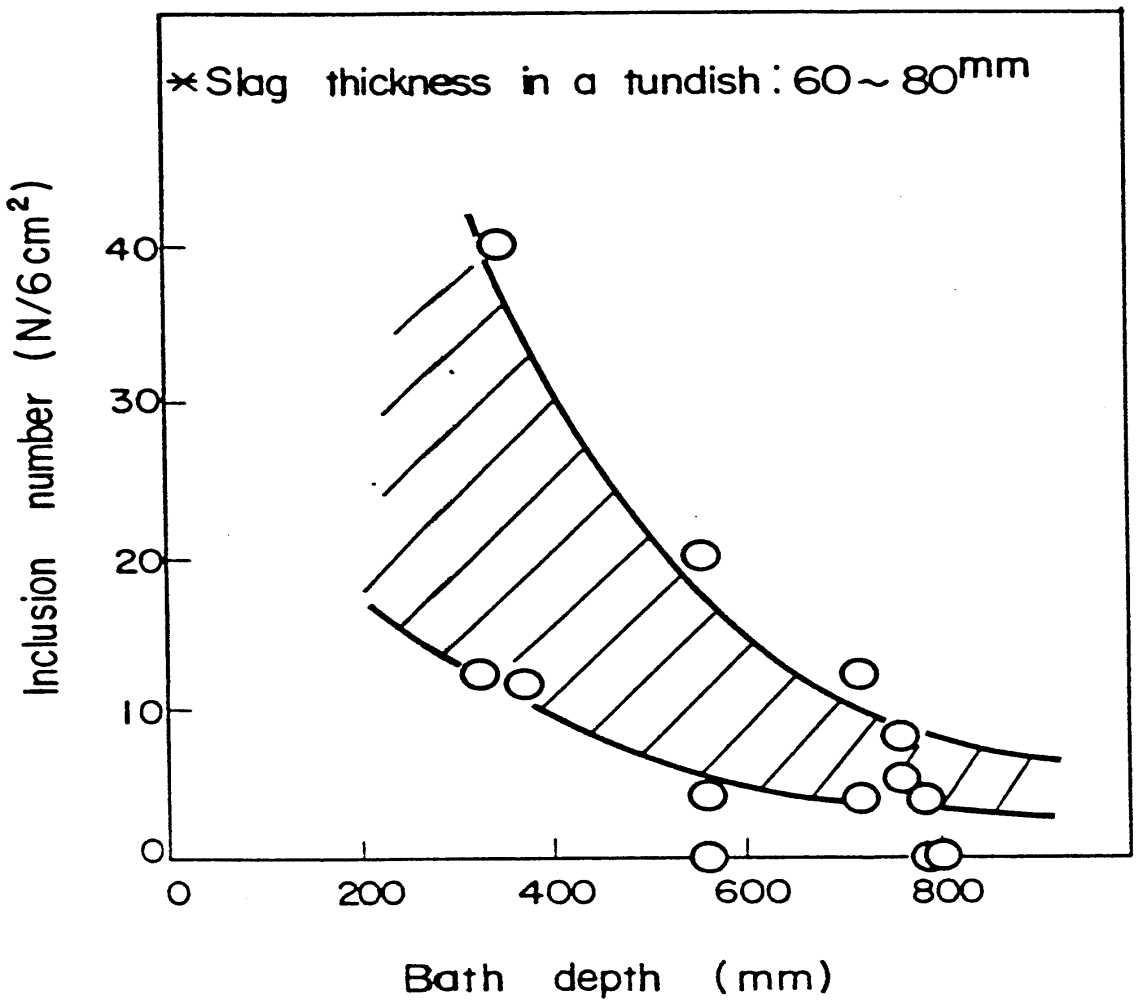
3) **<u>Baosteel</u>**: T.O measurement, Metallographical Microscope Observation, XPS, and SEM for small inclusions; Slime and SEM for large inclusions; nitrogen pickup; slag composition analysis.

Effect of Stirring Power on Steel Cleanliness



- Stirring helps to lower oxygen contents
- Too vigorous stirring is even bad for inclusion removal.

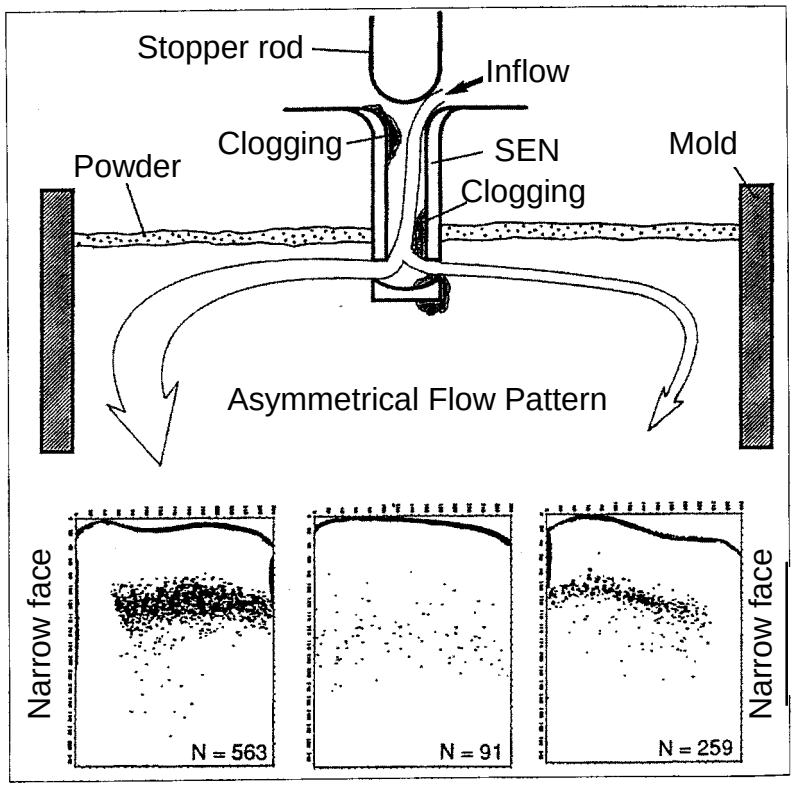
Deeper Tundish Lowers Inclusions



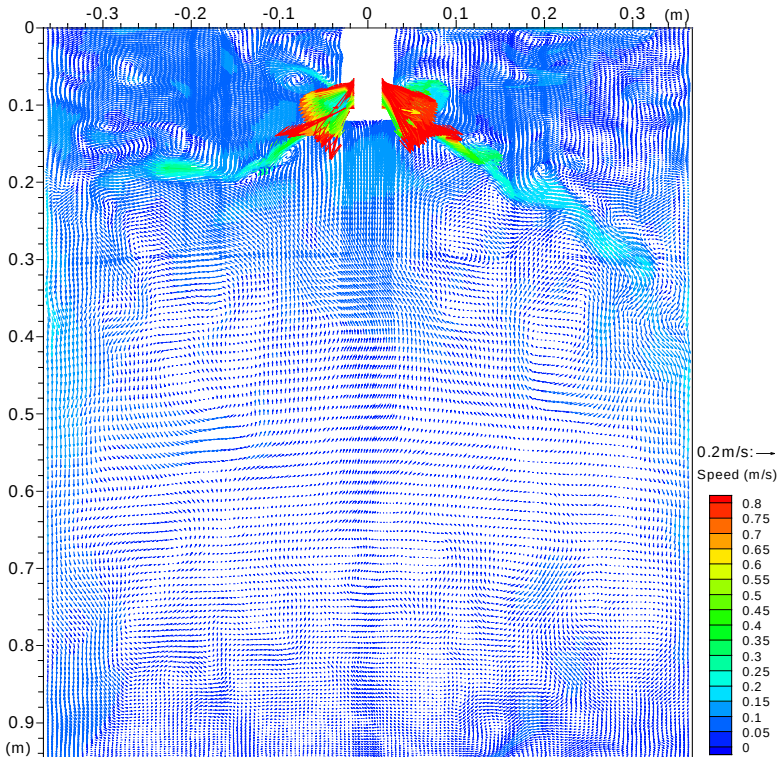
Asymmetrical Mold Flow Pattern Lowers Steel Cleanliness

Asymmetrical flow pattern in mold caused by:

1) Nozzle clogging
2) Turbulence



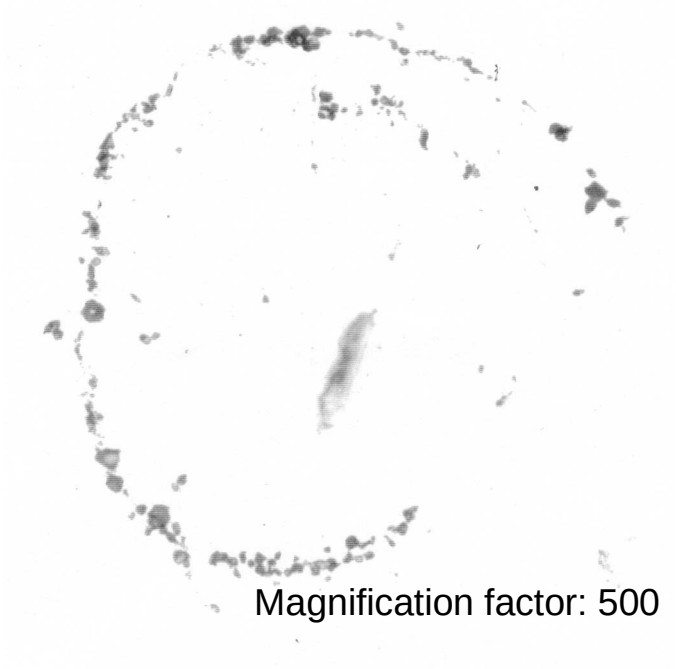
From the SEN clogging (N—inclusion number index by the methods of MIDAS)



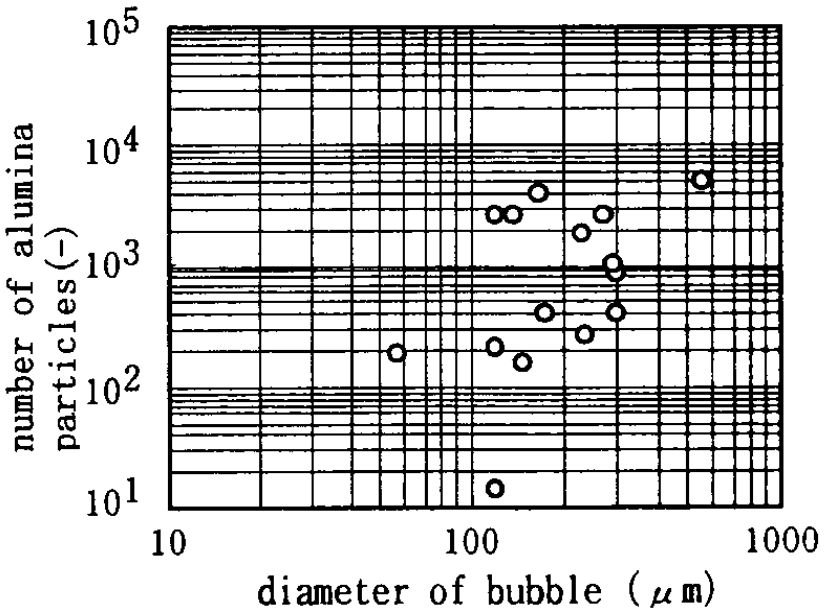
From transient behavior of fluid flow

Inclusion Attachment to Bubble

- Good for inclusion removal if bubbles float out;
- Bad for steel cleanliness if bubbles was entrapped by the solidifying shell



Example of inclusion captured by a bubble



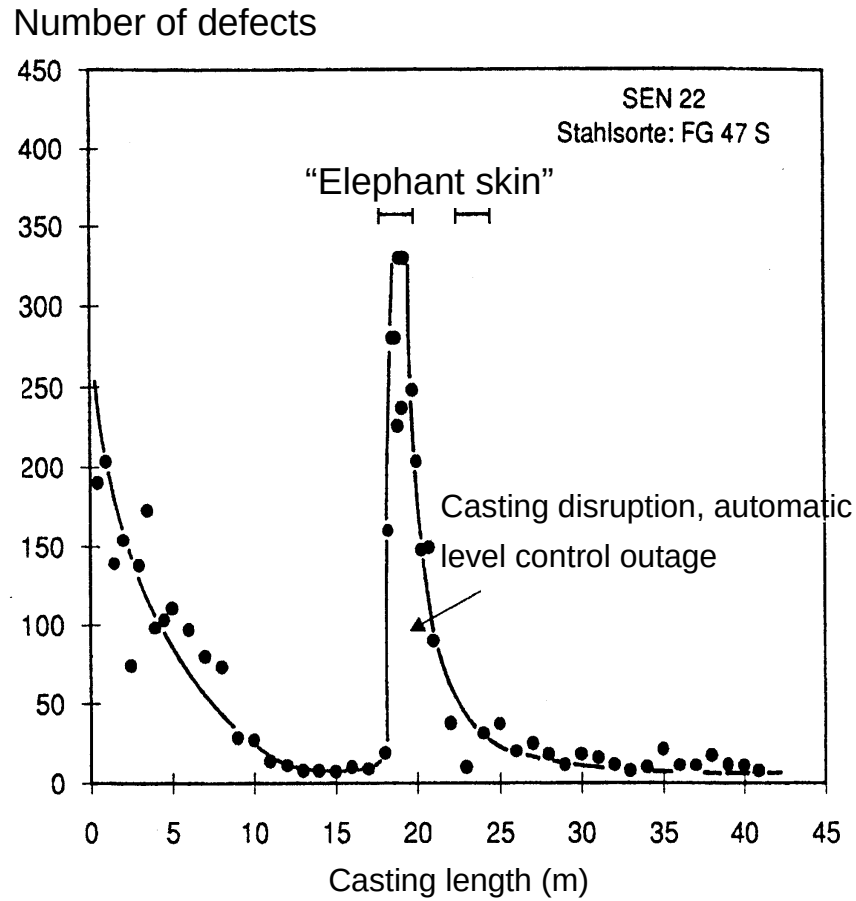
Observed inclusions number attached to different size bubbles for LCAK steel slab

Level Control Variations Cause Defects

Trace investigation at WISCO (China): inclusions from slag entrainment in slab, 5.17% from ladle slag, 40.4% from tundish flux and 13.52% from mold powder.

The surface level change can be induced by

- Oscillation of mold
- Cast speed change
- Too much gas injection
- Asymmetrical flow in mold



Variation in cleanliness at the start of casting with accidental disruption of automatic level control

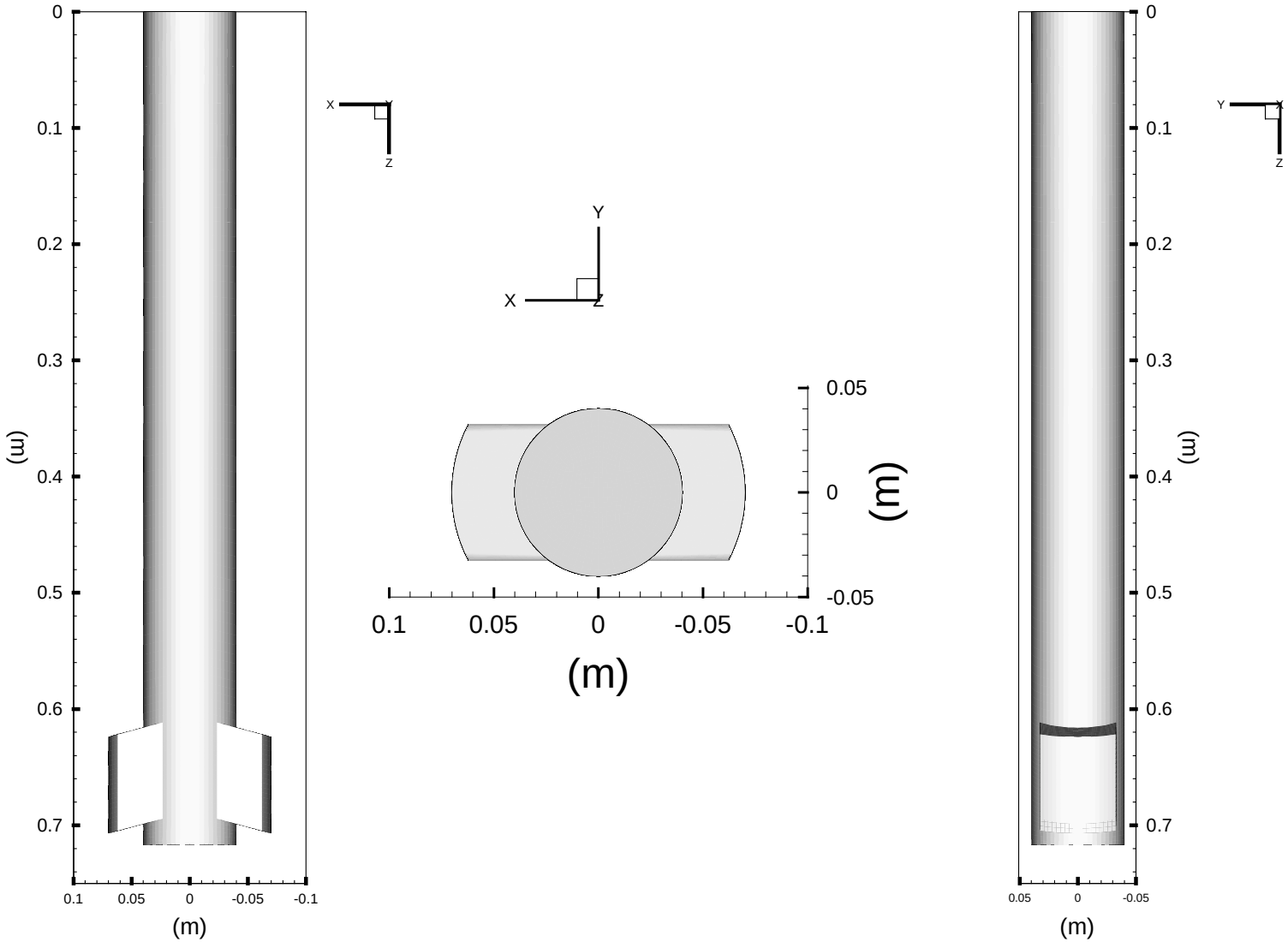
Inclusion Entrapment to SEN Lining Walls

SEN Simulation Parameters (Case C)

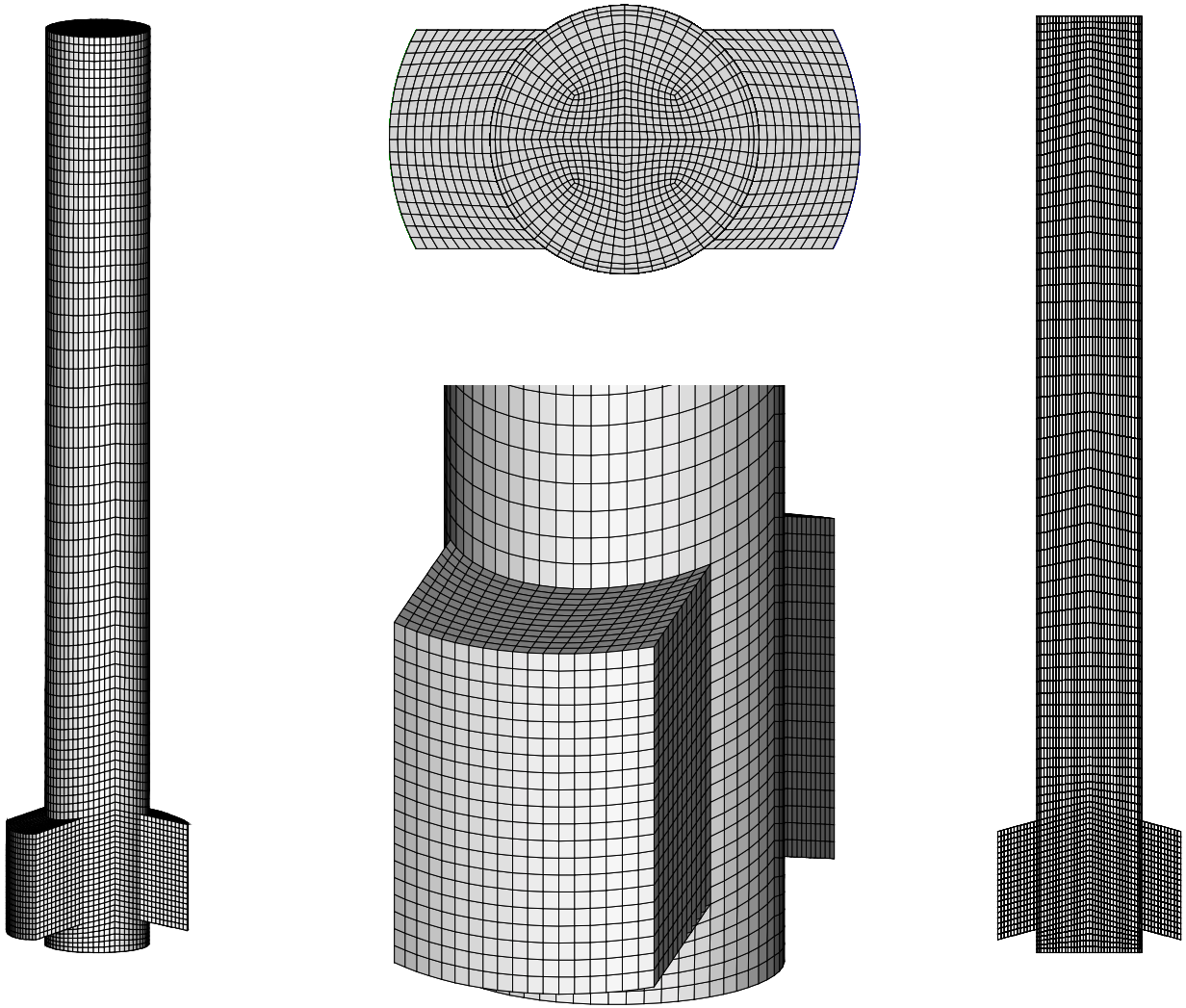
Turbulence	k-ε two equation, Fluent
Inclusion motion model	Random-Walk, 15000 particles each size

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

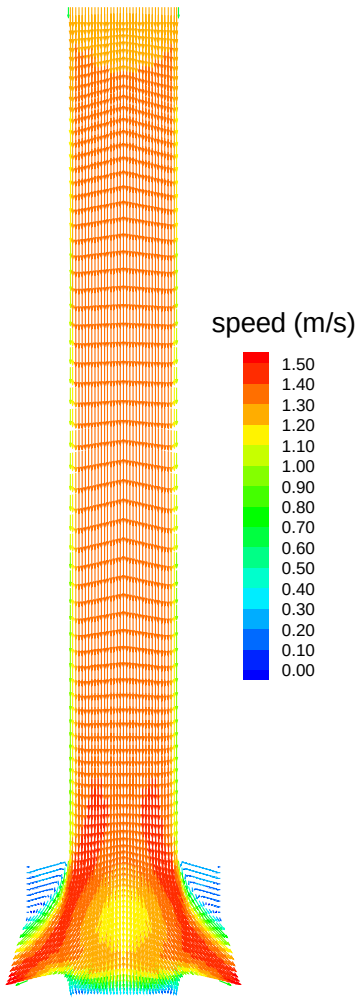
Geometry of SEN (Case C)

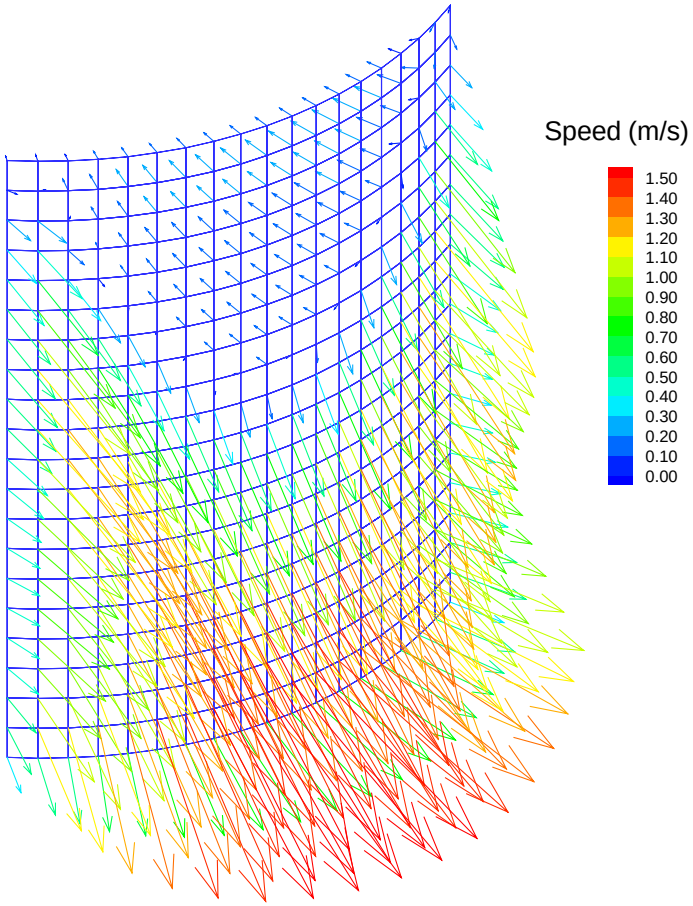


Mesh for Fluid Flow and Inclusion Motion Simulation in SEN

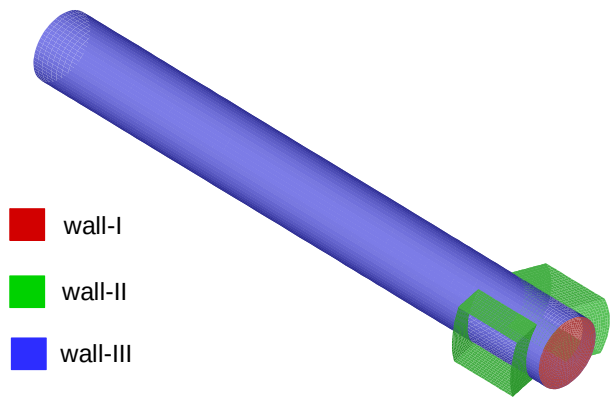


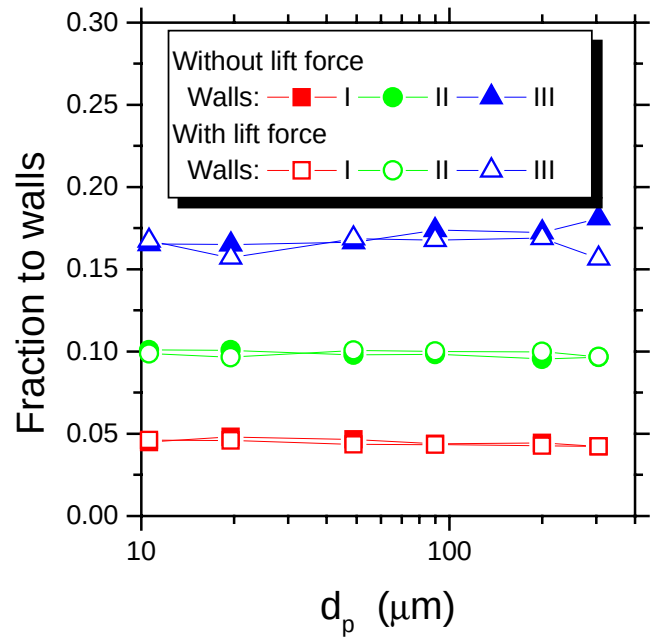
Velocity Distribution in SEN





Inclusion Entrapment to Walls of SEN





180000 inclusions to different places:

Nozzle Bottom: 4%

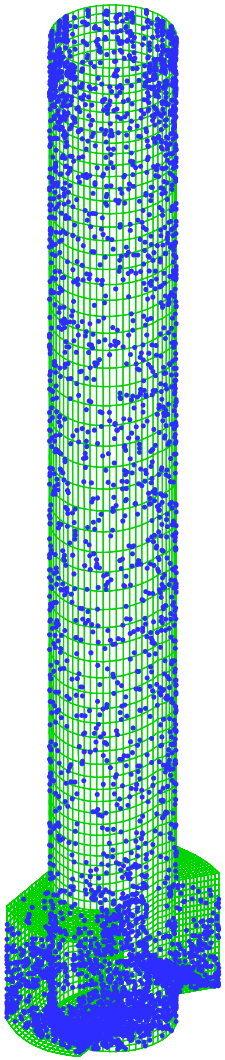
Nozzle Port Walls:10%

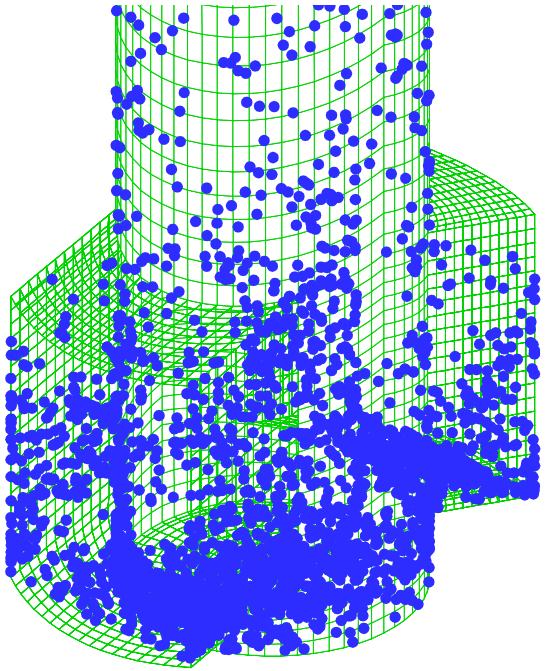
Nozzle bore wall: 17%

Total: 31%

Inclusions fraction to walls is independent on inclusions sizes.

Nozzle Clogging Simulation





Most particles are entrapped at bottom.

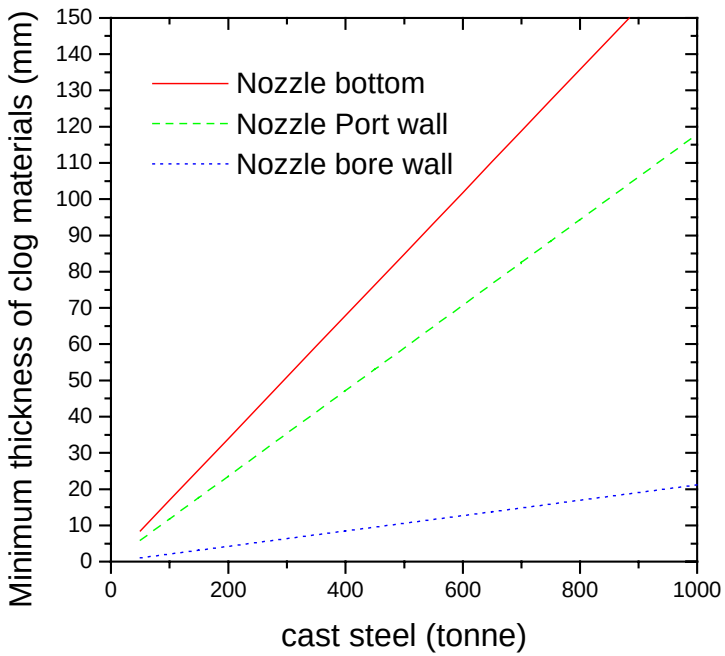
Estimate Clog Growth Rate

Assumptions:

1) Once inclusions collide with wall, they are entrapped;

2) Uniform clog distribution along each SEN surface;

3) Total oxygen entering nozzle is 30ppm.



$$\text{Thickness} = \frac{[\text{T.O}] \times W \times \alpha}{\rho_p \times S} \times 10^{-3}$$

Thickness: m

T.O: total oxygen, ppm

W: Casting weight, tonne

α: Fraction of inclusions collide with walls

ρ_p: Inclusion density, 3500kg/m^3

S, surface area of SEN inner walls, m^2

Conclusion: The current inclusion entrapment model (once colliding with wall inclusions are entrapped) overpredict the effect of entrapment of inclusion to SEN walls.

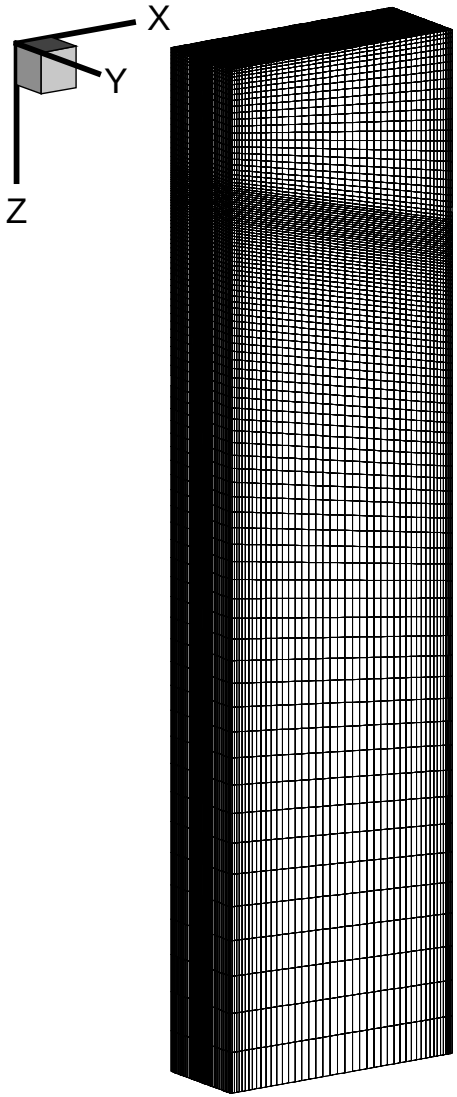
Fluid Flow and Inclusion Motion in Continuous Casting Mold

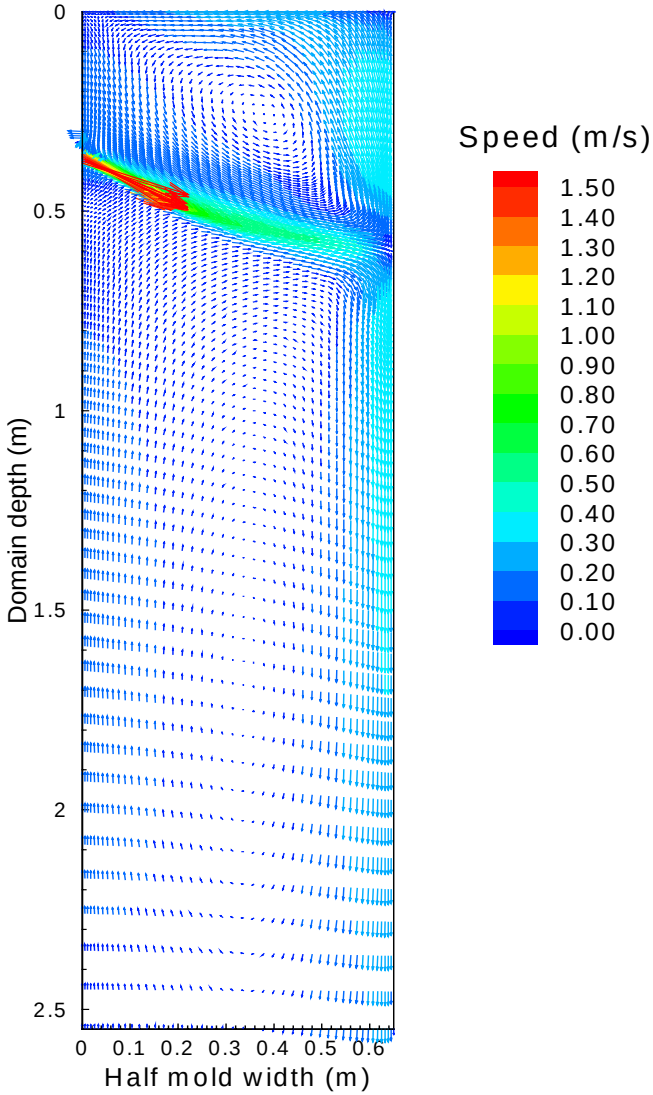
Parameters for Mold (Case C)

Turbulence model	k-ε, by Fluent
Inclusion motion model	Random walk model , 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$\times$ height) (m $\times$ m)	0.065$\times$0.080
Nozzle angle	15° (down)
Inlet jet angle	26° (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/s)	0.02
Fluid density (kg/m^3)	7020
Fluid kinetic viscosity (m^2/s)	0.954 $\times 10^{-6}$
Particle size (diameter) (μm)	0.5-300
Particle density (kg/m^3)	5000/2700
Inlet condition	Nozzle simulation result

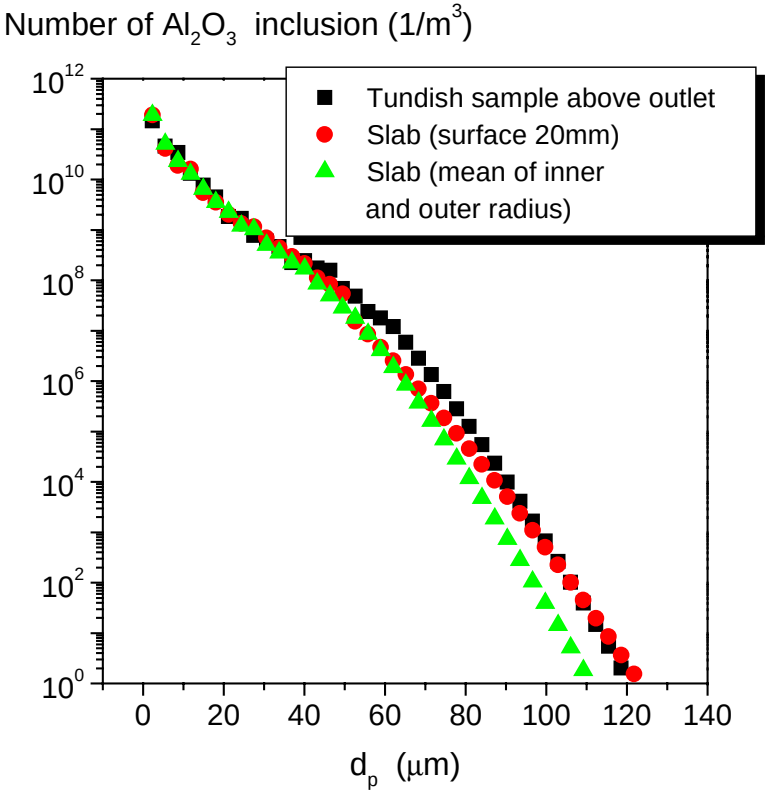
Mesh and Velocity Vector Distribution in Mold



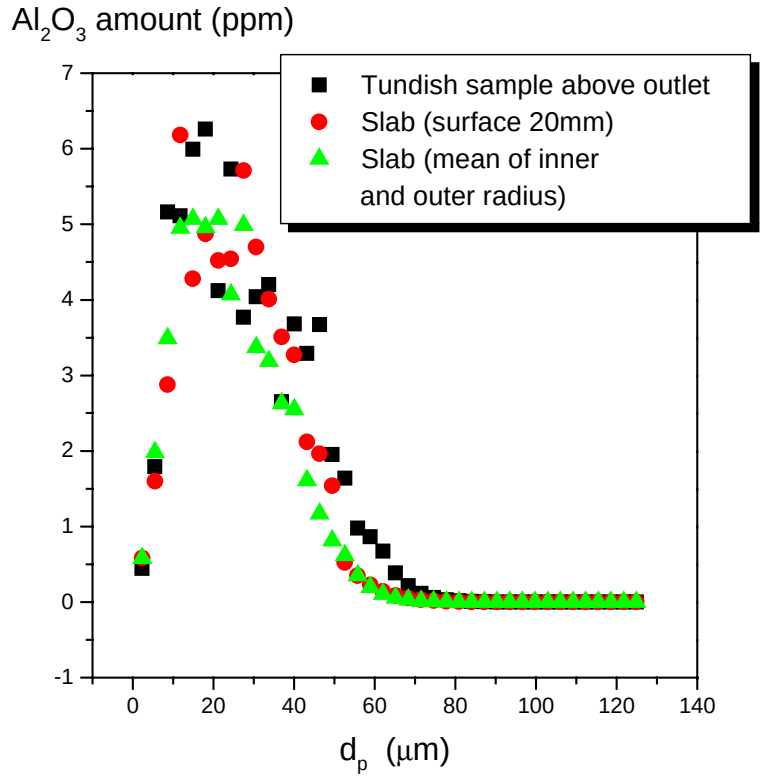


Inclusion Removal by Trajectory Calculation

Inclusion Size Distribution in Steel



Number density distribution

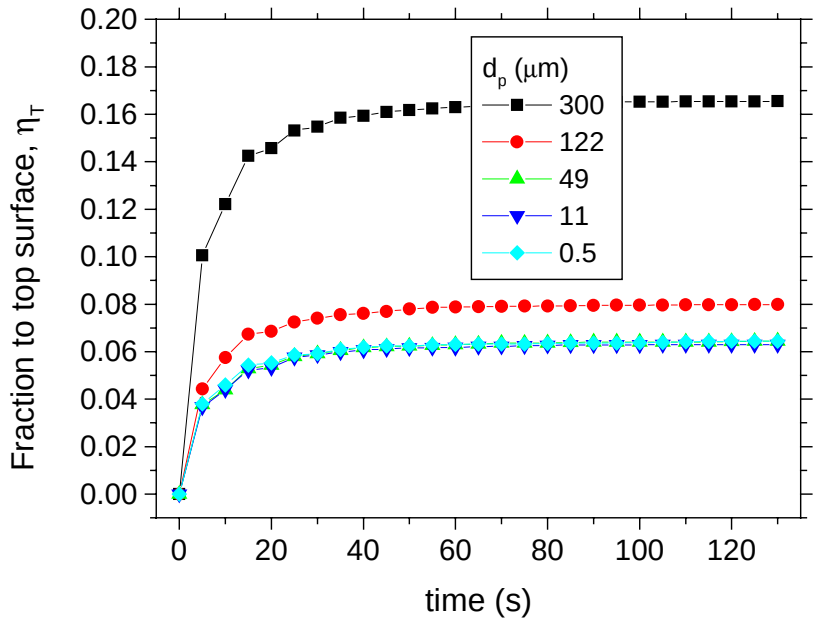


Mass fraction size distribution

1) Total oxygen content: Mold 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.

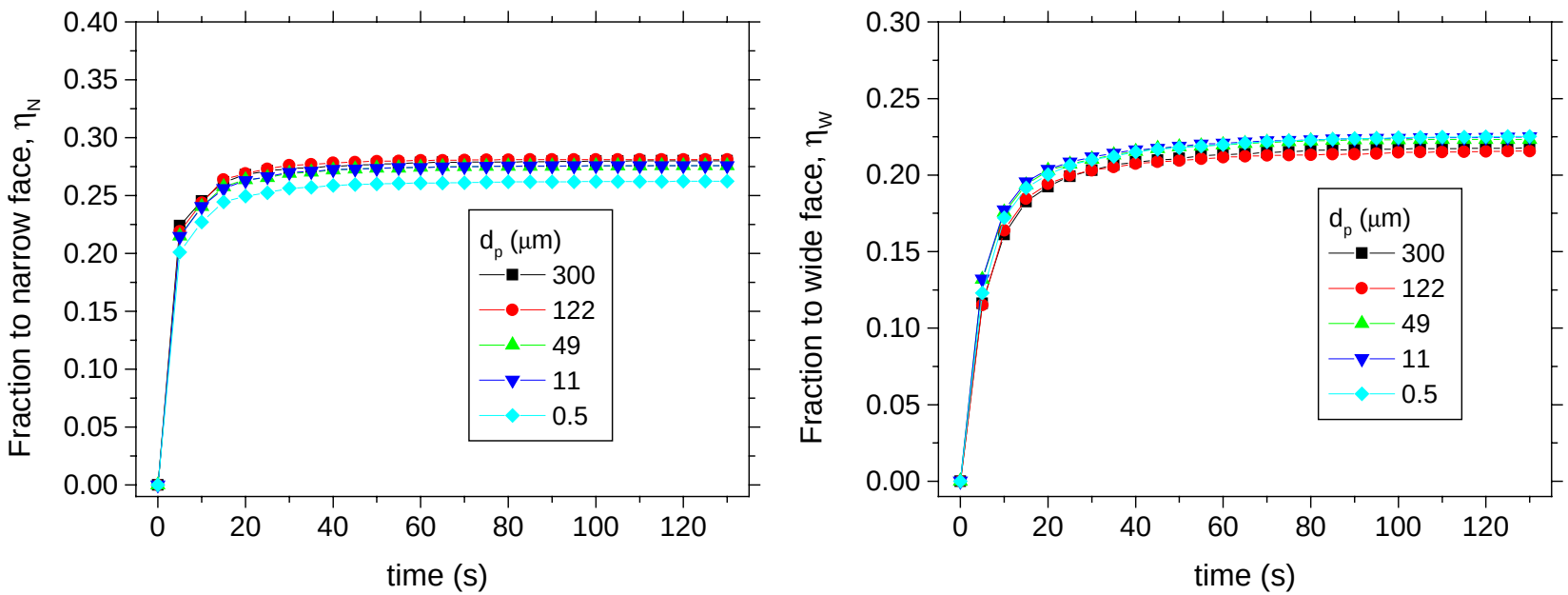
Fraction of Inclusion to Top Surface



1) For the inclusions smaller than 50 μm, the fraction to the top surface is independent on inclusion size, and this fraction is around 6% after 40seconds.;

2) Beyond that, the removal to top surface increases with size increasing.

Fraction of Inclusion to Narrow Face and Wide Face



Inclusions captured by the wide face and narrow is independent on inclusion sizes.

28% inclusions are captured by narrow face, and 22% are captured by wide face.

Inclusion Fractions by Trajectory Calculation

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

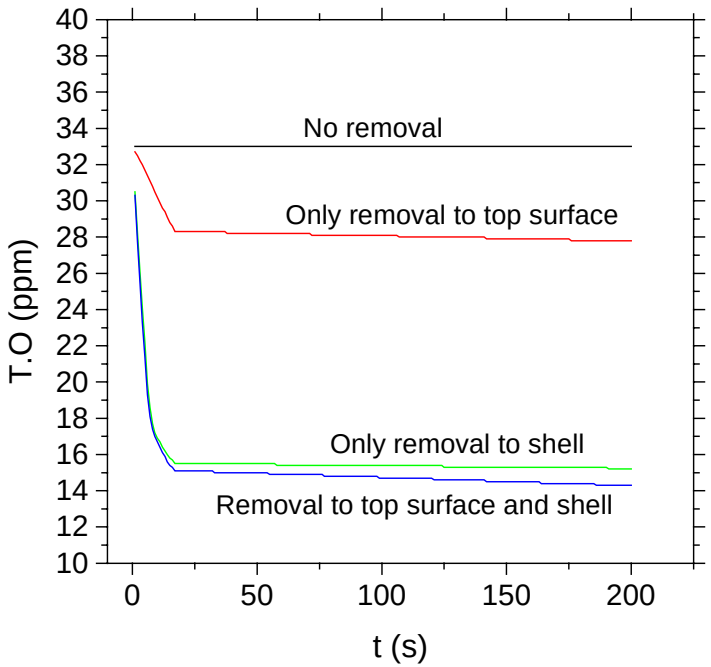
T.O entering mold: 30ppm

Inclusion Removal by Lumped Collision Model

$$\frac{dN_i}{dt} = -\phi N_i \sum_{j=1}^{\infty} \beta_{ij} N_j \quad {}_i + \frac{1}{2}\phi \sum_{j=1}^{i-1} \beta_{j,i-j} N_j N_{i-j} - S$$

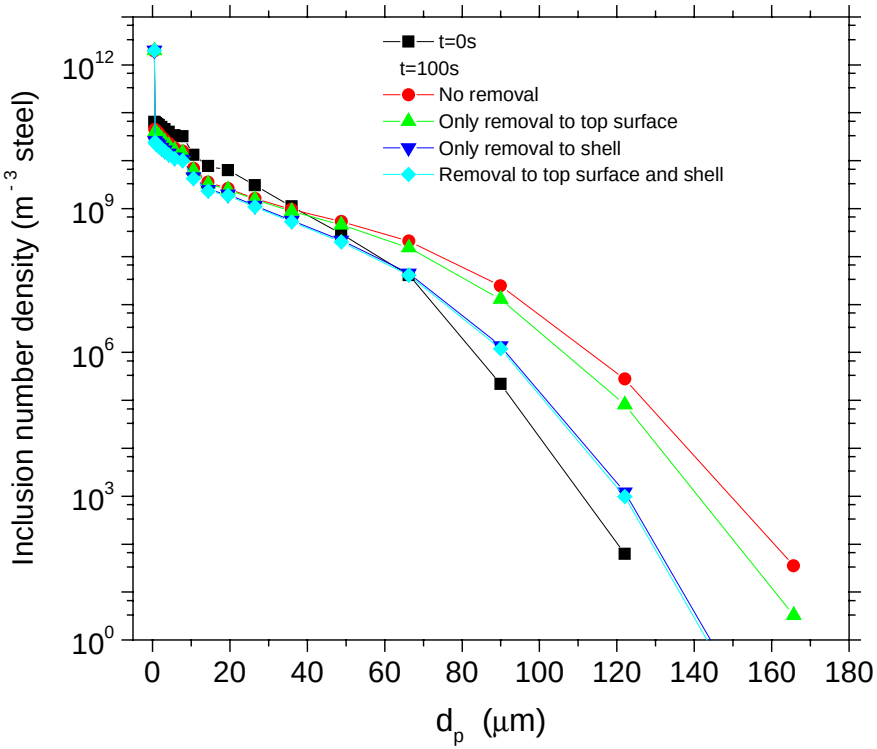
S is the source term for inclusion floating removal rate, which is decided by trajectory calculations.

Total Oxygen as Function of Time by Collision Model



When considering only removal to top surface, T.O. is around 27ppm after several hundreds seconds; When considering both removal to top surface and entrapment to solidifying shell, T.O. is asymptotic to 14ppm. Industrial T.O measurement of slab is 24.4ppm. Thus the real inclusion removal curve should be between the two cases. Thus the current entrapment to solidifying shell overpredict the inclusion removal.

Inclusion Size Distribution as Function of Collision Model



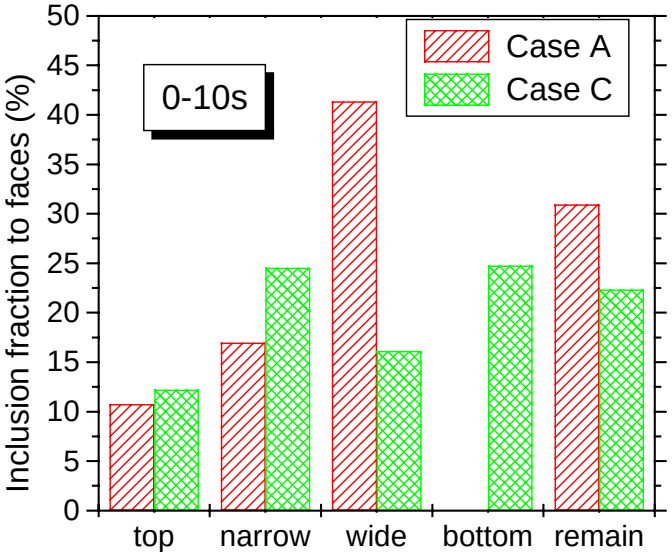
Inclusion Removal for Two Cases

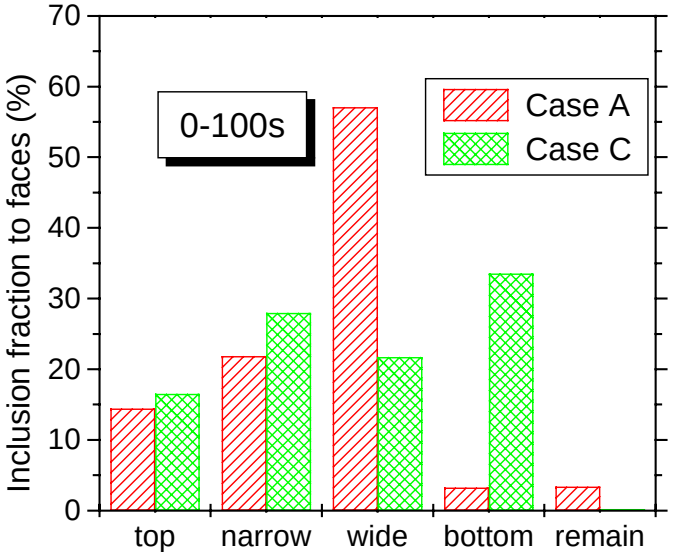
Turbulence model	k-ε, by Fluent
Inclusions number injected	15000
Inclusion motion model	Random walk model, by Fluent
Boundary condition for inclusions	Escape from top surface and open bottom, trapped at narrow and wide face walls

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

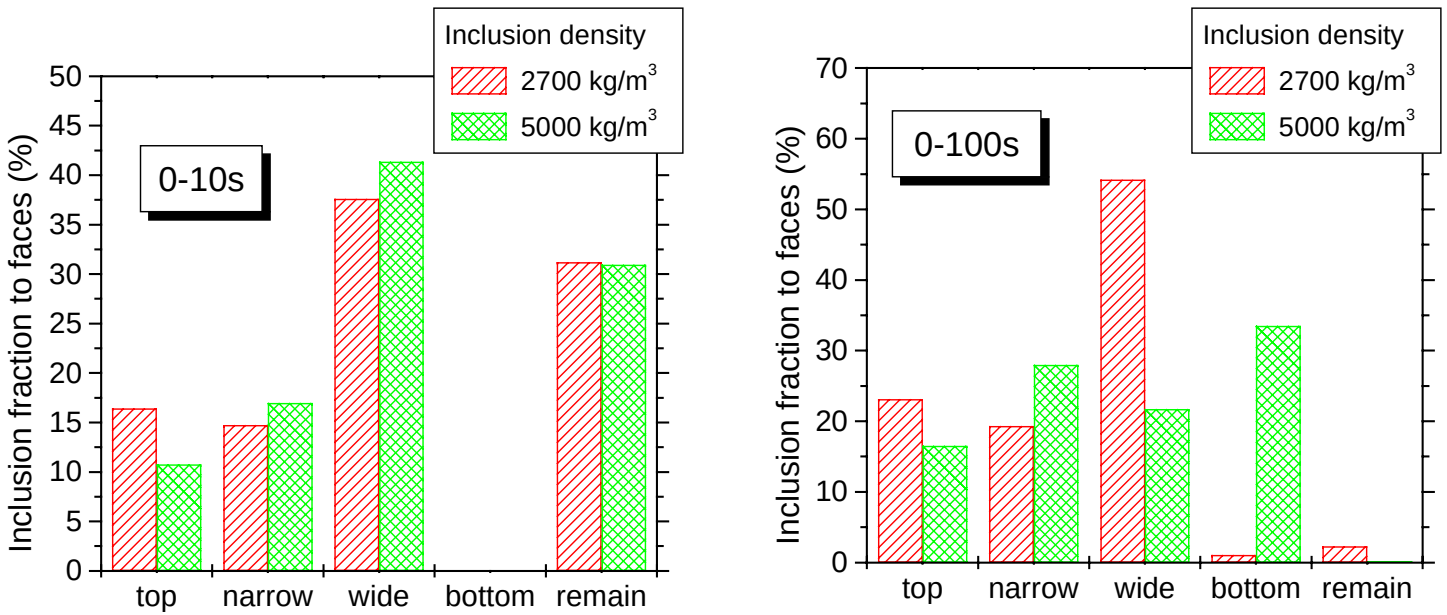
Inclusions density: 5000 kg/m^3





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 Inclusion Removal



Case A

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

The Accuracy of the Similarity Criterion of Stokes Velocity for the Particle Motion in Water and in Liquid Steel

Simulation Parameters for Water System and Steel System

	Water	Liquid Steel
Nozzle port size/ Inlet port size (x×y) (m)	0.051×0.056	0.051×0.056
Nozzle angle	25°	25°
Inlet jet angle	25°	25°
Submergence depth (m)	0.150	0.150
Mold/Domain height (m)	2.152	2.152
Mold/Domain width (m)	1.83	1.83
Mold/Domain thickness (m)	0.238	0.238
Average inlet flow rate (m^3/s)	0.00344	0.00344
Casting speed (m/s)	0.0152	0.0152
Fluid density (kg/m^3)	998	7020
Fluid kinetic viscosity (m^2/s)	1.0×10^{-6}	0.954×10^{-6}
Inlet condition	LES pipe simulation results[1]	

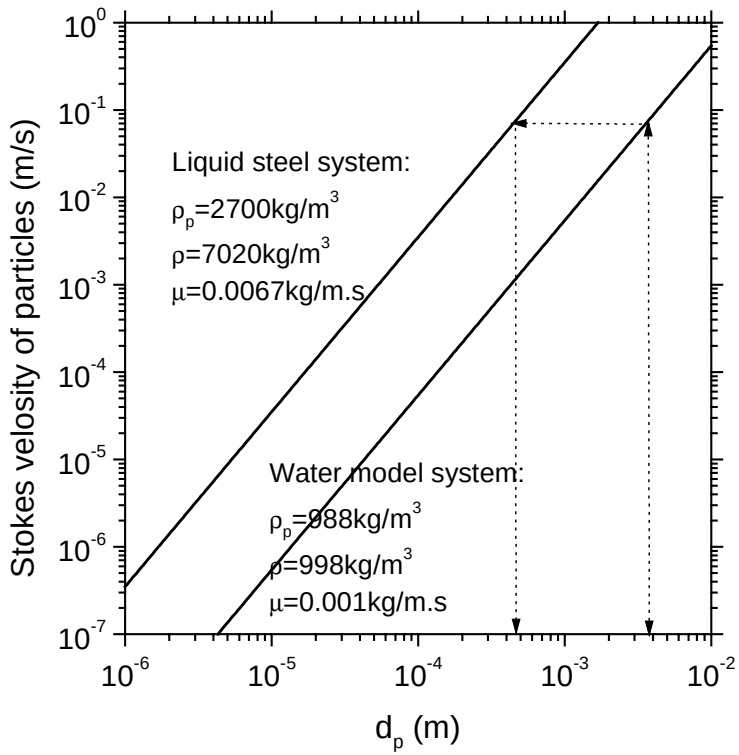
[1] Yuan, Q., S.P. Vanka, and B.G. Thomas. *Large Eddy Simulatios of Turbulence Flow and Inclusions Transport in Continuous Casting of Steel*. Turbulence and Shear Flow Phenomena Second International Symposium, June 27-29. 2001: KTH, Stockholm

Model and Parameters for Water System and Steel System

Turbulence model	k-ε, by Fluent
Inclusions number injected	15000
Inclusion motion model	Random walk model, by Fluent
Boundary condition for inclusions	Escape from top surface and open bottom, reflected off walls

	Steel Caster	Water Model
Mold Geometry	Same (The previous water model case)	
Outlet	Two holes on lower part of one wide face	
Viscosity (m^2/s)	0.954×10^{-6}	1.0×10^{-6}
Particle size	473 μm, 300 μm, 200 μm	3.8mm
Particle density (kg/m^3)	2700	988

Particle Stokes Terminal Rising Velocity in Liquid



$$V_s = \frac{(\rho - \rho_P) d_P^2}{18\mu} g$$

V_S: Stokes velocity, m/s

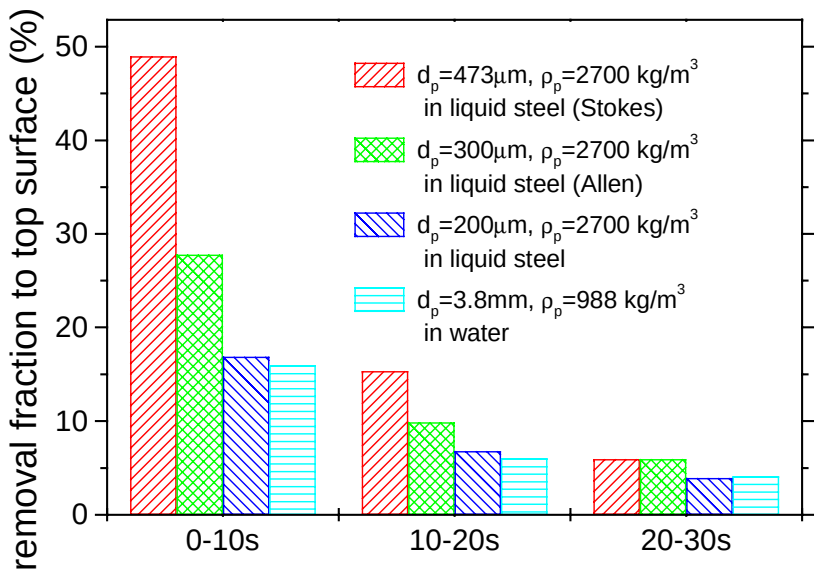
ρ, ρ_p, liquid and particle density, kg/m^3

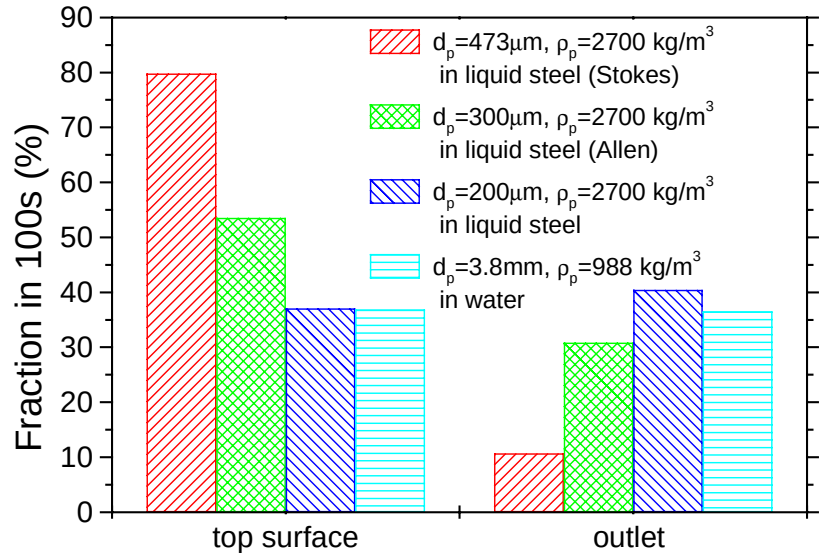
d_p, particle diameter, m

μ, liquid viscosity, kg/m.s

g, gravitational acceleration, m/s^2

Comparison of Particle Removal in Water Model and Liquid Steel





The removal fraction of the 200μm inclusion in liquid steel is almost similar with the mentioned 3.8mm particle in water model.

Conclusions

1) Of inclusions entering nozzle, 31% collide with nozzle surfaces (18% with SEN walls, 4% with bottom, 9% with port walls).

2) For the inclusions smaller than 50 μm, the fraction to the top surface is independent of inclusion size, and this fraction is around 6%. For the inclusions larger than 50 μm, their removal to top surface increases with increasing size.

3) Inclusion fraction captured by the wide and narrow face is independent of inclusion size.

4) 28% of inclusions are captured by narrow face, and 22% are captured by wide face.

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

6) The current entrapment model at the walls overpredicts inclusion removal.

7) Standard similarity criteria for particle motion in water model and in liquid steel (Stoke and Allen) are not accurate enough.

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.