ANNUAL REPORT 2006

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Asymmetric Fluid Flow and Particle Entrapment in the Nozzle and Mold

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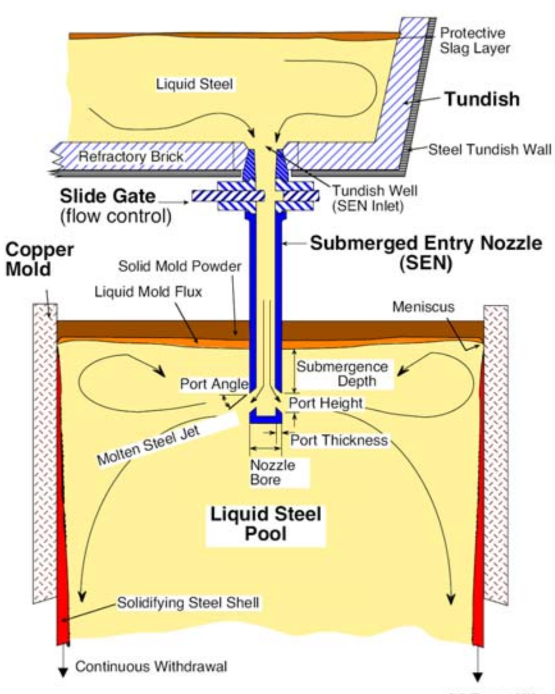
Acknowledgements

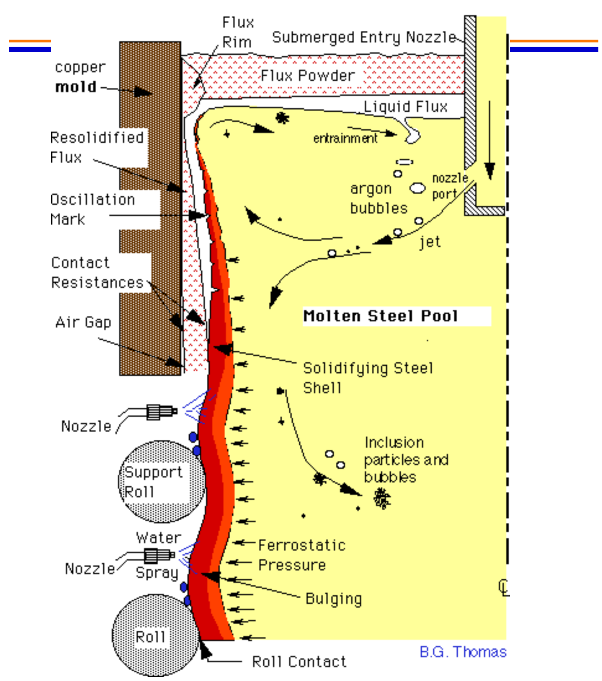
- Continuous Casting Consortium Members at University of Illinois at Urbana-Champaign
- Fluent, Inc.
- Jun Aoki, Bret Rietow, Claudio Ojeda, Liefeng Zang, Quan Yuan, Gogi Lee

Outline

- Part 1: Flow Asymmetries
  - Background and Importance
  - Objectives
  - Validation
  - Results (Asymmetries encountered due to various reasons)
  - Conclusions and Future Work

- Part 2: Flow in Mold (with shell) and Particle Entrapment in Nozzle and Mold
  - Background and Importance
  - Objectives
  - Results
    - Mold flow validation
    - Particle Entrapment Model
    - Particle Transport and Entrapment in Mold simulation
  - Conclusions and Future Work

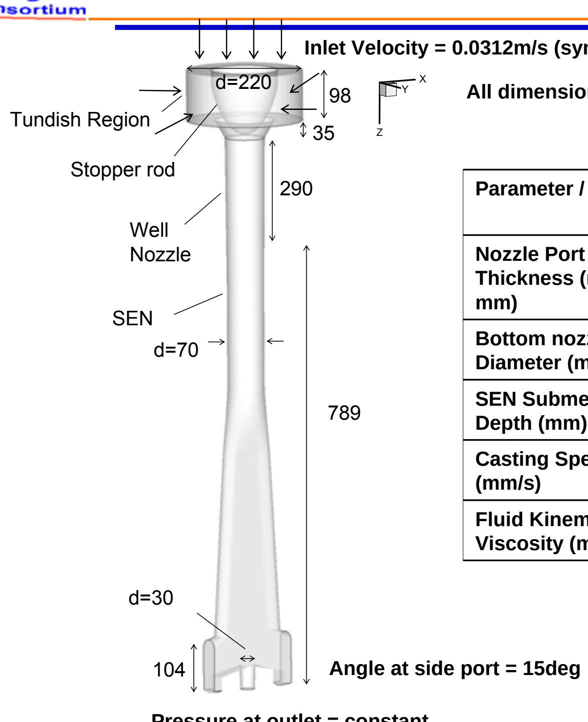




Objectives Part 1

- Validate $(k-\varepsilon)$ model with LES time averaged results for nozzle
- Investigate various causes of asymmetric fluid flow in a tundish nozzle, including:
  - Asymmetric flow entering the nozzle from tundish
  - Asymmetric flow due to the presence of slide gate
  - Asymmetric flow cased by various types of nozzle clogs
- Introduce Asymmetric flow in the mold with no shell

Model Formulation (validation)

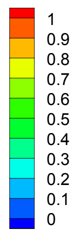


All dimensions are in mm

Parameter / Property	Value
Nozzle Port Height x Thickness (mm x mm)	75 x 32 (inner bore)
Bottom nozzle Port Diameter (mm)	32
SEN Submergence Depth (mm)	127
Casting Speed (mm/s)	25.4
Fluid Kinematic Viscosity (m2/s)	7.98×10^{-7}

Validation Nozzle

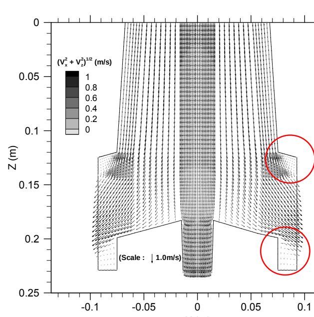
	Left Port outlet	Right Port outlet
Average Velocity (Jet speed) (m/s)	**0.68**	**0.675**
Angle with the X-axis (deg)	**33.76**	**33.08**
Back Flow Zone Fraction	**0.092**	**0.094**



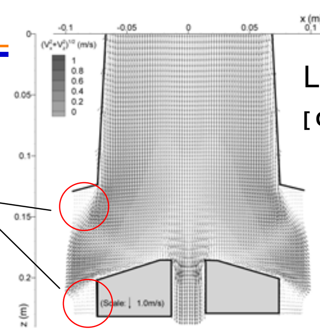
Front View **Side View**

Validation Nozzle

$(k-\varepsilon)$

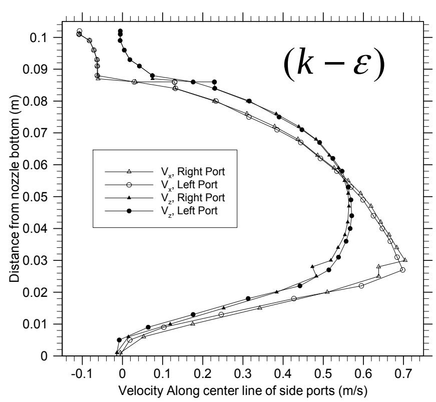


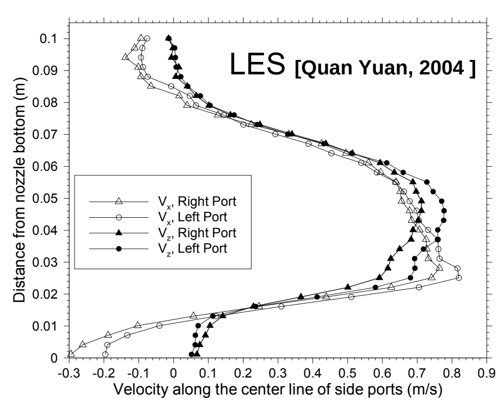
Back Flow Zones



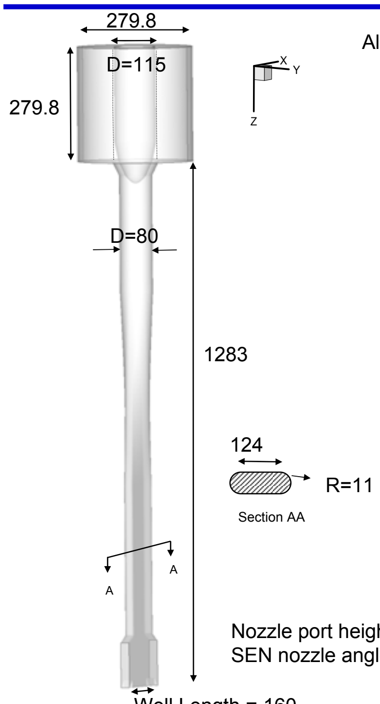
LES

[Quan Yuan, 2004]

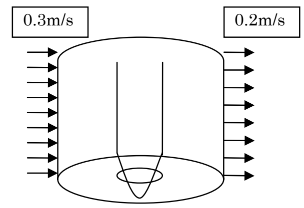




Asymmetry Caused by Flow in Tundish



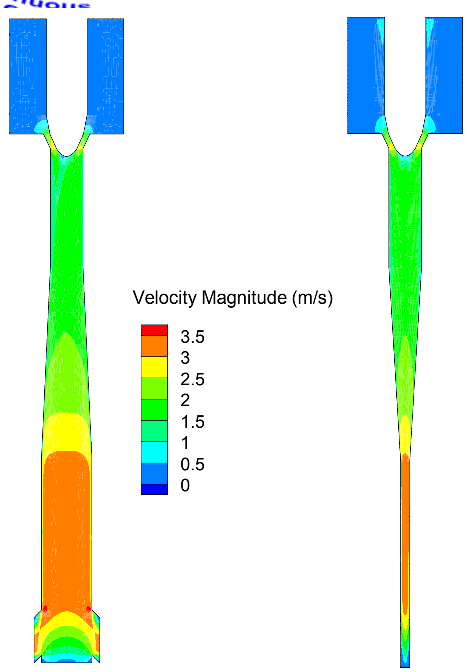
All dimensions are in mm



Asymmetric velocity at the inlet of tundish region modeled

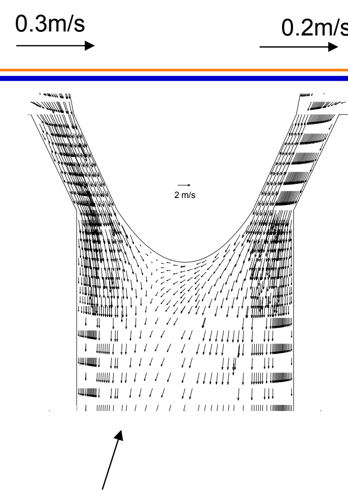
Nozzle port height x thickness (mm X mm) =110 X 22
SEN nozzle angle at side port = 45 deg

Asymmetry Caused Near Stopper Rod

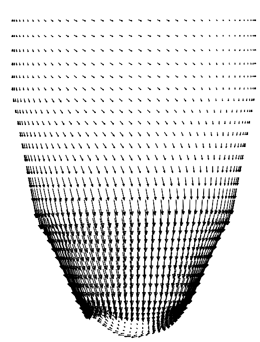


Front View

Side View

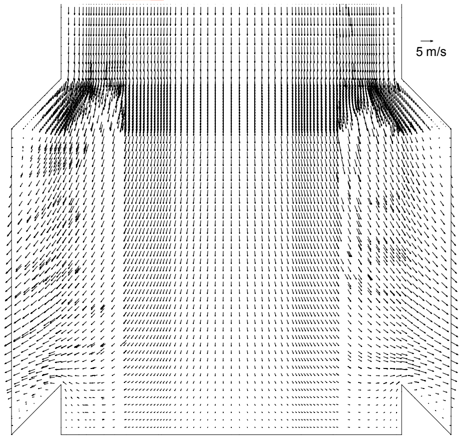


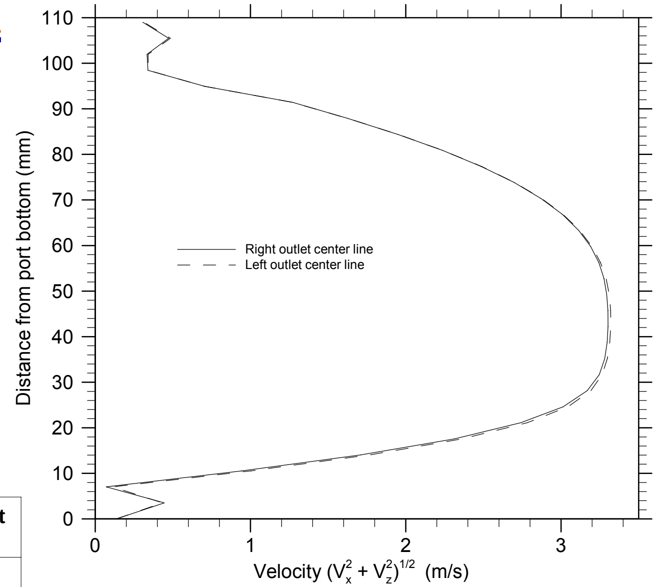
Why shift towards the left ?



Flow goes around the cylindrical portion of the stopper rod and more enters from the right side

Velocity at Nozzle Bottom





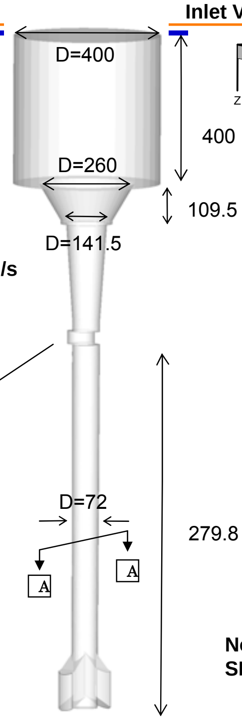
	Left Port outlet	Right Port outlet
Average Velocity (Jet speed) (m/s)	**2.56**	**2.55**
Angle with the X-axis (deg)	**31.15**	**30.69**
Back Flow Zone Fraction	**13.3**	**13.3**

Conclusion:

Asymmetric flow across tundish bottom does not appear to cause significant time-average flow asymmetry

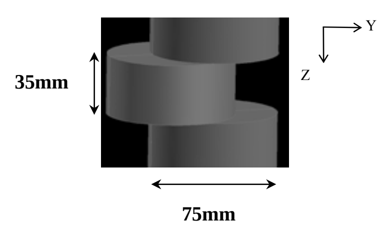
Asymmetry Caused by Slide Gate

Inlet Velocity = 0.014m/s (symmetric velocity)



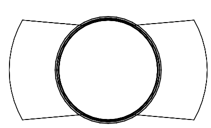
Mass Flow Rate = 61.6kg/s

Slide Gate



Slide Gate

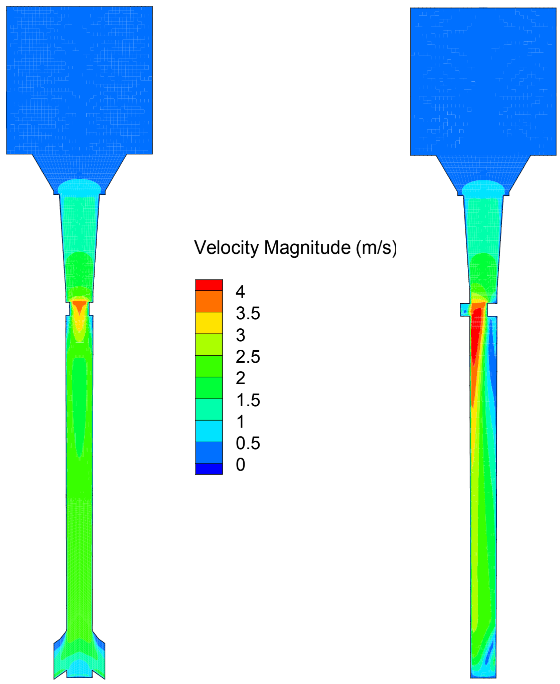
All dimensions are in mm



Section A-A

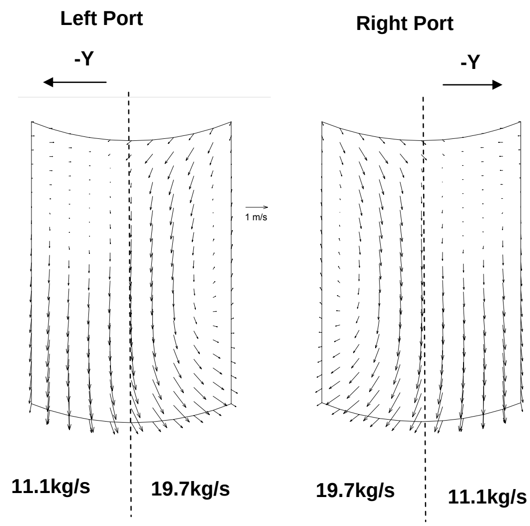
Nozzle port height x thickness (mm X mm) =98 X 70
SEN nozzle angle at side port = 35 deg

Asymmetry Caused by Slide Gate



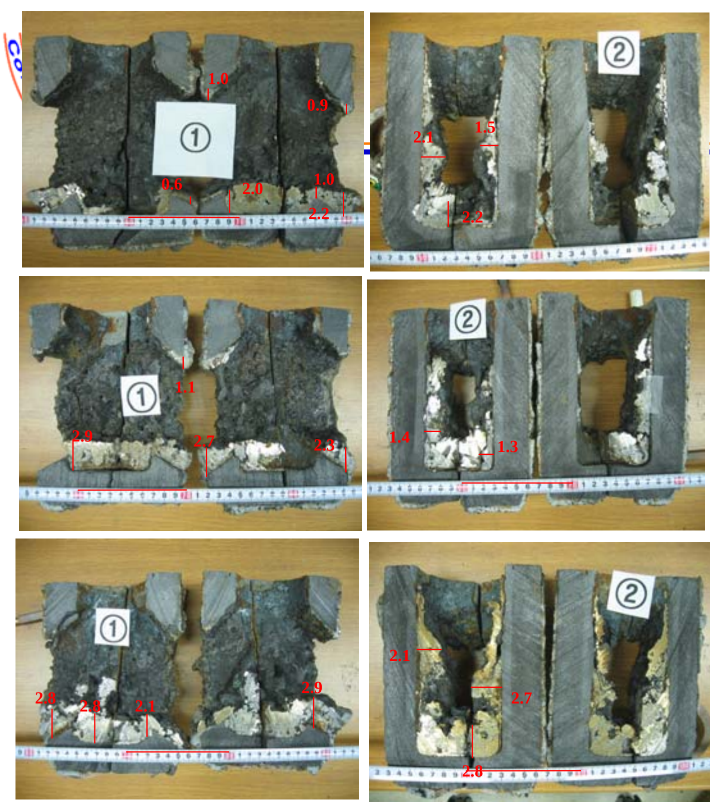
Front View

Side View

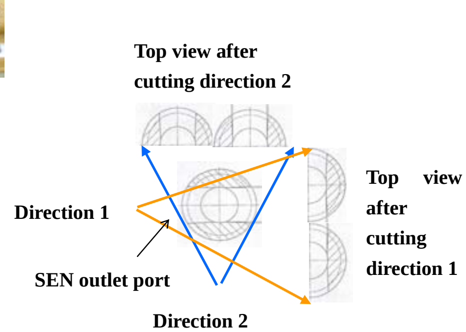


Asymmetry within each port

Cut Section of Nozzle Bottom to see Clog Shapes

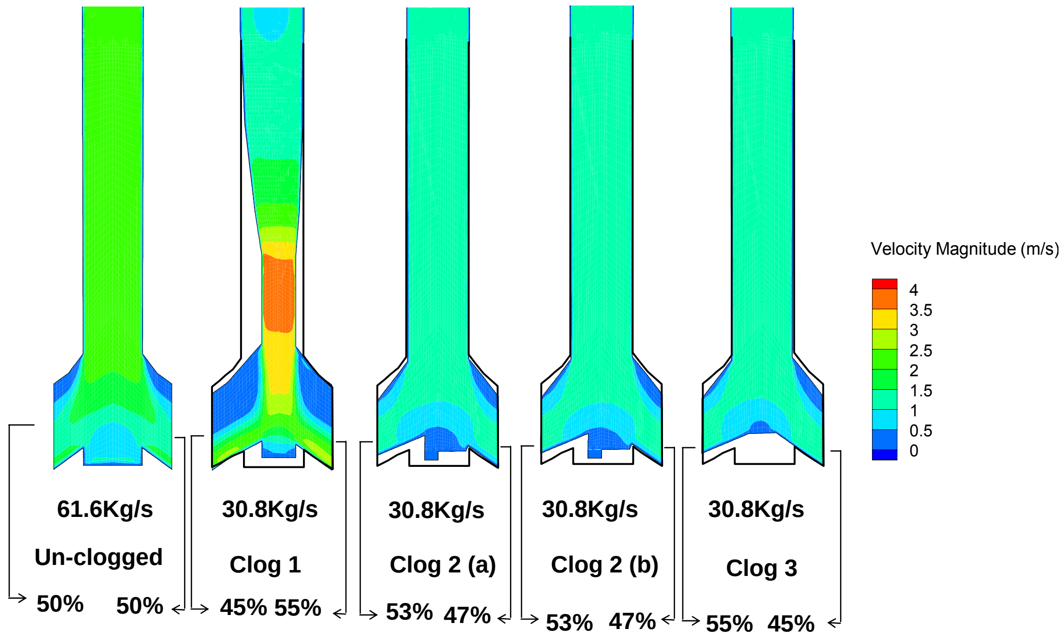


Cut sections measured for 3 nozzles by Gogi Lee, 2005

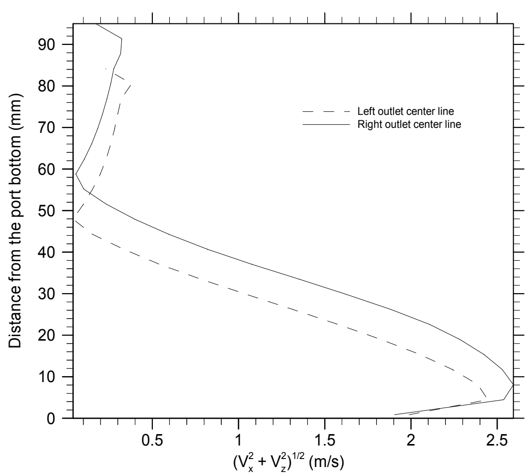


All dimensions on pictures are in cm

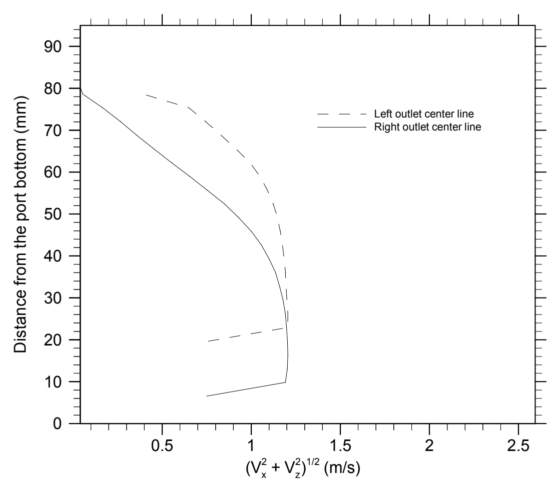
Asymmetry Due to Clogging



Velocity Magnitude at Ports



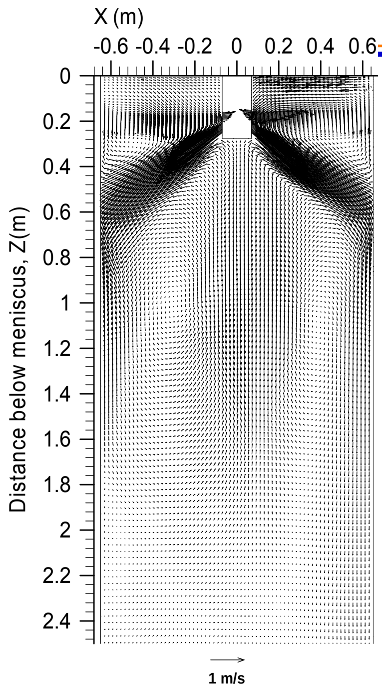
Clog 1



Clog 3

Velocity Magnitude on centerline of Left and Right outlet ports for two different clog shapes

Asymmetry in Mold (no shell)

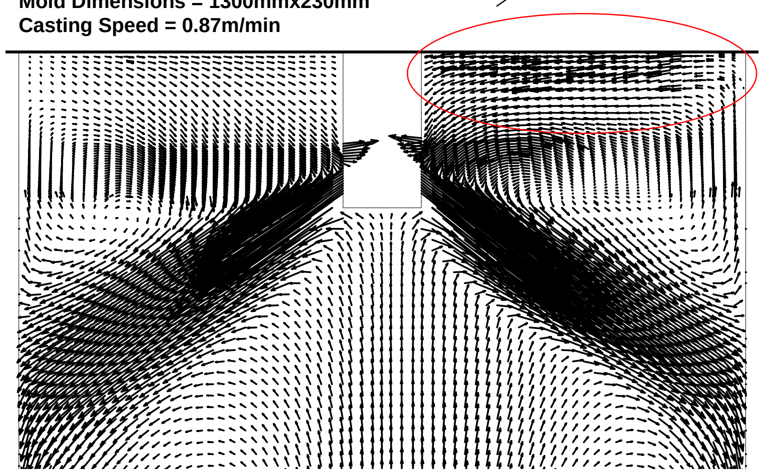


Velocity vectors in plane mid way between wide faces

Velocity from the outlet of Clog shape 1 was placed as the inlet velocity at mold inlet

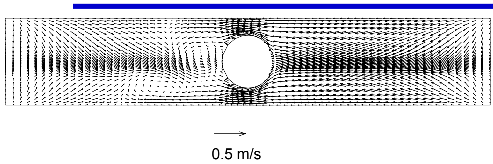
Increased Velocity at the right side

Mold Dimensions = 1300mmx230mm
Casting Speed = 0.87m/min



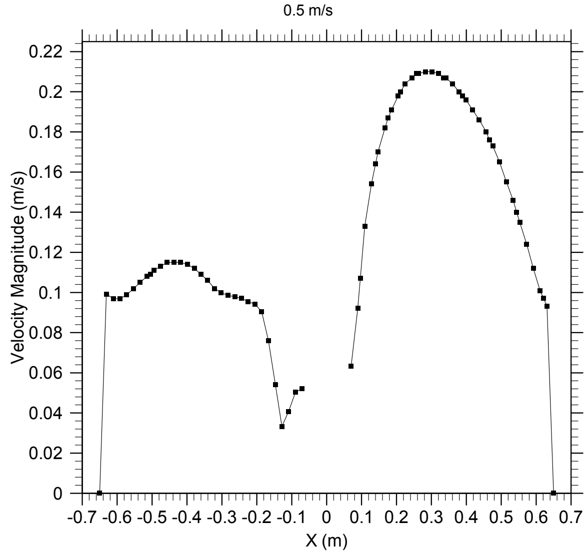
Enlarged View of the Top section of mold

Surface Velocity



30.8Kg/s

See generation of vortexes on the left side of the mold



Note: asymmetric flow from a clogged bore causes 2X velocity across top surface

Conclusions (Part 1)

- The averaged flow results from LES agree reasonably with results from k-ε model
- Although asymmetry in the tundish does not cause asymmetry at the outlet ports, it increases the likelihood of asymmetric clogging near the nozzle top
- The asymmetry due to the 90deg slide gate orientation causes high swirling within each port, and encourages asymmetric flow at outlet towards the opposite mold wide face
- Clogging of the bore (clog 1) reduces port utilization significantly
- Asymmetry between left and right ports increases with increasing severity of clogging of the well region (Clog 3)
- Clogging causes severe asymmetry across the top surface of the mold (2X velocity difference between sides)

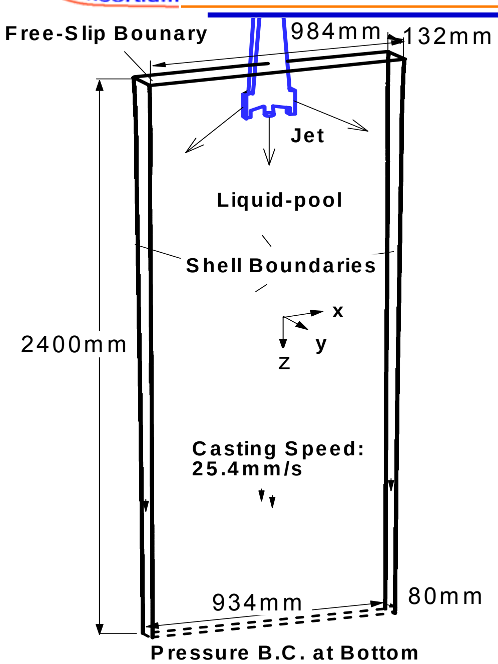
Part 2: Particle Entrapment in Nozzle and Mold

- Particle transport and entrapment are an important phenomenon during continuous casting of steel affecting the steel quality
- Entrapped inclusions cause defects such as internal cracks and blisters in the final product
- The inclusions are carried by the steel jets entering the mold and can either be removed by the top liquid slag layer or can be trapped by the solidifying dendrite arms
- Behavior of transport of particles within the mold depends highly on their size and density
- Entrapment of particle depends on the forces present upon it when close to the dendrite arms

Objectives Part 2

- Validate flow in the mold (with shell) obtained from $(k-\varepsilon)$ model with LES time averaged results
- See where inclusions are trapped inside the nozzle to cause clogging
- See how varying casting parameters can affect particle capture based on the entrapment model developed
- See how particle trajectories are affected with variation in particle size and density
- Add capture criterion at the boundary of the mold as boundary condition in the simulation

Mold Flow Validation

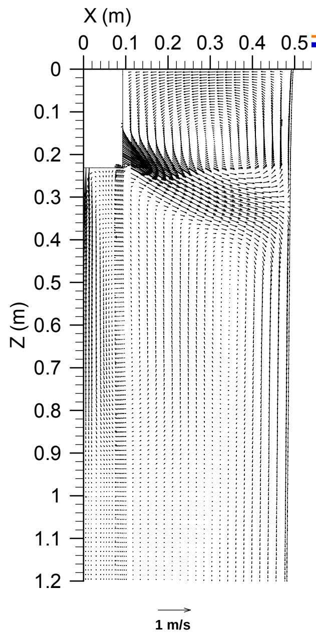


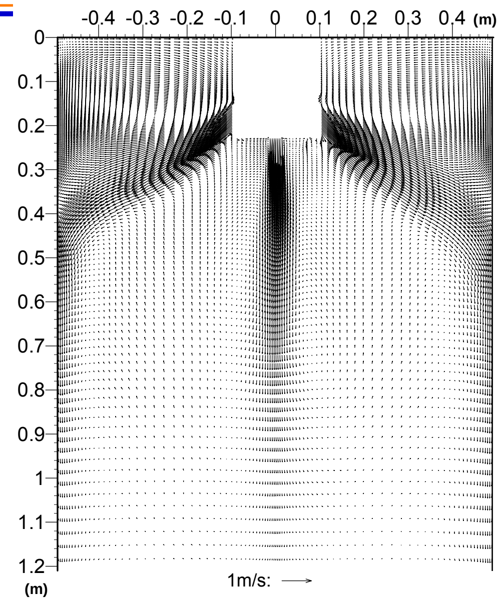
[Quan Yuan, 2004]

Parameter/Property	*Case 2-S*
Mold Width (mm)	**984**
Mold Thickness (mm)	**132**
Domain Width (mm)	**984 (top)** **934.04 (domain bottom)**
Domain Thickness (mm)	**132 (top)** **79.48 (domain bottom)**
Domain Length (mm)	**2400**
Nozzle Port Height × Thickness (mm × mm)	**75 × 32 (inner bore)**
Bottom nozzle Port Diameter (mm)	**32**
SEN Submergence Depth (mm)	**127**
Casting Speed (mm/s)	**25.4**
Fluid Kinematic Viscosity (m^2/s)	**7.98×10^{-7}**

- Negative Source terms added to mass and momentum equations in Fluent (by writing user defined functions) to model fluid extraction due to solidification down the mold

Velocity vectors in plane mid way b/w wide faces (Mold Validation)



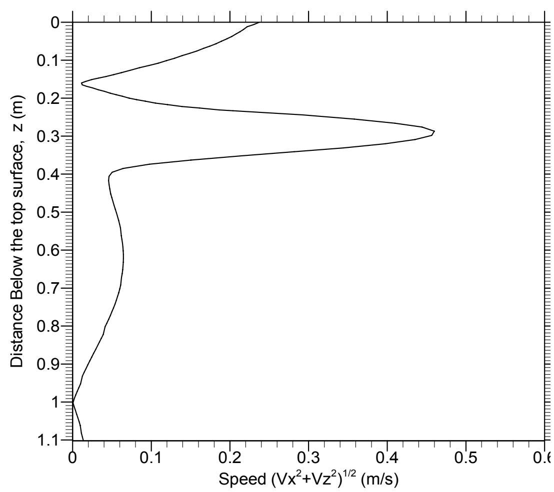


Velocity vectors obtained for half mold $(k-\varepsilon)$

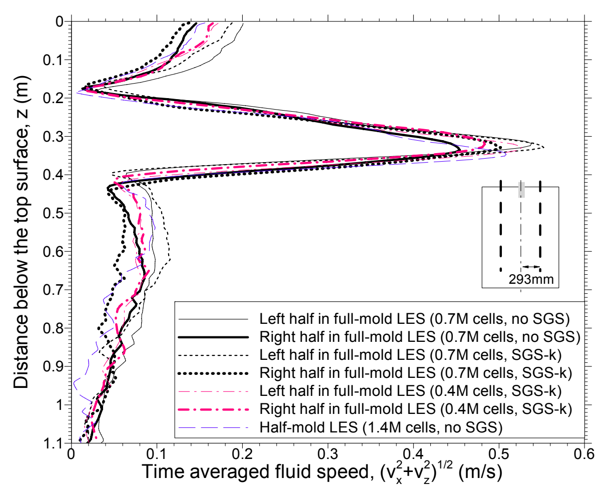
Time averaged velocity vectors obtained for full mold (LES)

[Quan Yuan, 2004]

Velocity down the mold on a line 293mm from the center (validation)



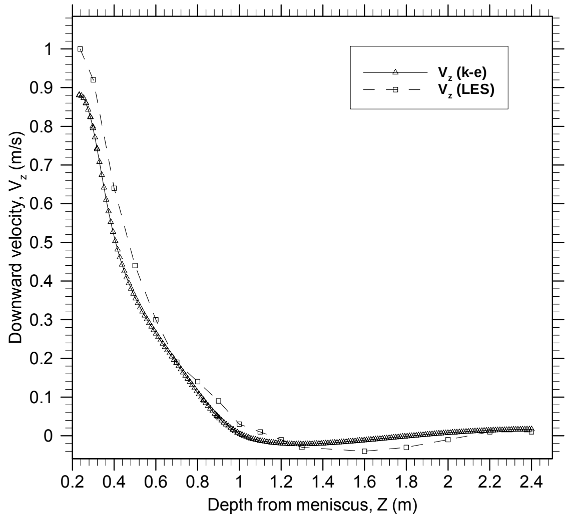
$(k-\varepsilon)$



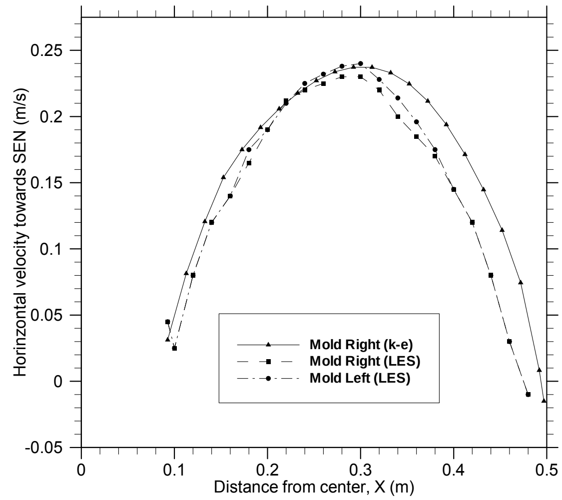
LES [Quan Yuan, 2004]

Validation (cont.)

Velocity along center jet center line

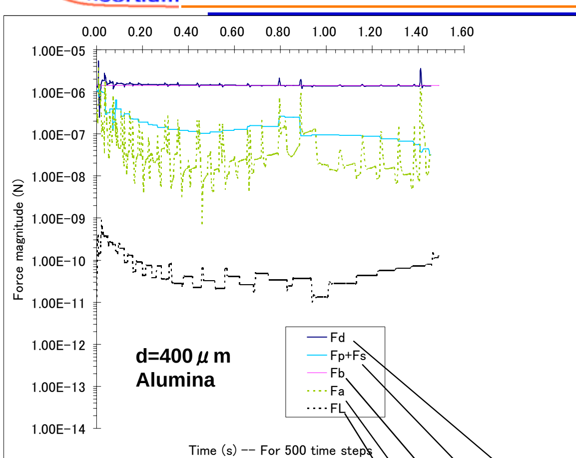


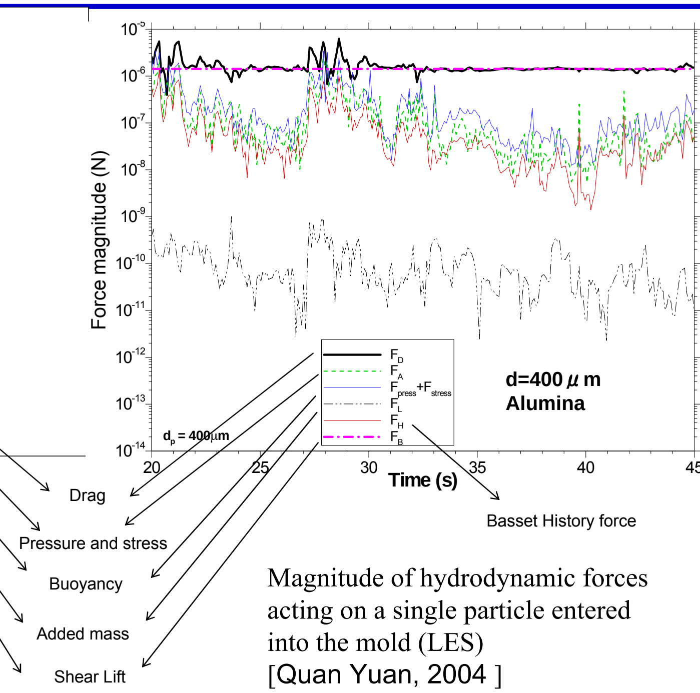
Horizontal velocity towards SEN



LES results obtained by
[Quan Yuan, 2004]

Particle Transport (validation of Hydrodynamic Forces acting)



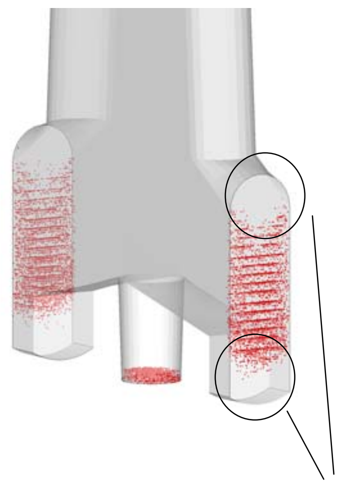


Magnitude of hydrodynamic forces acting on a single particle entered into the mold $(k-\varepsilon)$

Magnitude of hydrodynamic forces acting on a single particle entered into the mold (LES)
[Quan Yuan, 2004]

Particles trapped on nozzle walls

Validation nozzle introduced in Part 1



No particles coming out from the recirculation regions

Stochastic Random walk method used

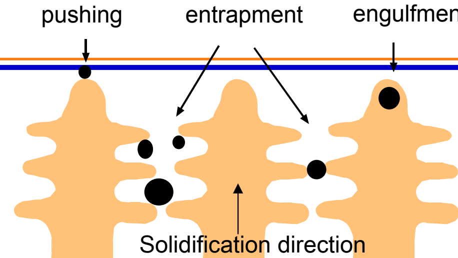
20,000 particles randomly distributed at the inlet of tundish region:
500 particles, diameter 10μm, density 5000kg/m^3
500 particles, diameter 40μm, density 5000kg/m^3
500 particles, diameter 10μm, density 2700kg/m^3
500 particles, diameter 40μm, density 2700kg/m^3

Particles are trapped as they touch the walls - 39% particles are trapped at the walls

Most particles are trapped near in the middle of well nozzle and at the bottom of SEN – These are potential clogging areas

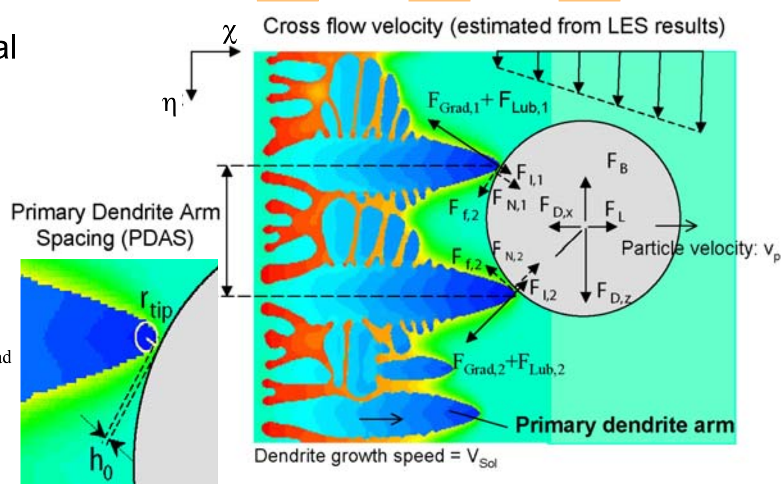
Particle Capture by Dendritic Interface

particle pushing and capture by engulfment and entrapment.



Forces acting on a spherical particle close to dendritic front of mushy-zone:

Buoyancy: F_B
Drag force: $F_{D\chi}$ and $F_{D\eta}$
Lift force: F_L
Lubrication force: F_{Lub}
Van der Waals force: F_I
Concentration Gradient force: F_{Grad}
Reaction force: F_N
(Press gradient, stress gradient added mass and Basset forces neglected.)

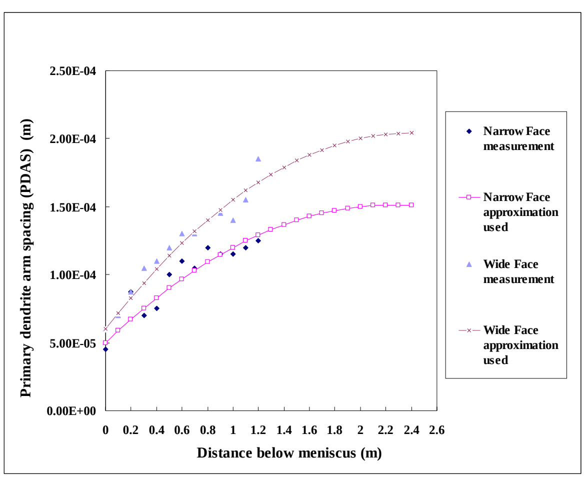


Dendrite shape computed by N. Provatas, N. Goldenfeld, and J. A. Dantzig, 1998.

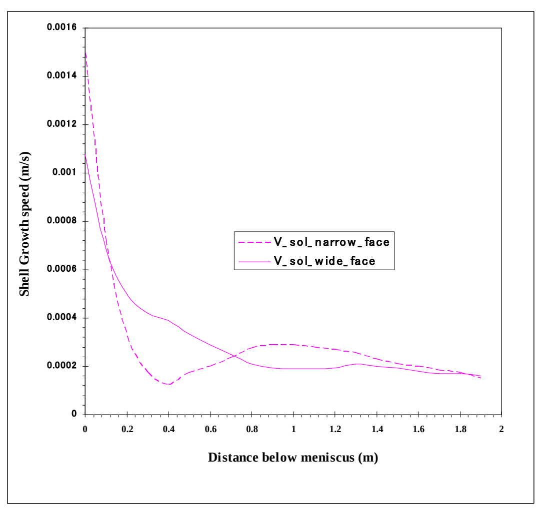
How the Entrapment Model is Incorporated in Fluent

- Particle Entrapment model is incorporated at the mold (with shell) boundaries in Fluent by writing user defined functions
- The η and ℵ directions are evaluated from the solidification front angle and fluid flow direction
  - ℵ is in the direction of the vector normal to the face (boundary) that the particle hits
  - η is in the direction of the component of: sum of buoyancy and flow drag force, lying in the face plane
- Primary dendrite arm spacing (PDAS) varies down the mold length and is incorporated as the function representing the measured PDAS [B.G.Thomas et al, 1998]
- Solidification front velocity also varies down the mold length and is incorporated by using the data obtained from [Quan Yuan, 2003]
- Forces acting on the particles when close to the solidifying front are evaluated
- The entrapment equations (force balance equations) are then used to evaluate the particles fate

Variation of PDAS and solidification front velocity used down the caster



Variation of PDAS down the caster on narrow face and wide face



Variation of solidification front velocity down the caster on narrow face and wide face

Particle Capture Criterion [Quan Yuan, 2004]

Particle contacts a boundary representing mushy-zone front?
- no → Continue
- yes ↓

Particle size larger than PDAS ($d_p \geq$PDAS)?
- no → Capture
- yes ↓

In solidification direction, repulsive force smaller than attractive force?

$$F_L - F_{D,\chi} - 2\left(F_{Lub} - F_{Grad} - F_I\right)\cos\theta < 0$$

- no → Drift back to flow
- yes ↓

Can cross-flow and buoyancy drive particle into motion though rotation?

$$\left(F_{D,\eta} + F_{B,\eta}\right)\cos\theta + \left(F_L - F_{D,\chi}\right)\sin\theta > \left(F_{Lub} - F_{Grad} - F_I\right)\sin 2\theta$$, if $F_{D\eta}$ and $F_{B\eta}$ in same direction

or

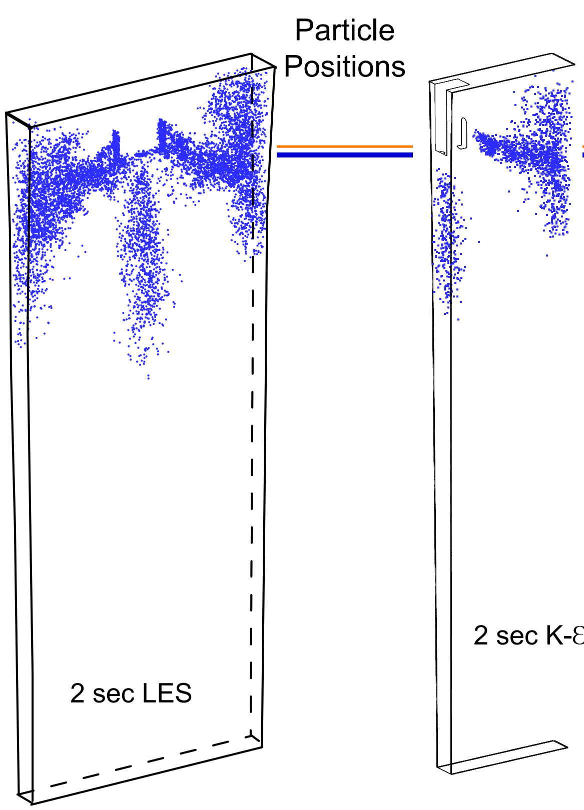
$$\left(F_{D,\eta} - F_{B,\eta}\right)\cos\theta + \left(F_L - F_{D,\chi}\right)\sin\theta > \left(F_{Lub} - F_{Grad} - F_I\right)\sin 2\theta$$, if $F_{D\eta}$ and $F_{B\eta}$ in opposite direction and $F_{D\eta} \geq F_{B\eta}$

or

$$\left(F_{B,\eta} - F_{D,\eta}\right)\cos\theta + \left(F_L - F_{D,\chi}\right)\sin\theta > \left(F_{Lub} - F_{Grad} - F_I\right)\sin 2\theta$$, if $F_{D\eta}$ and $F_{B\eta}$ in opposite direction and $F_{D\eta} < F_{B\eta}$

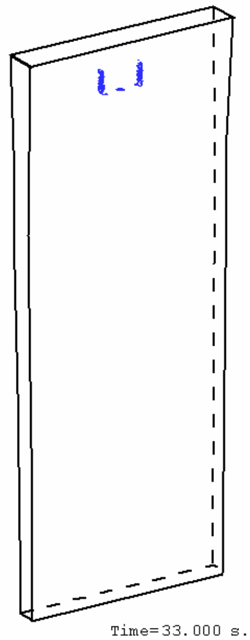
- yes → Drift back to flow
- no → Capture

LES: 40,000 particles were introduced into the mold in 9sec
- •500 particles, diameter 10µm, density 5000kg/m^3
- •500 particles, diameter 40µm, density 5000kg/m^3
- •500 particles, diameter 10µm, density 2700kg/m^3
- •500 particles, diameter 40µm, density 2700kg/m^3



[Quan Yuan, 2004]

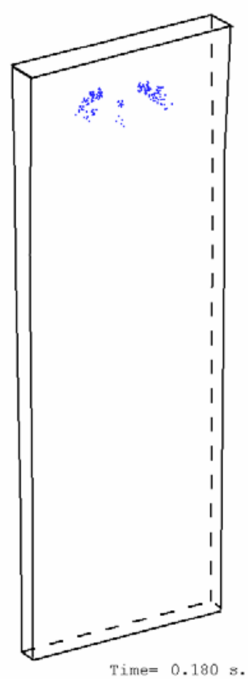
Small particles



[Quan Yuan, 2004]

100um Particles

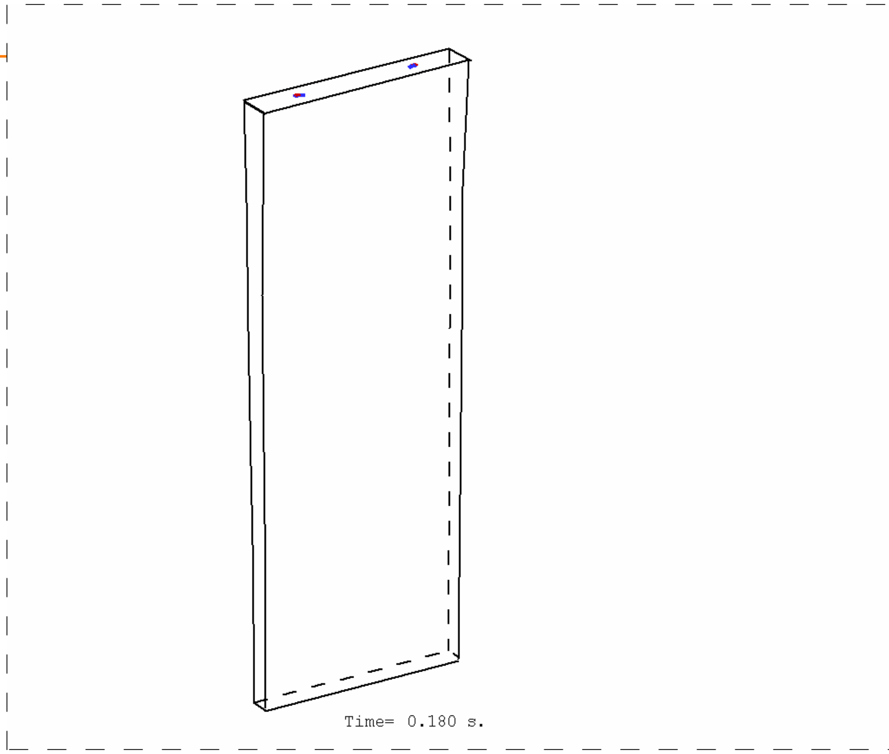
10,000 particles of 100μm diameter introduced into the domain from the nozzle ports (LES) [Quan Yuan]



[Quan Yuan, 2004]

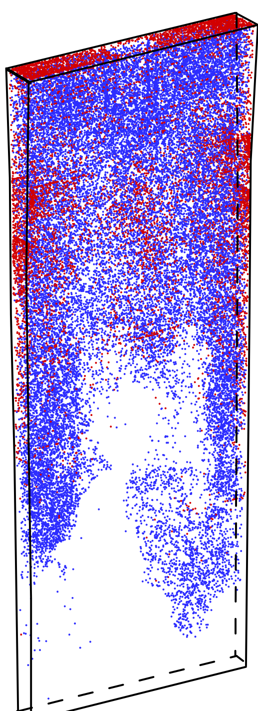
Slag Entrainment

4000 slag particles of 100µm diameter introduced into the domain from the top surface (LES) [Quan Yuan]

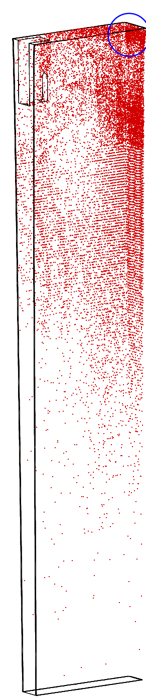


[Quan Yuan, 2004]

Particles Trapped (Red dots show the position of trapped particles)



Particles trap once they touch the boundary



~ 3% getting trapped at the top narrow face in K-Ɛ model not present in LES

8% reach the top surface

LES

3.5% reach the top surface

K-Ɛ

[Quan Yuan, 2004]

Particle capture: parameters investigated

- Particle diameter
- Particle density
- Primary dendrite arm spacing (PDAS)
- Sulfur concentration
- Dendrite tip radius (rd)
- Solidification front velocity (Vsol)
- Solidification front angle: angle of solidifying shell (wall) with the horizontal (ø)
  (decreases with distance below meniscus and with decreasing machine radius)

- Plots are made for critical cross-flow velocity in
  - Horizontal direction
  - Vertical direction (up and down)

- Fluid velocity across the dendrite tips with magnitude exceeding “critical cross-flow velocity” will prevent particle capture

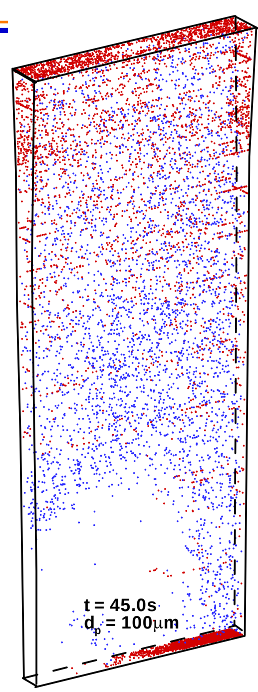
Diameter = 100μm, Alumina particles entering from nozzle outlet

Red dots show the position of trapped particles

10,000 particles in full mold

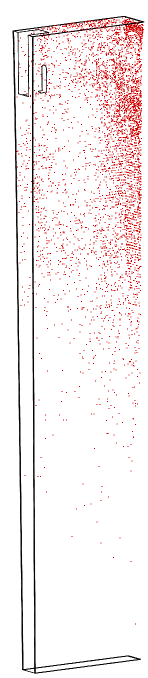
12.58% reach the top surface

LES



[Quan Yuan, 2004]

Particles are trapped based on the entrapment model



5,000 particles in half mold

4.62% reach the top surface

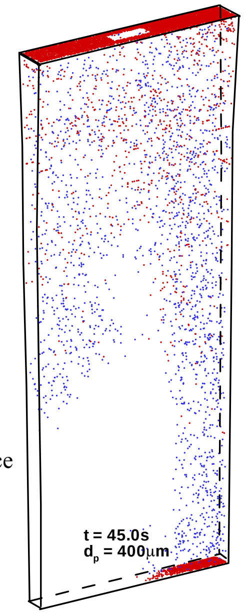
K-ε

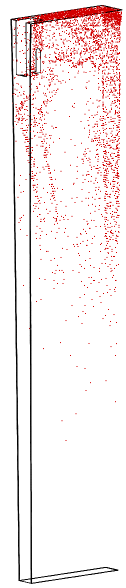
Diameter = 400μm, Alumina particles entering from nozzle outlet

10,000 particles in full mold

69.89% reach the top surface

LES





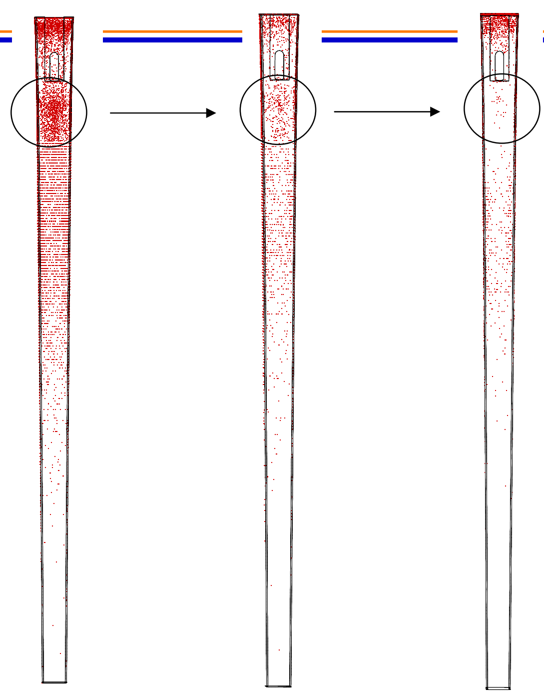
5,000 particles in half mold

25.5% reach the top surface

K-Ɛ

[Quan Yuan, 2004]

Particles Trapped on Narrow Face (K-Ɛ)



Diameter=10μm and 40μm Diameter=100μm Diameter=400μm

- Number of Particles Entrapped in the encircled region (where Jet hits the wall) reduces with increasing particle diameter
- Number of particles being trapped on the narrow face reduces

Analysis (K-Ɛ)

Size (400um)	Particles removed by top surface (K-Ɛ)
Argon (Density ≃ 0 kg/m^3)	41.00%
Alumina (Density ≃ 2700 kg/m^3)	25.50%
Slag (Density ≃ 5000 kg/m^3)	12.84%

Alumina (Density = 2700 kg/m^3)	Particles removed by top surface (K-Ɛ)
100 μm	4.62%
250 μm	11.20%
400 μm	25.50%

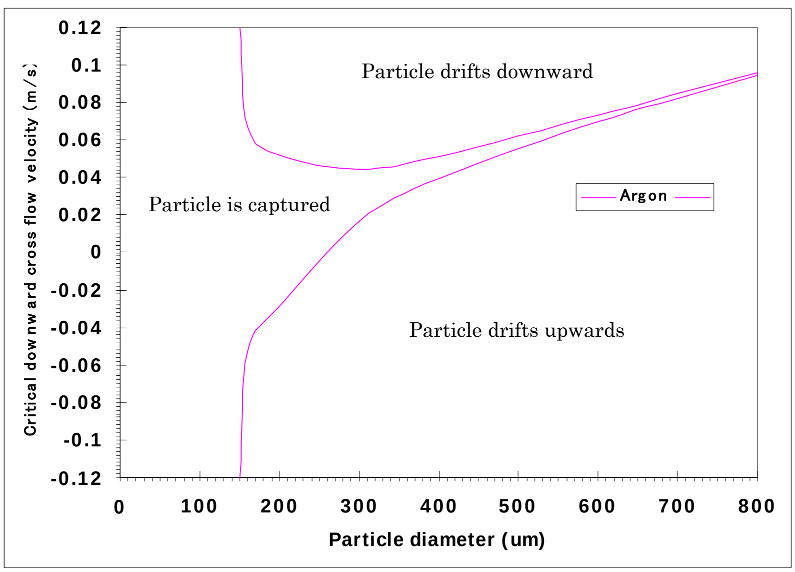
To Investigate more parameters for any mold (Behavior of Particle)

Conditions:

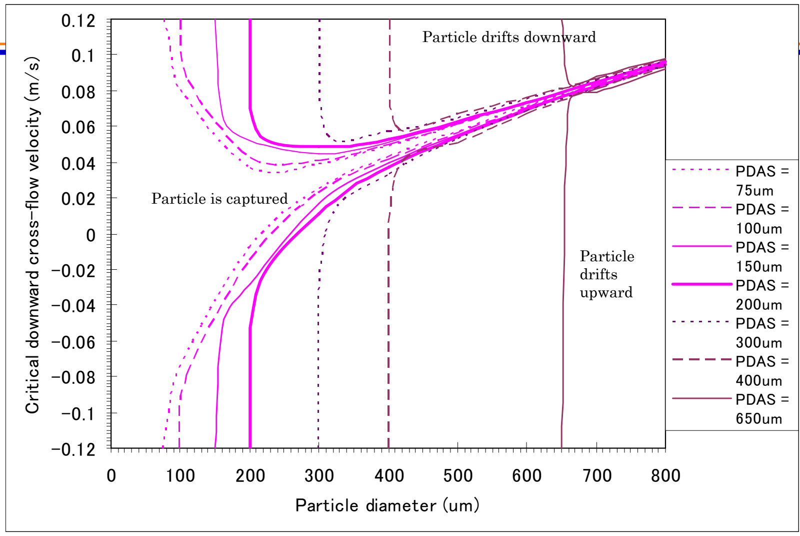
Tip radius = 2.13um

Solidification Velocity = 500um/s

PDAS = 150um



Effect of dendrite arm spacing on bubble capture



Conditions:

Density Argon gas ≃ 0 kg/m3

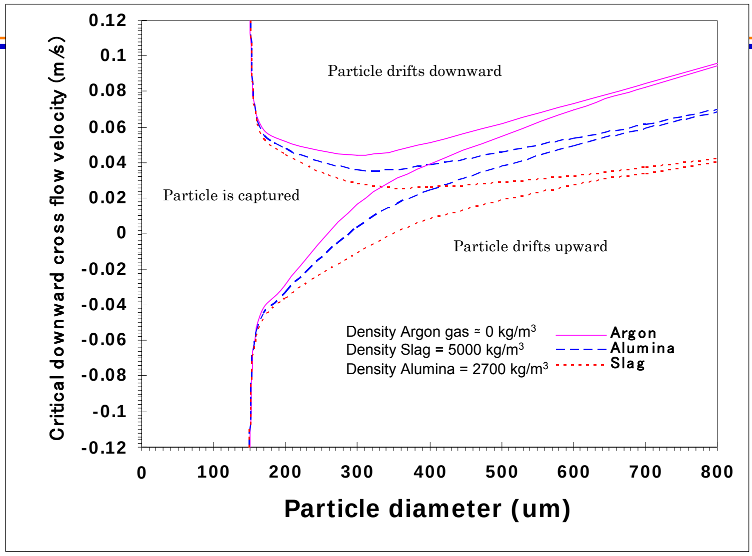
Tip radius = 2.13um

Solidification Velocity = 500um/s

PDAS = 150um

- **Increasing PDAS, tends to capture larger particles**
- **Larger particles are less likely to be captured (capture region is narrower, because they can rotate more easily)**
- **If cross-flow velocity exactly matches buoyancy, then particle is suspended in front of dendritic interface and is eventually captured**

Effect of particle composition on particle capture (Vertical Cross flow velocity)



Conditions:

Tip radius = 2.13um

Solidification Velocity = 500um/s

PDAS = 150um

- **Increasing particle density lowers the buoyancy force**
- **The chances for the particle to drift upwards are less**
- **Large argon bubbles can move upward more easily than slag or alumina, and avoid capture**
- **The fluid velocity "capture window" moves down, but is still significant for all densities**

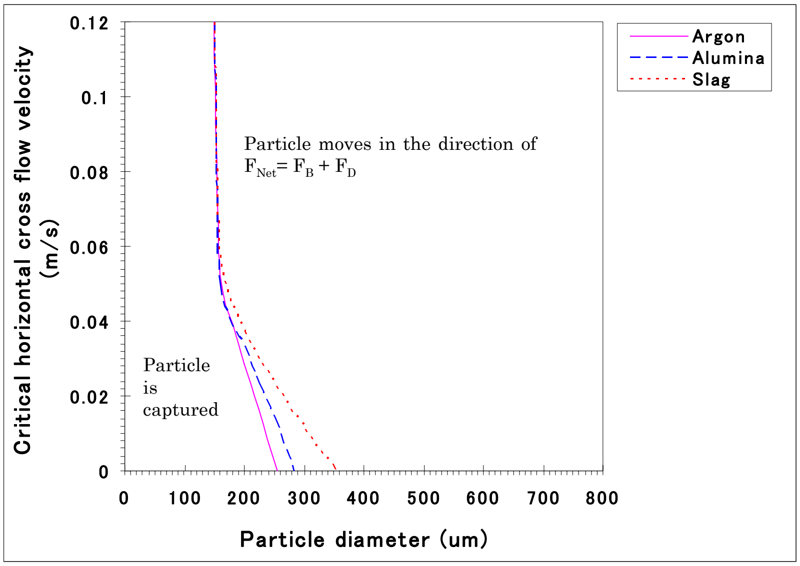
Effect of particle composition on particle capture (Horizontal Cross Flow Velocity)

Conditions:

Tip radius = 2.13um

Solidification Velocity = 500um/s

PDAS = 150um



Effect of steel sulfur content on bubble capture

Conditions:

Density Argon gas ≈ 0 kg/m3

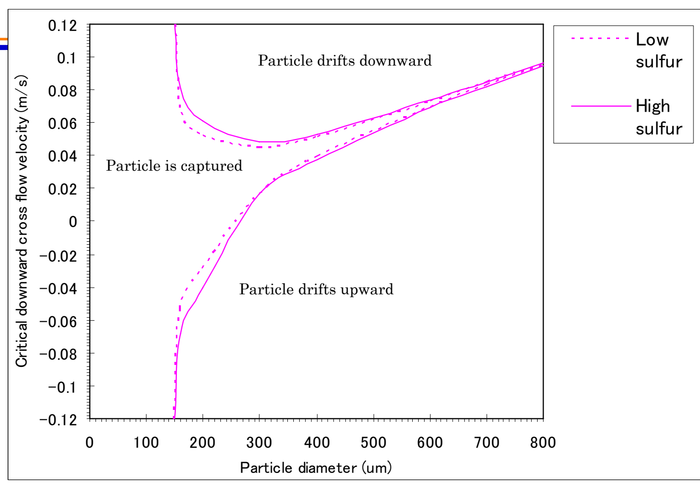
rd = 2.13um

Vsol = 500um/s,

Low sulfur = 0.0028 wt pct

High sulfur = 0.03 wt pct

PDAS = 150um



• Increasing sulfur concentration **increases** the surface gradient force, by lowering surface t ension near the solidification front, due to S rejection during solidification

• Increasing sulfur concentration from 0.0028 to 0.03 wt pct only **slightly increases** particle capture. (capture window expands).

Effect of dendrite tip radius and sol. front velocity

Condition 1:

Density Argon gas ≈ 0 kg/m3

Tip radius = 2.13um

Solidification Velocity = 500um/s

PDAS = 150um

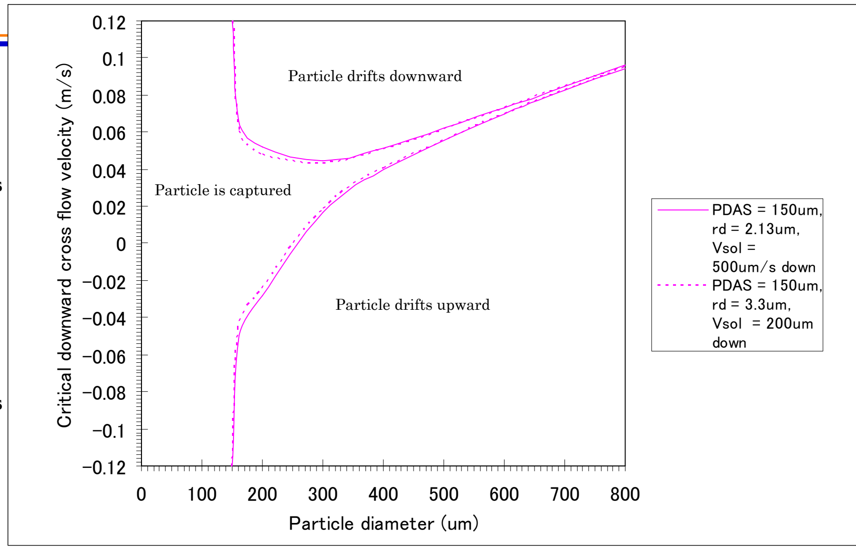
Condition 2:

Density Argon gas ≈ 0 kg/m3

Tip radius = 2.13um

Solidification Velocity = 500um/s

PDAS = 150um



- **Increasing solidification velocity only slightly increases lubrication force**
- **Decreasing dendrite tip radius only slightly increases the surface gradient force**
- **These two parameters together have negligible effect on increasing particle entrapment near top of caster or at higher casting speed**

Effect of solidification front angle on alumina particle capture (inner radius)

Conditions:

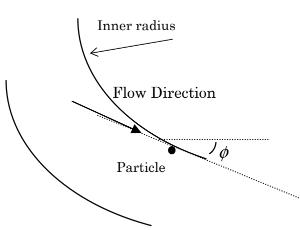
Density Alumina ≈ 2700 kg/m3

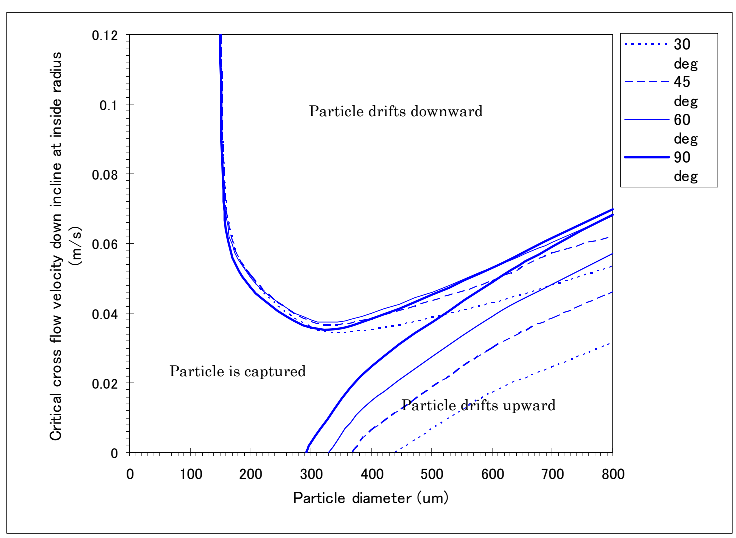
rd = 2.13um

Vsol = 500um/s

PDAS = 150um

Curved mold caster: Inner radius





Particle capture becomes easier on the inner radius with decreasing solidification front angle (ø) (capture window extends to lower flow velocities)

Effect of solidification front angle on alumina particle capture (outer radius)

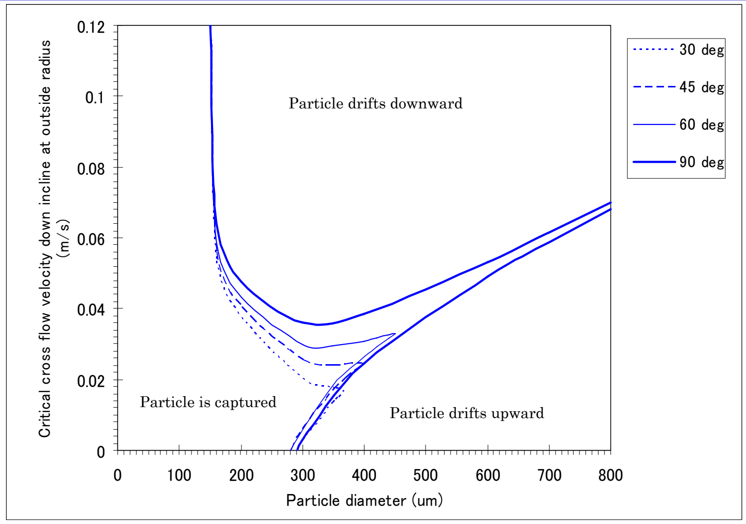
Conditions:

Density Alumina ≃ 2700 kg/m3

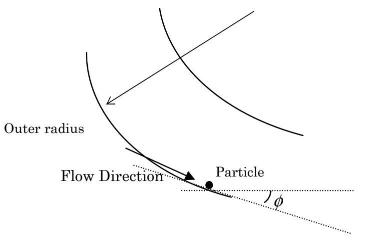
rd = 2.13um

Vsol = 500um/s

PDAS = 150um



Curved mold caster: Outer radius



- **Lowering solidification front angle (ø) (towards horizontal) decreases capture likelihood (particles rotate away more easily)**
- **Critical particle size exists that will avoid capture for any flow condition**

Critical alumina particle size to avoid capture (outer radius)

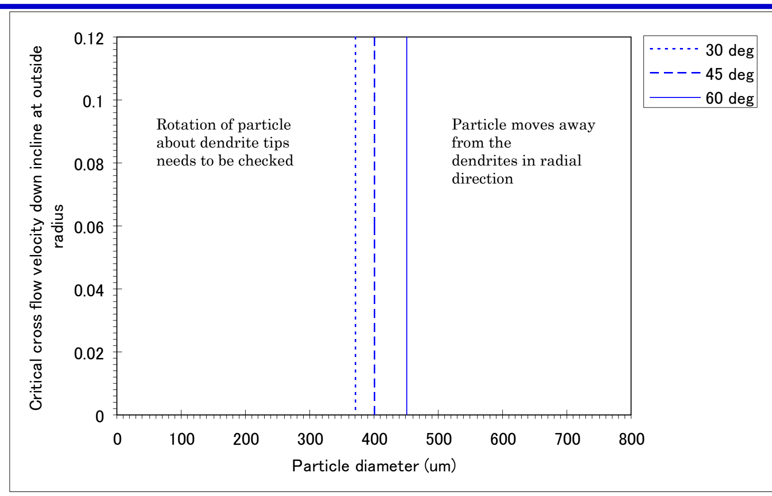
Conditions:

Density Alumina ≃ 2700 kg/m3

rd = 2.13um

Vsol = 500um/s

PDAS = 150um



- **Buoyancy force is high, allowing particles to float upward, away from capture**
- **Smaller particles may still be captured (must check rotation about dendrite tips)**
- **Critical particle diameter exists that always escapes!**

Conclusions

Model Validation

- The k-Ɛ model prediction for steady flow in the nozzle and mold match well with the time averaged results from LES
- Particle transport and entrapment model has been implemented into FLUENT and compared with LES model predictions

Entrapment Model Predictions:

- Increasing primary dendrite arm spacing has the most important effect increasing particle capture: small particles are always captured when they touch the solidification front
- Particle composition (density: bubble vs. inclusion) shifts the capture window
- Bubbles escape more easily than solid inclusions in stagnant flow regions, but their capture depends on the flow pattern
- Although steels with low sulfur content tend to have less particle entrapment, the effect is small
- The increased ease of particle capture on the inner radius is a large effect (relative to vertical or outer radius)

Future Work

- The model uses isotropic velocity fluctuations and the velocity magnitude in all spatial directions is significantly different, so match with LES is not perfect. Therefore better fluid flow / turbulence model is needed (eg. Reynolds Stress)
- The model shows high concentration of particle at the top of the narrow face (not seen in LES results)
- Use model to fully investigate effect of other casting conditions and geometries