Continuous Casting Consortium

MechSE

ANNUAL REPORT 2008

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Multi-phase flow, argon bubble size, and inclusion entrapment in the slab casting mold

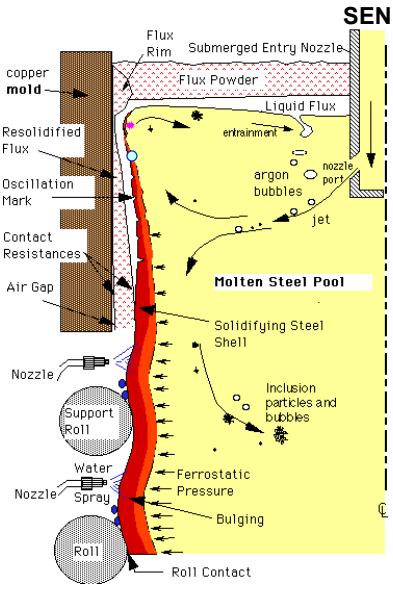
Go-Gi Lee
Materials Science and Engineering, POSTECH, South Korea

Brian G. Thomas
Mechanical Science & Engineering, UIUC, USA

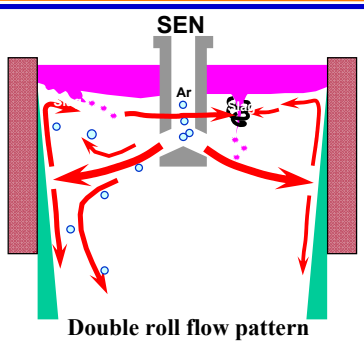
Seon-Hyo Kim
Materials Science and Engineering, POSTECH, South Korea

Ho-Jung Shin
POSCO Technical Research Laboratories, POSCO, South Korea

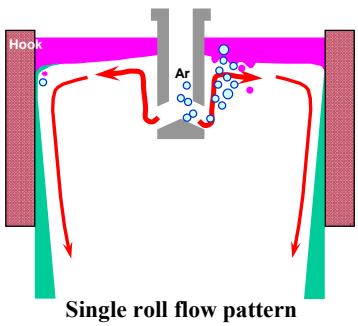
Flow and Particle Transport in Mold



"Continuous Casting Consortium website", ccc.me.uiuc.edu



Double roll flow pattern



Single roll flow pattern

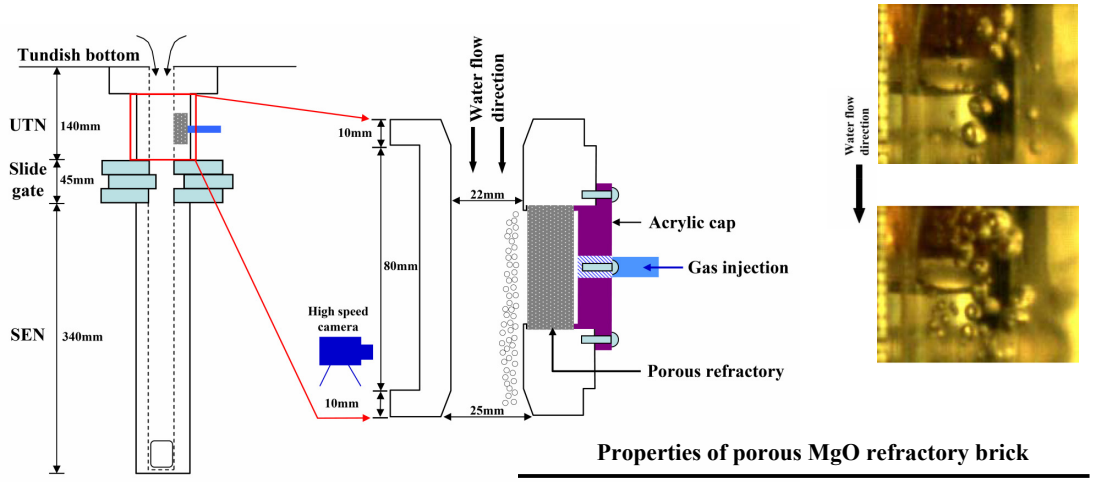
Entrained Slag Inclusions

Gas Bubbles

Parameters controlling Mold Flow

- Slab depth and width
- Casting speed
- Argon flow rate
- Nozzle shape
  - angle and size of outport
  - nozzle bore diameter
- Submergence depth
- Electromagnetic force

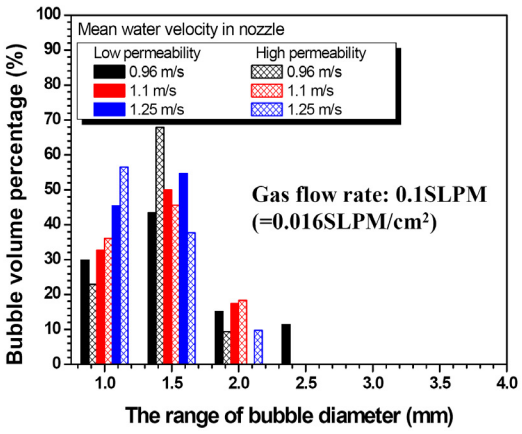
Water Model Bubble Measurements

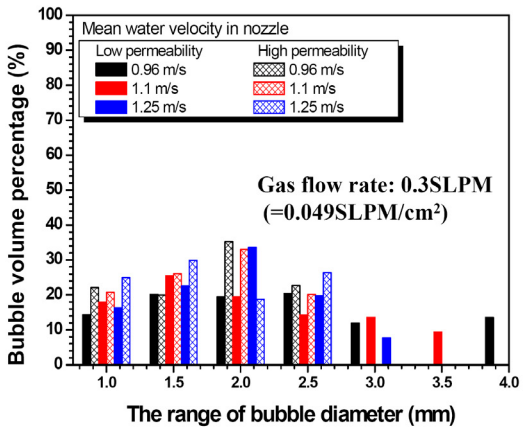


Properties of porous MgO refractory brick

	Brick 1	Brick 2
Fired B. D. (g/cc)	2.9	2.9
Porosity (%)	16.2	17.6
Modulus of rupture (psi)	1085	1119
Permeability (nPm)	7.52	16.32

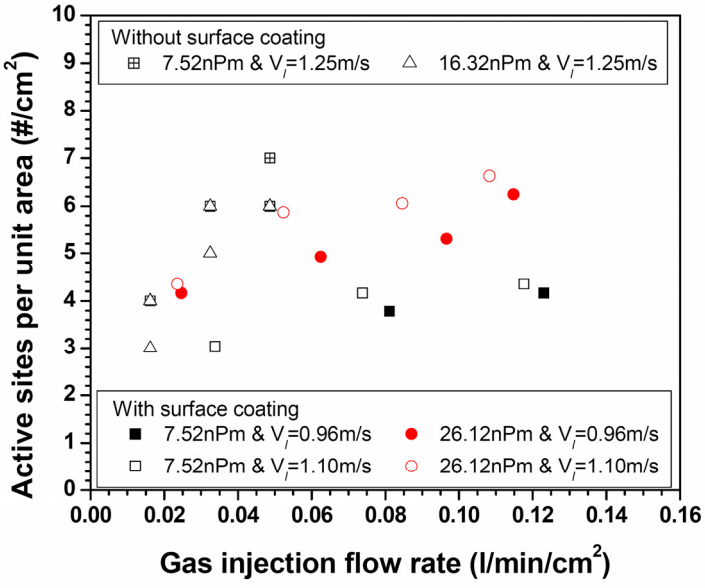
Bubble Size Distributions in Downward-flowing Water

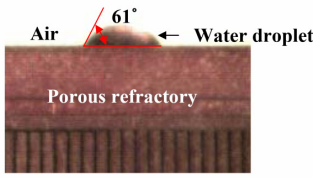




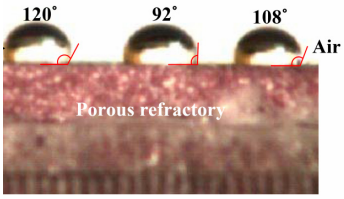
- Bubble size and size-range increase with gas flow rate

Active Bubble Sites





- No coating

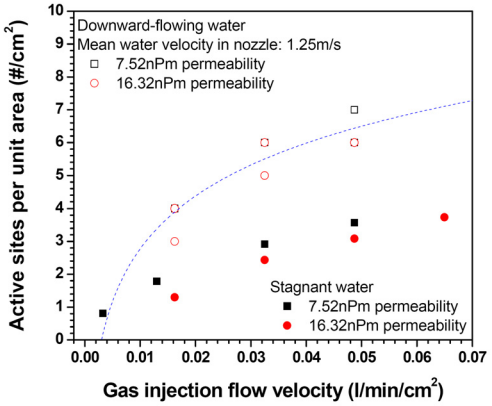


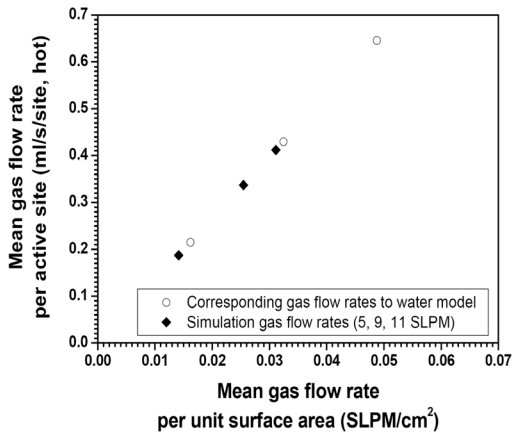
- With coating

- Fewer active sites with nonwetting surface coating

Relate Gas Flow Rates in Water Model and Steel Caster

Argon flow rate in steel caster (SLPM)	5	9	11
Water flow rate (Q_W, SLPM)	28.2	32.5	36.8
Liquid velocity in nozzle (U_W=U_S, m/s)	0.96	1.10	1.25
Steel throughput (Q_S, m^3/min)	0.25	0.29	0.33
Casting speed (m/min, 230mm thick x 1500mm wide	0.74	0.85	0.96

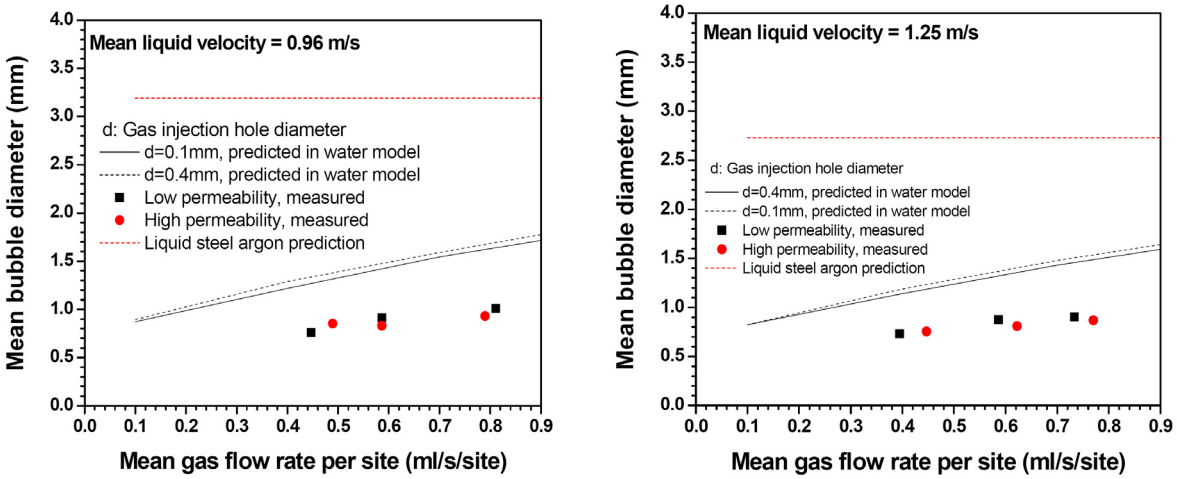




Bubble Size Prediction in Liquid Steel

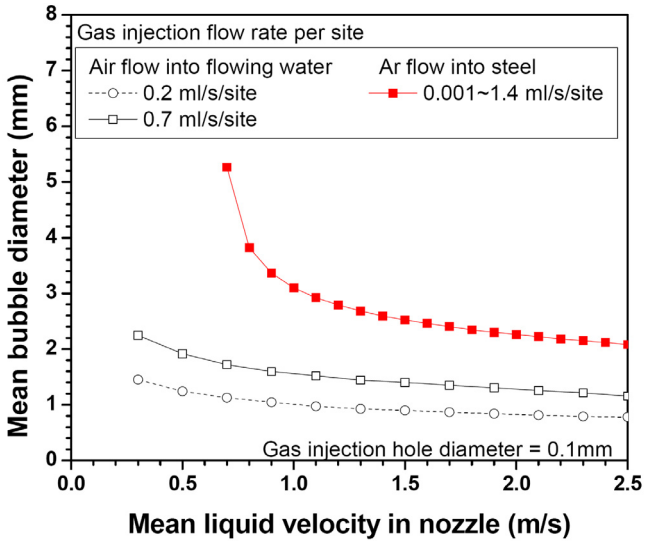
H. Bai and B.G. Thomas, MTB, 32(6), 2001, pp. 1143-1159

$$5.2692\frac{\pi U}{Q_{g\_hole}D_N^{1/17}}\int_{r_e}^{r_d}\left(r^{15/7}(ar+b)^{3/2}+\frac{ar^{22/7}}{2}(ar+b)^{1/2}\right)dr=2r_d e_d^{3/2}+\frac{d}{2}-r_e$$



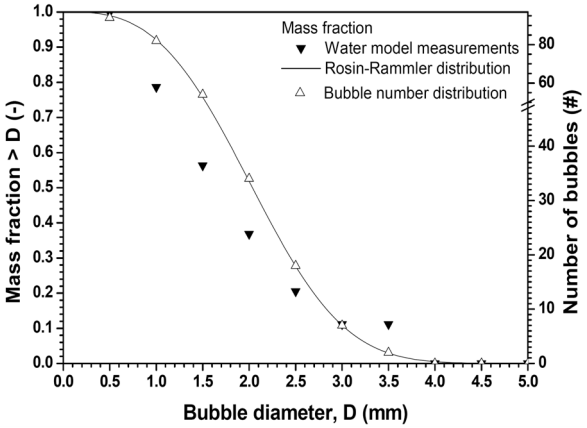
- Comparison of measured and predicted bubble size
- Ar bubble size in steel: larger than air bubble size in water

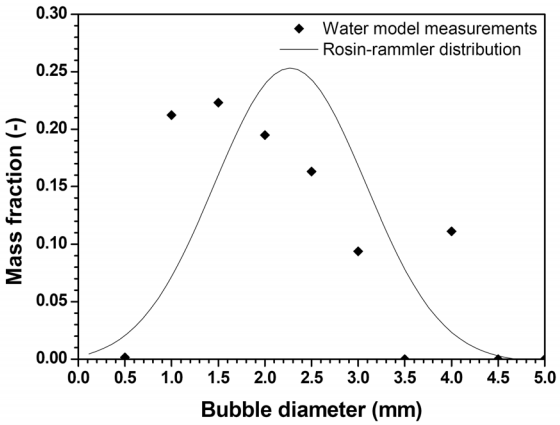
Steel Throughput Effect on Argon Bubble Size



- Decreasing water velocity below a critical minimum level allows the formation of very large bubbles

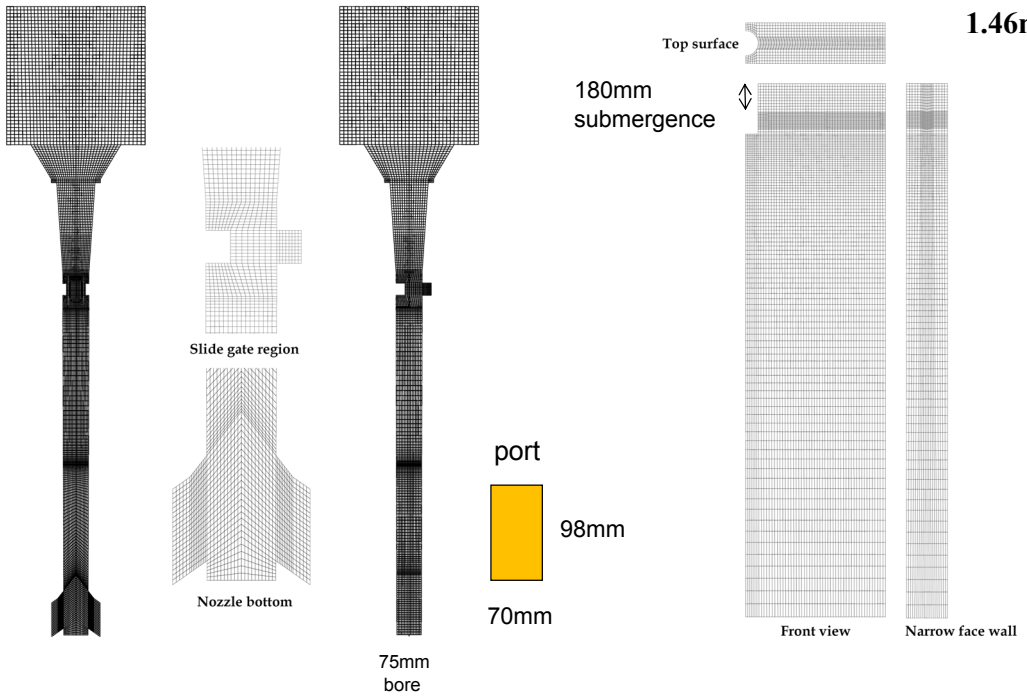
Bubble Size Distributions for Simulation



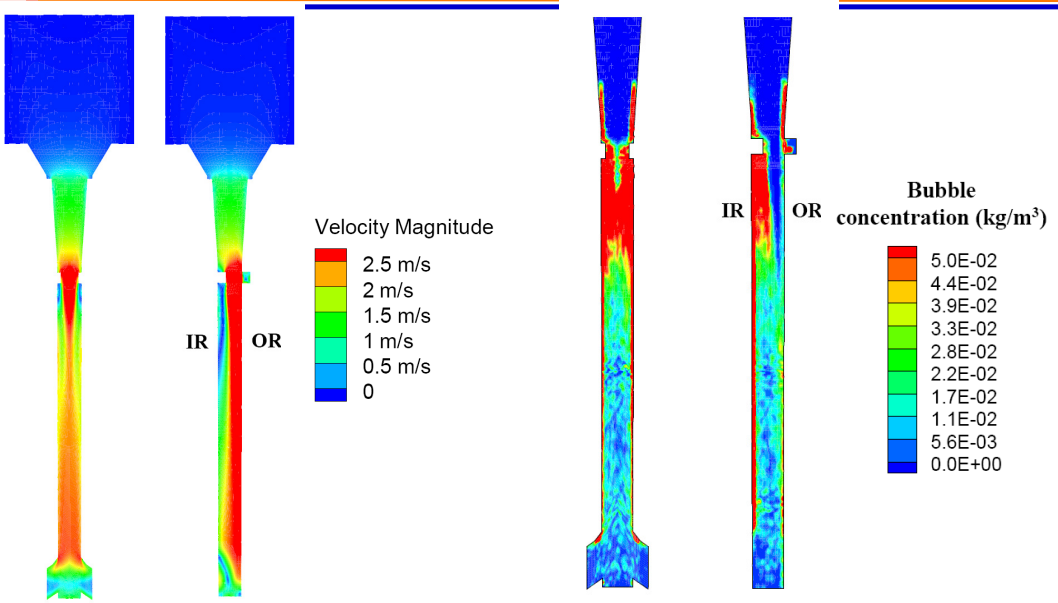


- Rosin-Rammler function used to simulate bubble size distribution, (from corresponding mass fractions)

CFD Model (Fluent with k-ε): Slide-gate, Nozzle & Half Mold



Velocity Profile and Bubble Concentration of Fluid Flow in Nozzle (9SLPM)



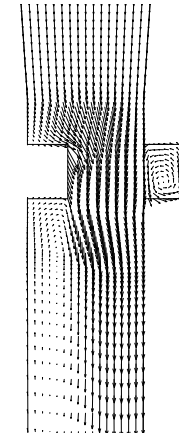
- Recirculation regions: Beneath slide gate and upper ports
- Gas bubbles accumulate in recirculation region

Simulation Conditions

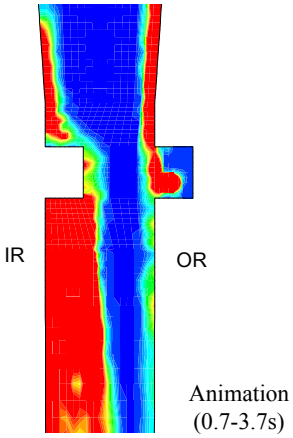
Mold size	**230mm thick x 1570mm wide x 3000mm long**
Casting speed	**1.46m/min (Average liquid velocity in nozzle: 2m/s)**
Submerged Entry Nozzle type	**Bifurcated**
SEN submergence depth	**180mm**
Nozzle port height x thickness	**98mm x 70mm**
Nozzle bore diameter	**75mm**
Nozzle port angle	**35 degree downward**
Density of molten steel	**7020kg/m^3**
Viscosity of molten steel	**0.0067kg/m·s**
Argon gas flow rate	**5, 9 and 11 SLPM**
Density of argon gas at 1560°C	**0.446kg/m^3**

Recirculation regions: bubble coalescence

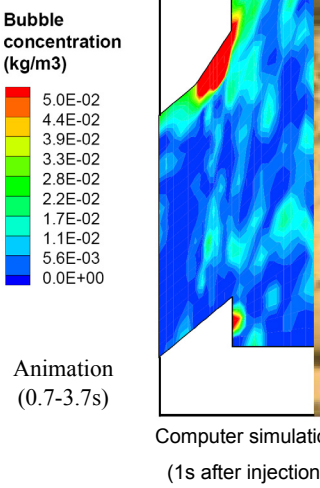
(9 SLPM)

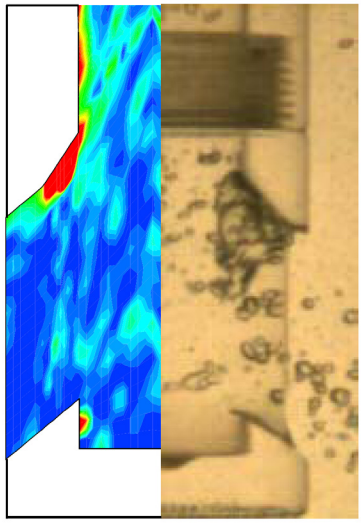


Velocity vectors



Bubble concentration





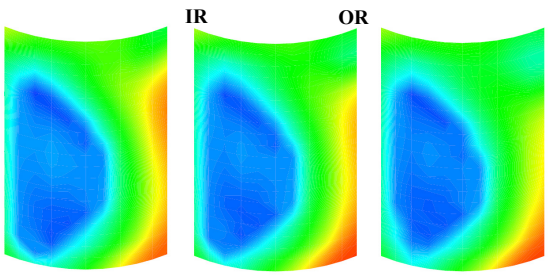
Computer simulation Water model

(1s after injection)

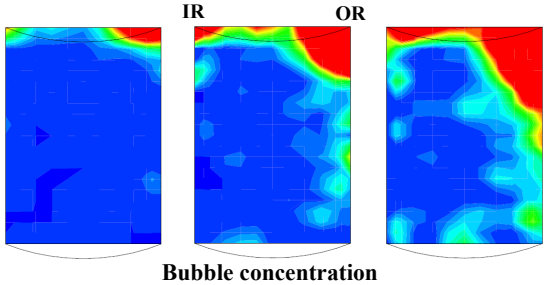
Slide gate region

Port region

Velocity and Bubble Concentration at Nozzle Port



Velocity profile



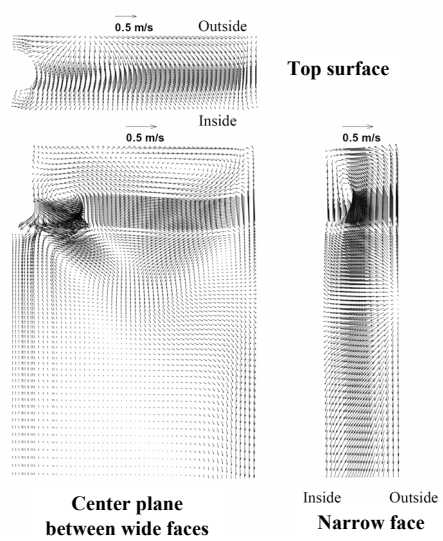
Bubble concentration

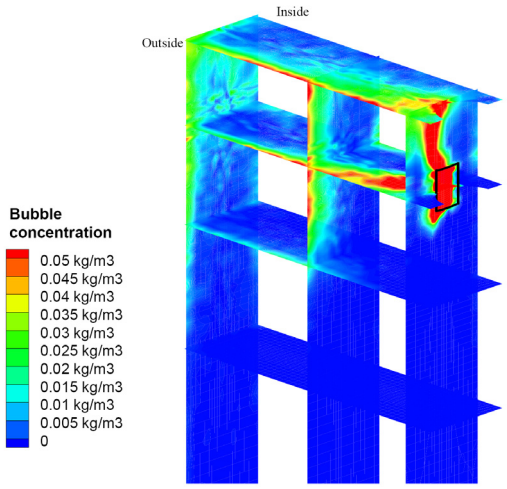
5SLPM 9SLPM 11SLPM

<Right port view>

- Stronger steel flow from bottom right (of right nozzle port)
- More gas exits top right
- Higher gas flow rate causes stronger asymmetric recirculation flow at nozzle outlet port

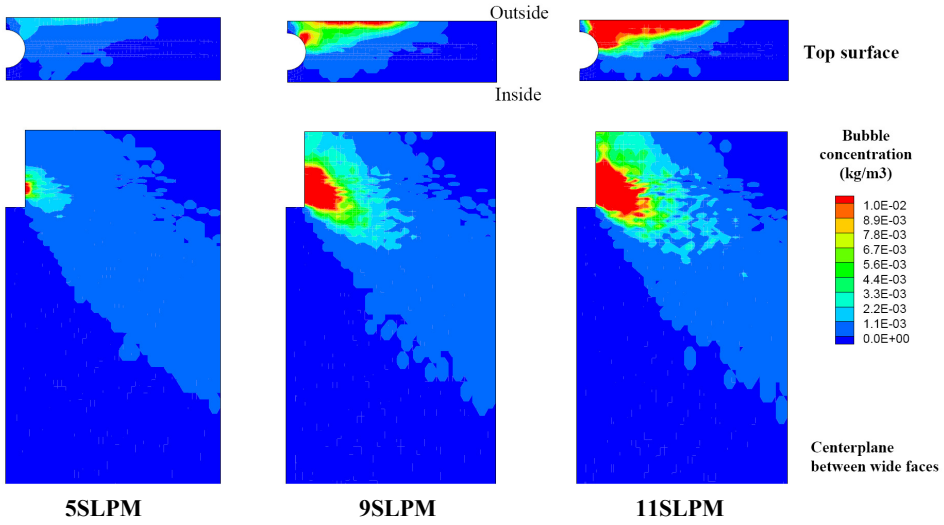
Flow pattern and Bubble Concentration
(30sec after Gas Injection with 9SLPM)





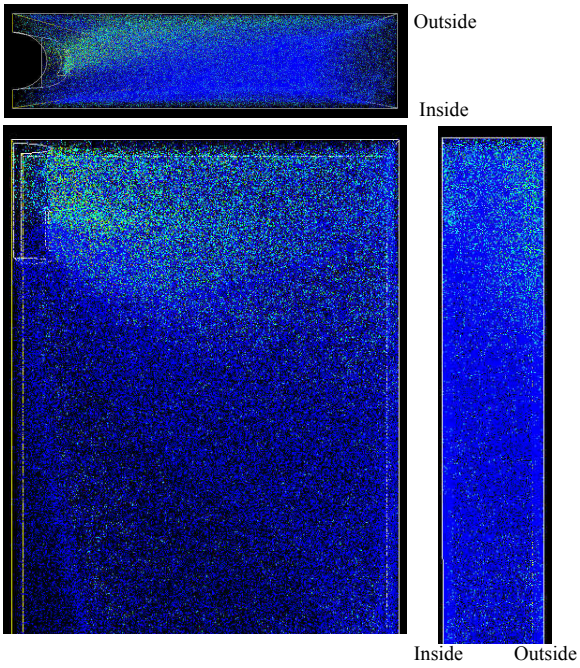
- Generally double-roll flow pattern, impinging on NF;
- Some flow up outside wide face, across top surface, and down inside wide face
- results match plant measurements

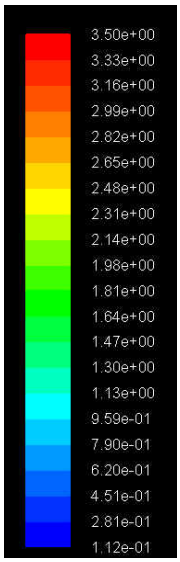
Bubble Concentration in Half Mold
(4sec after Gas Injection)



- Higher bubble concentration near SEN, due to buoyancy force
- Distribution of gas bubbles on the top surface is greatly affected by the asymmetric flow at the nozzle outlet port

Bubble size distribution in mold



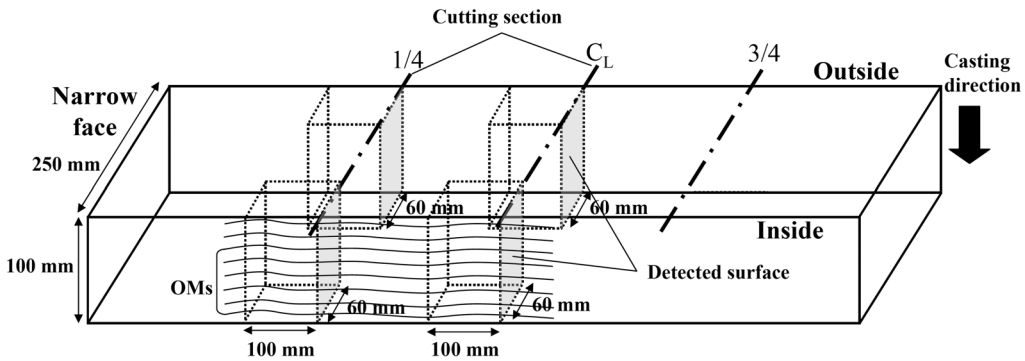


video

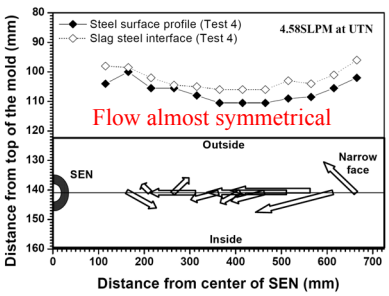
30.4sec

Plant Measurements: Nail Board Dip Tests and Particle Entrapment in Slab Samples

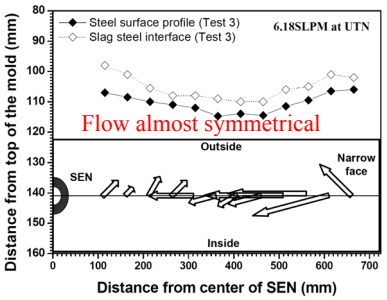
Test number	Slab thickness (mm)	Pour temperature (˚C)	Electromagnetic current (A)	Slab width (mm)	Casting speed (m/min)	Argon gas flow rate (SLPM)
Test 1	250	1567	250	1570	1.30	9.60
Test 2						12.20
Test 3				1450	1.34	6.18
Test 4						4.58



Flow Pattern measured by Nail-Board Dip Tests

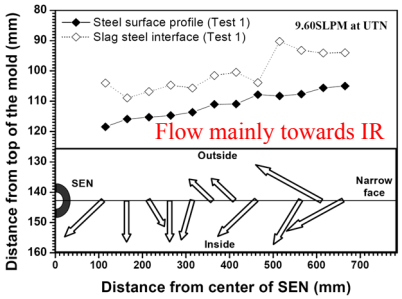


(3.6% gas)

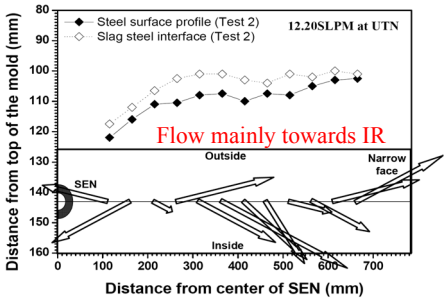


(4.8% gas)

Increasing gas flow rate
→Changes flow pattern
→Asymmetric flow across the top surface



(7.0% gas)



(8.7% gas)

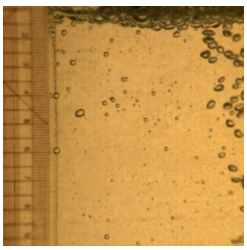
2006 tests

Flow past solidification front affects particle entrapment

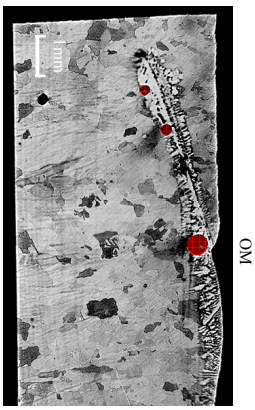
Entrapped bubbles revealed after scarfing

Water model
- 36.8 l/min water
- 9 SLPM gas

video

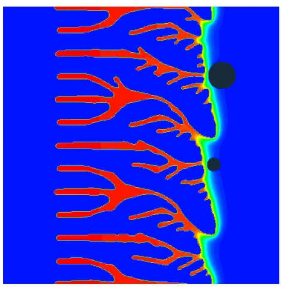


Bubble motion in meniscus region (water model)



Bubble trapped near meniscus (hook)

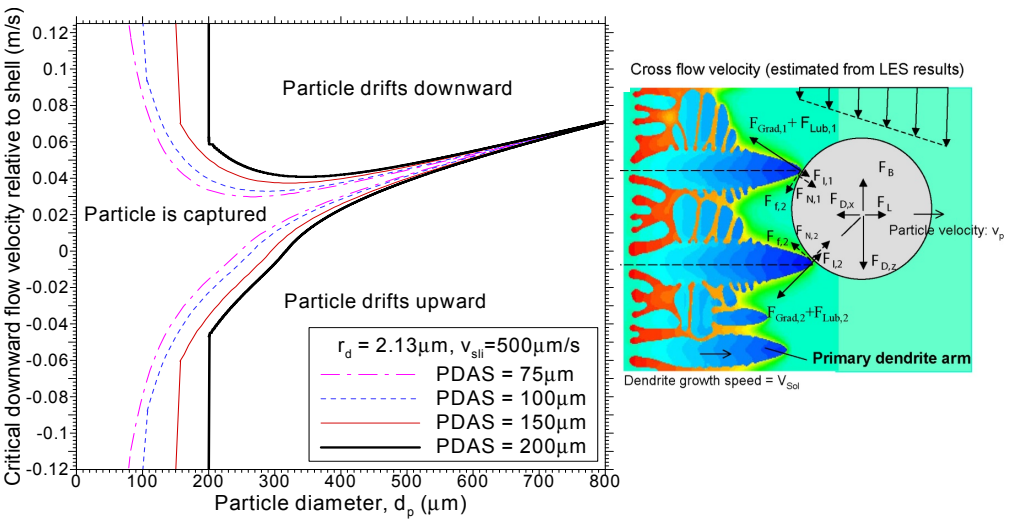
video



Capture at solidification front (only if stagnant)

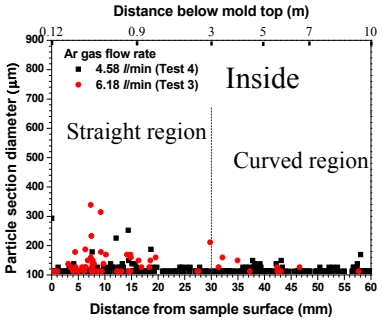
A. Chang & J. Dantzig, UIUC, 2006

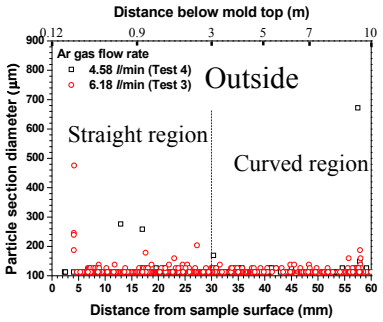
Cross-Flow Velocity Effect on Capture of Slag Droplets



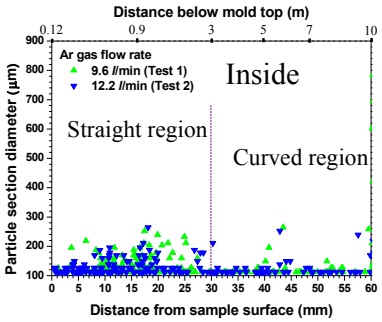
Critical downward cross-flow velocity (relative to shell) to capture slag droplets in solidifying steel dendritic interface

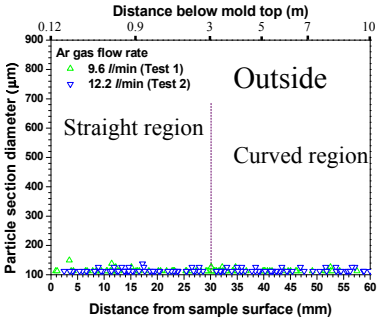
Particle distribution beneath slab surface (ultra-sonic analysis)





Distance down caster
- defects in both straight and curved regions
→ not controlled by surface hooks or by flotation effects





Higher Ar gas flow rate
- More defects on IR
→ caused by asymmetric flow toward inside radius

Conclusions

- Gas exits upper outside-radius corner of nozzle port (owing to asymmetric flow inside nozzle)
- Gas rises up outside radius of mold, causing top surface to have: high gas concentration at OR and flow towards IR
- Increasing gas flow rate (>9 l/min)
  - Flow towards inside radius, confirmed by nail-board measurements
  - Causes more particles entrapped, especially on inside radius, corresponding to asymmetric flow
  - Straight wall until shell is 30mm thick indicates that most defects are not due to machine curvature, but due to asymmetric flow
- Asymmetric flow towards one face increases entrapment (both frequency and particle size) on that face and decreases entrapment on the opposite face
- Particle entrapment seems mainly due to poor / asymmetric fluid flow conditions

Acknowledgements

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- Continuous Casting Consortium (UIUC), especially Rob Nunnington and LWB Refractories for supplying samples
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