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Hook formation near slab corners and prediction of argon gas bubble size in the slab casting mold

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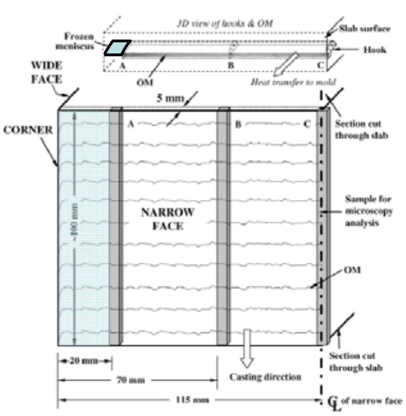
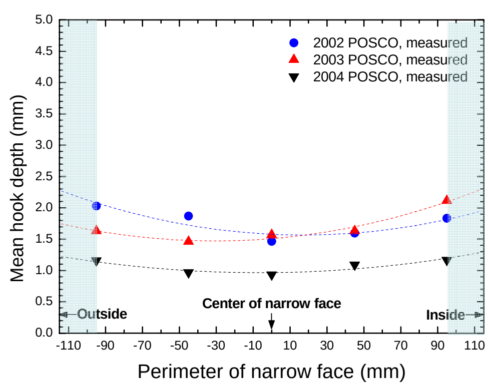
- Dr. Ho-Jung Shin, POSTECH

1. Investigation of 3-D Frozen Meniscus Shape

3-D Frozen Meniscus Region - corners of slab

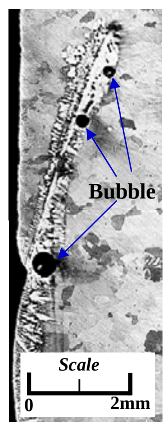


J. Sengupta et al., Acta Materilia, 2006



< Narrow face results >

H.-J. Shin, CCC Annual Report, 2005

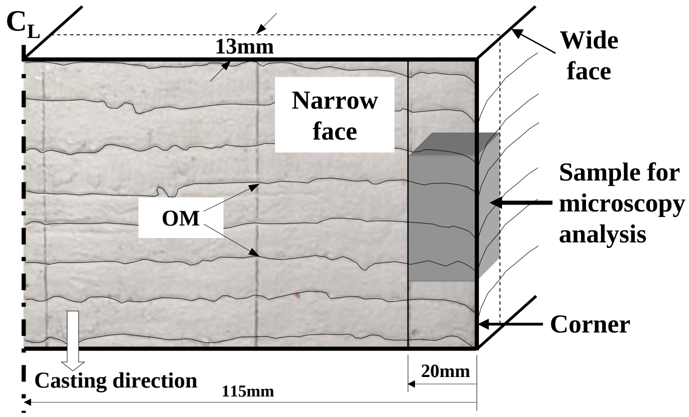


Curved hook at 20mm distance from the corner

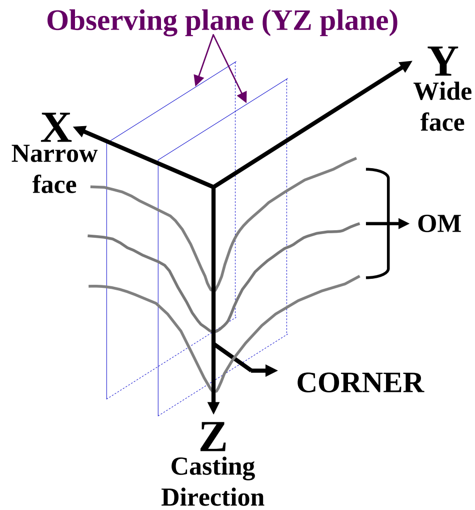
- Micrographs of the hook come from 2-D vertical section view of certain location
- Near the corners of the slab: deepest hook depth at corners; complex 3-D hook shape

→ 3-D shape of frozen meniscus at corners is not clear

Metallurgical Method



Sample size: 20mm(width) * 13mm(depth) * 30mm(height)



< Location of sample >

< Definition of axes >

- **Ten micrographs (2-D vertical section view) were obtained from YZ plane according to X distance(~6mm) from corners**

Casting Conditions

- Slab thickness: 230 mm; Slab width: 1300 mm; Casting speed: 1.45 m/min; Pour temperature: 1571˚C

Mold oscillation conditions

Stroke (mm)	Frequency (cpm)	Modification ratio for non-sinusoidal mode (%)	Negative strip time (sec)	Positive strip time (sec)
5.0	174	12	0.100	0.241

Steel composition of ultra-low carbon steel (wt. %)

C	Mn	Si	P	S	Cr	Ni	Cu	Ti	Al
< 0.005	0.08	≤ 0.005	~ 0.015	~ 0.01	0.01	0.01	0.01 ~ 0.02	0.05	~ 0.04

Mold powder composition and properties

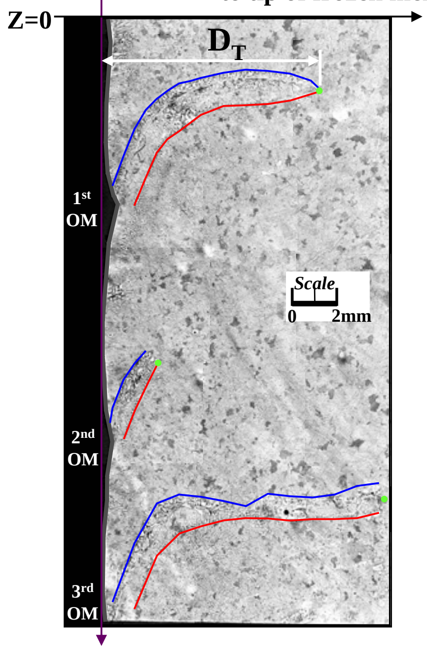
Chemical composition (wt. %)	Basicity	SiO_2	CaO	MgO	Al_2O_3	TiO_2	Fe_2O_3	MnO_2	P_2O_5	Na_2O	K_2O	F	B_2O_3	Li_2O
	1.10	36.3	39.8	0.84	5.97	0.18	0.34	0.03	0.03	3.43	0.11	6.72	0	0.35

Properties	Solidif. Temperature (°C)	Softening Temperature (°C)	Melting Temperature (°C)	Viscosity at 1300 °C (Poise)
	1149	1170	1180	3.21

Actual Measurement of Micrograph

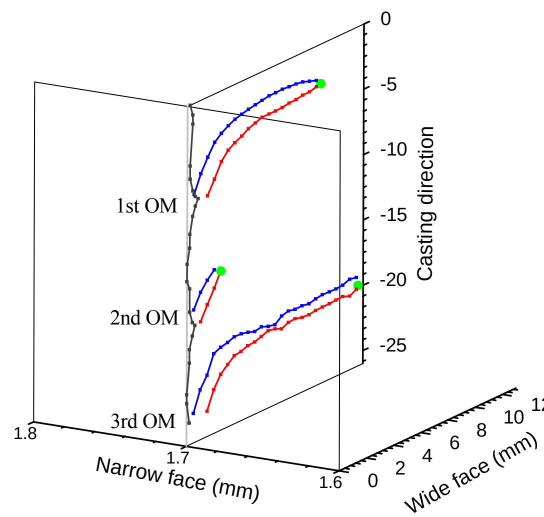
Slab surface
Y=0

D_T : Distance from slab surface to tip of frozen meniscus



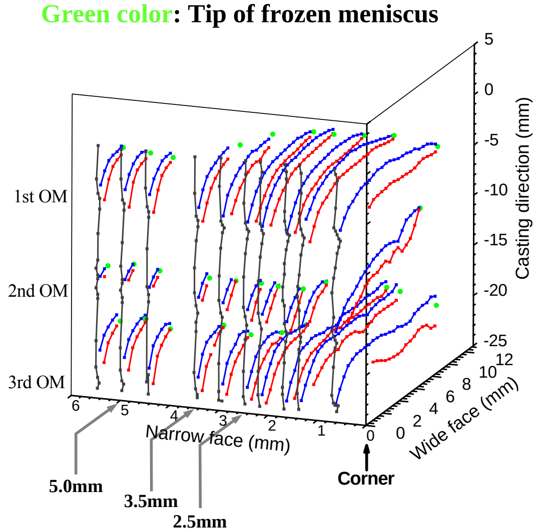
Micrograph of YZ plane at X = 1.7mm

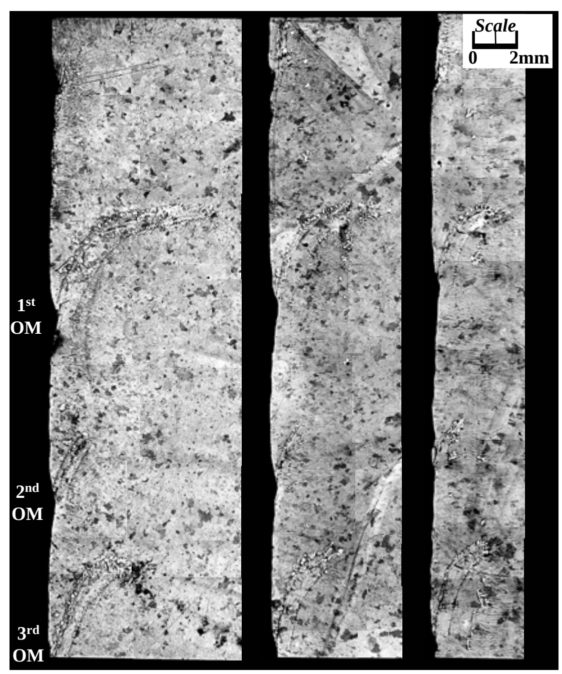
Blue color: Upper line of frozen meniscus
Red color: Lower line of frozen meniscus
Gray color: Profile of oscillation mark
Green color: Tip of frozen meniscus



Analysis of Micrographs

Blue color: Upper line of frozen meniscus
Red color: Lower line of frozen meniscus
Gray color: Profile of oscillation mark
Green color: Tip of frozen meniscus

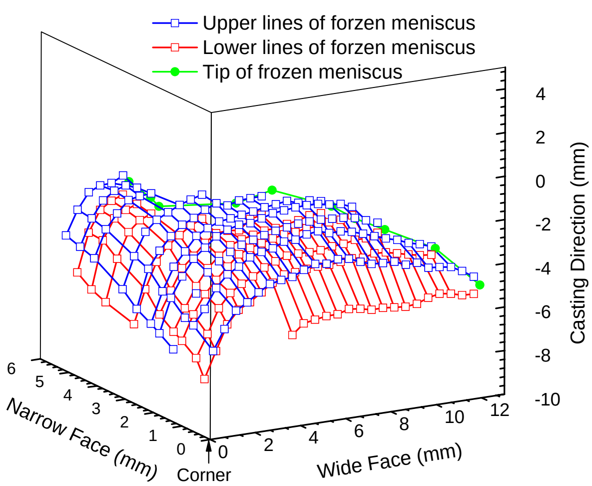




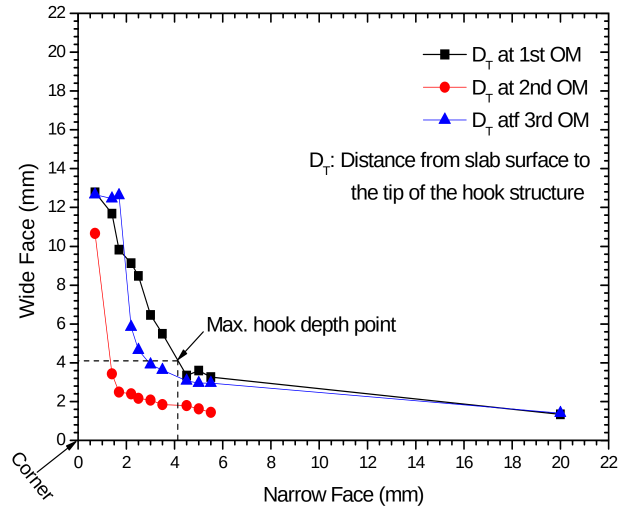
X = 2.5mm 3.5mm 5.0mm

< Micrographs according to the X direction >

Investigate of Frozen Meniscus Shape



Front view of frozen meniscus at 1st OM



Tops view of frozen meniscus

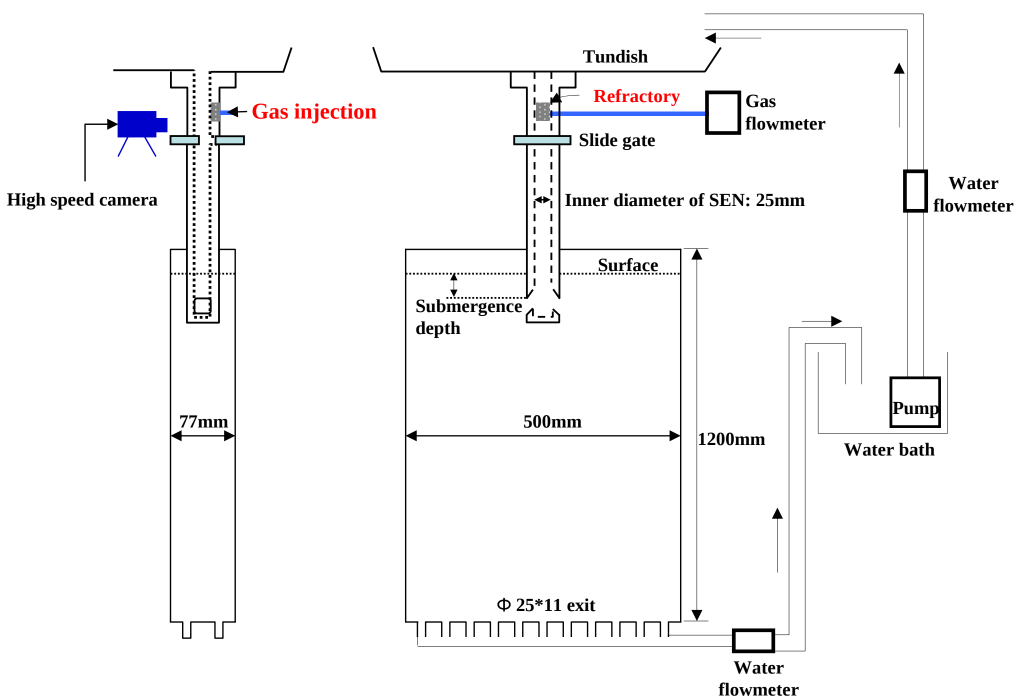
Hook characteristics:
Continuous defect along the OM; 3-D structure

Conclusions

- Frozen meniscus shape near the corner of slabs is investigated with metallurgical analysis:
  - Micrographs show the 3-D frozen meniscus shape
  - Hook is continuous defect at the oscillation mark running completely around the strand perimeter
  - Deepest hook depth appears near corners

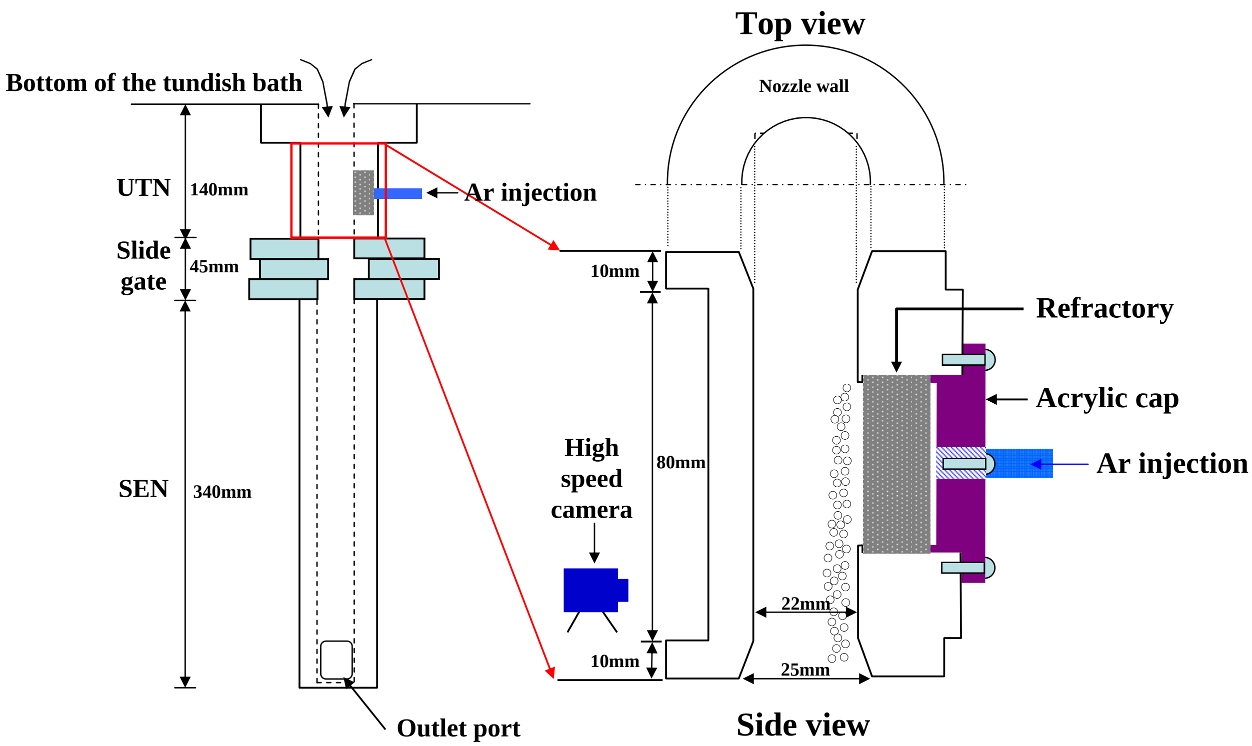
2. Investigation of Argon Bubble Size in Water Model using Porous Nozzle Refractory

Water Model Apparatus (1/3 scale)



Size of MgO refractory brick: 14mm(W)*44mm(L)*17mm(D)

Schematic of Upper Tundish Nozzle in Water Model



Conditions of the Experiment

•Fixed test conditions	
- Submergence depth:	**60mm**
- SEN outport angle:	**35°downward**
- Height of tundish bath:	**330mm**
• Factors	
- Total gas flow rate:	**0.1, 0.2, 0.3 *l*/min**
- Mean water velocity:	**0.96, 1.10, 1.25 m/s**

< Test conditions in water model >

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

< Properties of MgO refractory bricks >

Note: MgO uses to simulate the dolomite refractories

Similarity Analysis between Steel Caster & Water Model

Dimensionless groups

$$Fr_{liq} = \frac{Inertial\ force\ due\ to\ liquid\ momentum}{Buoyancy\ force} = \frac{\rho_l}{(\rho_l - \rho_g)}\frac{U_l^2}{Dg}$$

$$Fr_{gas} = \frac{Inertial\ force\ due\ to\ gas\ momentum}{Buoyancy\ force} = \frac{\rho_g}{(\rho_l - \rho_g)}\frac{d^2 V_g^2}{D^3 g}$$

$$Re_{liq} = \frac{Inertial\ force\ due\ to\ liquid\ momentum}{Viscous\ force\ of\ liquid} = \frac{\rho_l D U_l}{\mu_l}$$

$$Re_{gas} = \frac{Inertial\ force\ due\ to\ gas\ momentum}{Viscous\ force\ of\ gas} = \frac{\rho_g d V_g}{\mu_g}$$

$$We_{liq} = \frac{Inertial\ force\ due\ to\ liquid\ momentum}{Surface\ tension\ force} = \frac{\rho_l D^2 U_l^2}{\gamma D}$$

$$We_{gas} = \frac{Inertial\ force\ due\ to\ gas\ momentum}{Surface\ tension\ force} = \frac{\rho_g d^2 V_g^2}{\gamma D}$$

where,

D : average bubble diameter at a pore, d : gas injection pore diameter,
ρ_l : liquid density, ρ_g : gas density, μ_l : liquid viscosity,
μ_g : gas viscosity, U_l : liquid velocity, V_g : gas velocity,
γ : liquid / gas surface tension coefficient, g : gravitational acceleration

Physical properties used in calculation

Parameters	Water-air system	Steel-hot Ar system
Liquid density (ρ_l, kg/m^3)	1000	7020
Gas density (ρ_g, kg/m^3)	1.331*	0.446*
Liquid viscosity (μ_l, kg/m·s)	0.001	0.0056
Gas viscosity (μ_g, kg/m·s)	1.70E-05	7.42E-05
Surface tension coefficient (γl/g , N/m)	0.073	1.192

**) Note: Gas density was calculated for the temperature in liquid and the pressure due to the height of liquid in tundish (see appendix 2)

Ref.) H. Bai: Ph. D. Thesis. UIUC, Urbana, IL, 2000

Liquid Flow Rate between Two Systems

From mass balance

$$Q_W = U_{W,nozzle} \cdot A_{W,nozzle} \qquad \therefore U_{W,nozzle} = \frac{Q_W}{A_{W,nozzle}}$$

We choose the same liquid velocity between two systems, because the refractory geometry scale is 1:1

$$U_{W,nozzle} = U_{S,nozzle}$$

$$\therefore Q_S = U_{S,nozzle} \cdot A_{S,nozzle}$$

$$\therefore V_C = \left(\frac{Q_S}{Cross-setional\ area\ of\ the\ strand}\right)$$

Here,

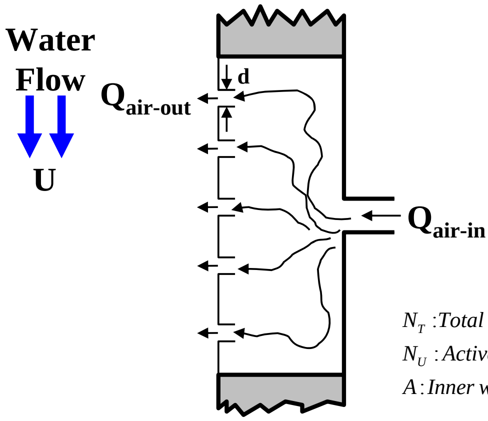
Q_W is the water flow rate (m^3/s),
Q_S is the steel flow rate (m^3/s),
$U_{W,nozzle}$ is the water velocity in water model nozzle (m/s),
$U_{S,nozzle}$ is the steel velocity in actual nozzle (m/s),
$A_{W,nozzle}$ is the cross-sectional area of water model nozzle (m^2),
$A_{S,nozzle}$ is the cross-sectional area of actual nozzle (m^2),
V_C is the casting speed (m/min)

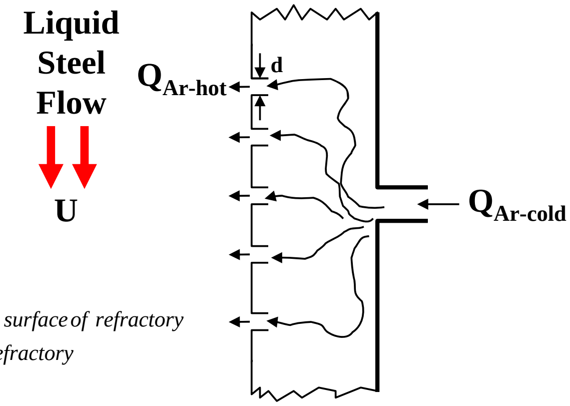
Table. Relationship between the liquid flow rate and casting speed

Water flow rate (l/min)	**Qw**	**28.2**	**32.5**	**36.8**
Liquid velocity in nozzle (m/sec)	Uw,nozzle(=Us,nozzle)	0.96	1.10	1.25
Steel thoughput (m^3/min)	Qs	0.25	0.29	0.33
		↓	↓	↓
Casting speed (m/min, 230mm*1500mm slab)	**Vc**	**0.74**	**0.85**	**0.96**

Note) Bore diameter of SEN is 25mm in water model and 75mm in steel caster, respectively

Gas Flow Rate Ratio caused Surface Area of Refractory





N_T : *Total active sites on inner wall surface of refractory*

N_U : *Active sites per unit area of refractory*

A : *Inner wall area of refractory*

$$Q_{air-out} = \frac{Q_{air-in}}{N_{T,W}} = \frac{Q_{air-in}}{N_{U,W} \cdot A_W}$$

< Schematic of water model experiment >

$$Q_{Ar-hot} = \frac{\beta \cdot Q_{Ar-cold}}{N_{T,S}} = \frac{\beta \cdot Q_{Ar-cold}}{N_{U,S} \cdot A_S}$$

< Schematic of steel caster >

$$\frac{Q_{Ar-hot}}{Q_{air-out}} = \beta \frac{A_W}{A_S} \frac{Q_{Ar-cold}}{Q_{air-in}}$$

β : *Ar gas expansin coefficient*

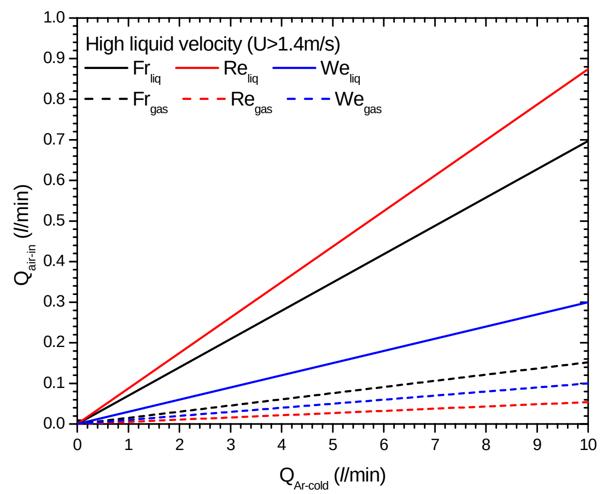
A_W / A_S : *Surface area ratio of two refractory* *

*) *see the appendix 1*

Summary of Dimensionless Number Analysis

Similarity requirement for gas flow rate

Dimensionless number	$Q_{air-in}/Q_{Ar-cold}$ (This work)	$Q_{air-in}/Q_{Ar-cold}$ (Bai's calculation)
Fr_{liq}	0.07	0.285
Re_{liq}	0.087	0.356
We_{liq}	0.03	0.123
Fr_{gas}	0.0152	0.067
Re_{gas}	0.005	0.026
We_{gas}	0.01	0.044

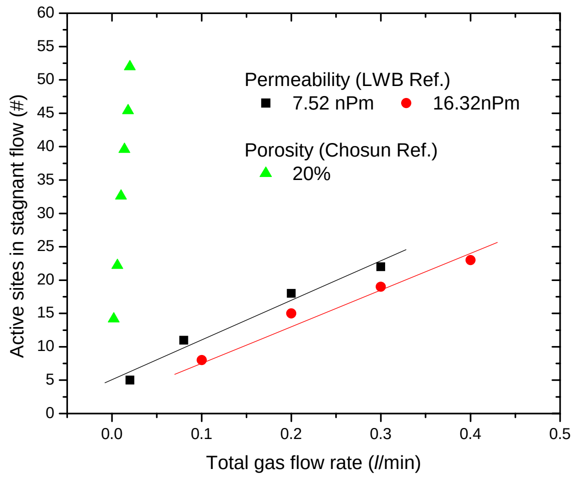


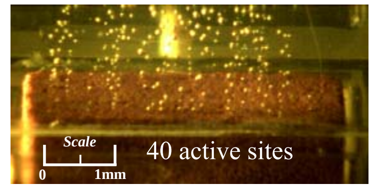
At high liquid velocity (U>1.4m/sec): $D_{air} \approx D_{Ar}$ at the same gas flow rate

→ Matching all of the dimensionless groups at the same time is impossible

Active Sites in Stagnant Flow

LWB Refractories
Low permeability(7.52nPm)
Q_g = 0.3 *l*/min



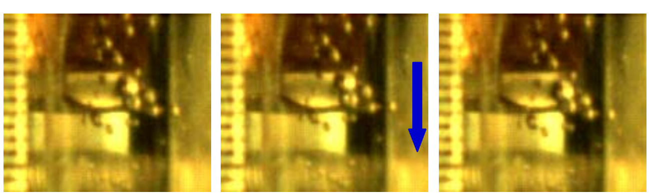


Chosun Refractories
Porosity = 20%
Q_g = 0.018 *l*/min

- Number of active site and bubble size through the porous refractory in stagnant flow are mainly dependent of the texture of porous refractory
- Generally speaking, active site increases as gas flow rate increases

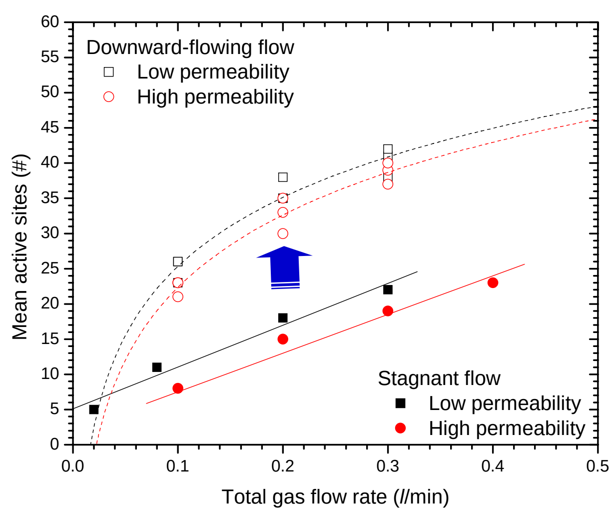
Comparison of Mean Active Sites between Flowing and Stagnant Flow

Test conditions
- Low permeability (7.52nPm)
- Mean liquid velocity: 1.25 m/s
- Total gas flow rate = 0.1 *l*/min
- Camera speed: 4000 frames/s



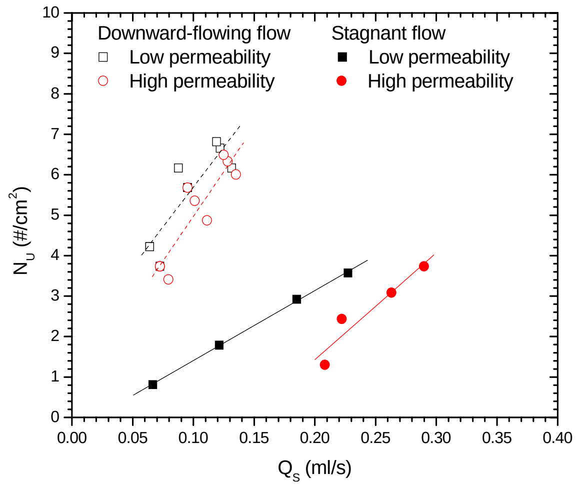
t=0 t=0.25ms t=0.5ms

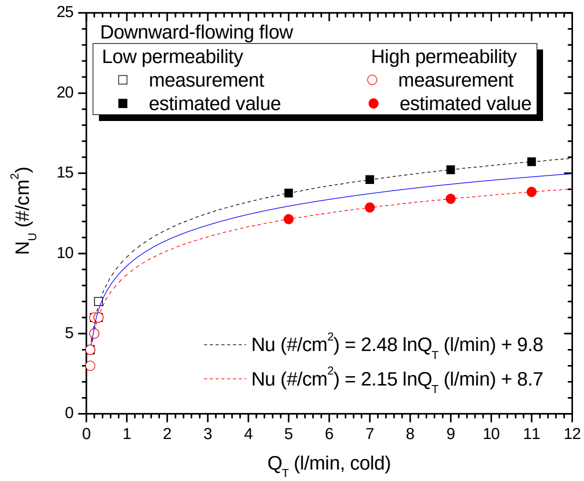
< Example of experiment photograph series >



- Active sites in downward flow are about 2 times those in stagnant flow
- Gas flow rate per site of high permeability is slightly higher than that of low permeability in downward-flowing flow at the same total gas flow rate

Calculation of Total Active Sites in the Steel Caster Nozzle Wall





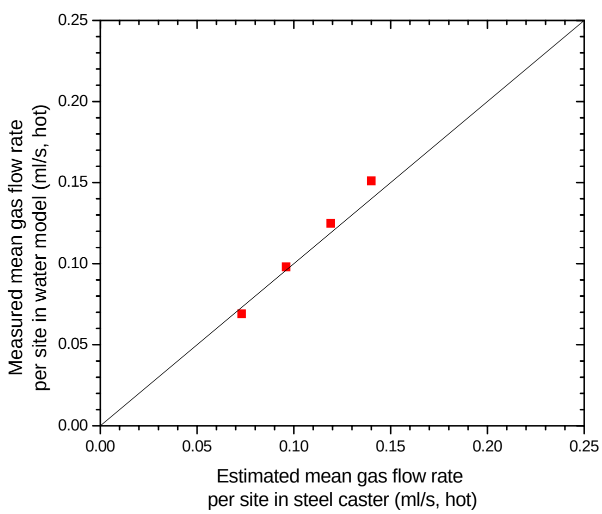
$$Q_S\left(Mean\ gas\ flow\,rate\ per\ site\right)=\frac{Q_T\left(Total\ gas\ flow\,rate\right)}{N_T\left(Total\ active\ sites\right)}$$

	Water Model	Steel Caster
Q_T (Total gas flow rate-cold, l/min)	0.2	7
N_U (Mean active sites per unit area, #/cm^2)	**5.5**	**13.732**
A (Inner wall area of refractory*, cm^2)	6.2	353.4
N_T (Total active sites, #)	**34**	**4853**

***) see appendix 1**

- **Low permeability is much more active sites**

Comparison of Estimated Mean Gas Flow Rate per Site between Two Systems



N_U (Mean active sites per unit area on inner wall of refractory) = 2.3154 lnQ_T(cold, l/min) + 9.2263

Estimated mean gas flow rate per site in steel caster (ml/s, hot)

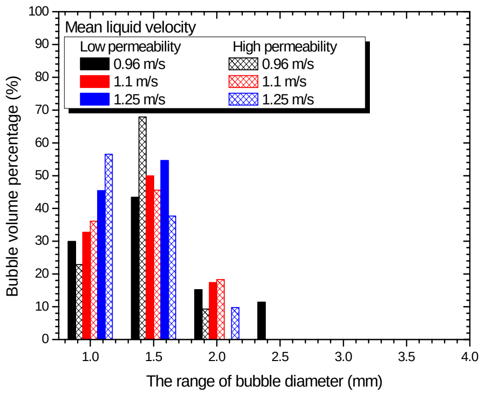
$$=\frac{\beta\times Q_T\left(cold,l/min\right)}{A_S^{\ *}\left(cm^2\right)\times N_U\left(\#/cm^2\right)}$$

***) A_S = 353.4cm^2, see appendix 1**

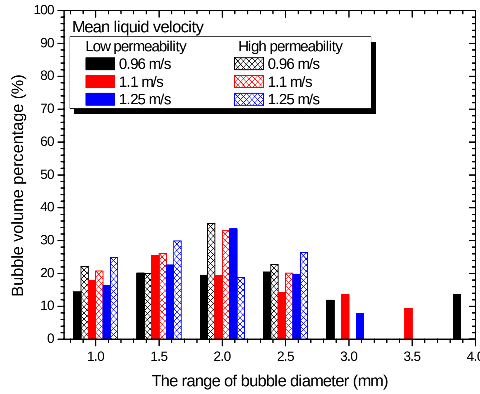
	Water Model				Steel Caster			
Q_T (Total gas flow rate-cold, l/min)	0.1	0.2	0.3	0.4	5	7	9	11
β (Gas volume expansion coefficient**)	1				4			
N_T (Total active sites on inner wall area, #)	24	34	40	44	4578	4853	5058	5223
Estimated mean gas flow rate per site (hot, ml/s)	**0.069**	**0.098**	**0.125**	**0.151**	**0.073**	**0.096**	**0.119**	**0.140**

Similarity of mean gas flow rate per site between two systems
→ It makes the result of water model is meaningful

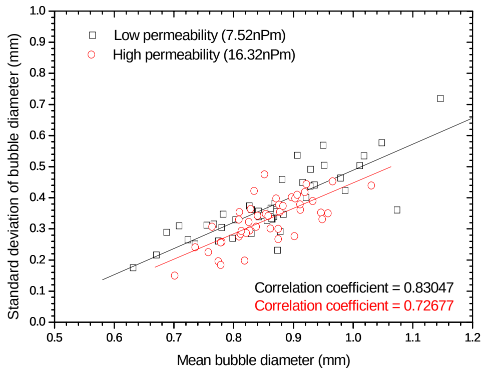
Bubble Size Distributions: measured in water model nozzle



Total gas flow rate = 0.1 *l*/min

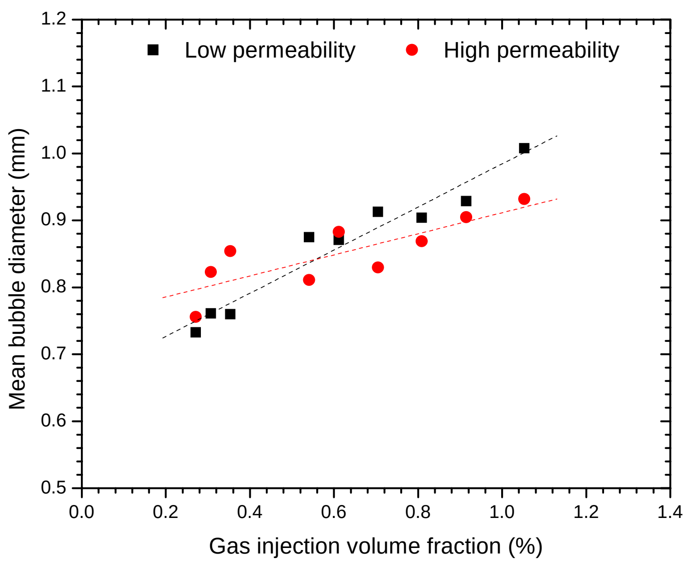


Total gas flow rate = 0.3 *l*/min



- **Bubble size variations increase with increasing gas flow rate and increasing bubble diameter**

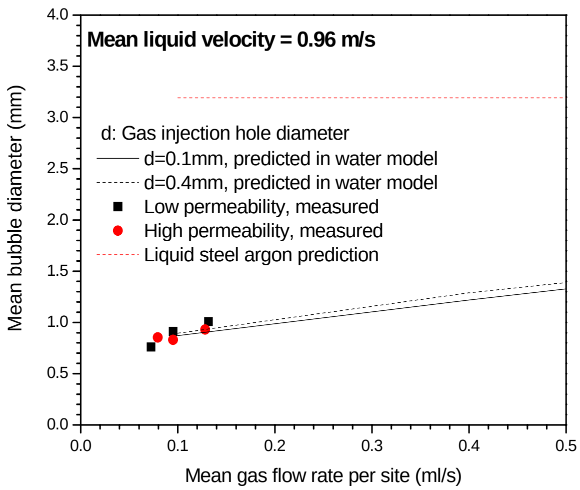
Effect of Liquid Velocity and Gas Flow Rate on Bubble Diameter (water model)

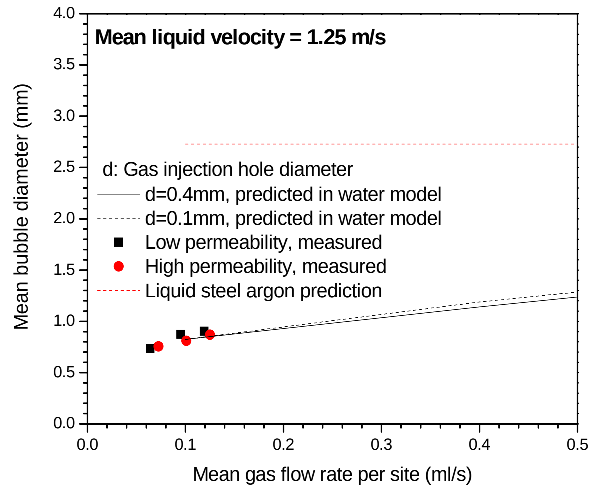


$$Gas\ injection\ volume\ fraction = \frac{Total\ gas\ flow\,rate}{(Total\ gas\ flow\,rate + Liquid\ flow\,rate)} * 100$$

- **The mean bubble size increases with increasing gas flow rate and decreasing liquid velocity**

Comparison of Measured and Predicted Gas Bubble Size





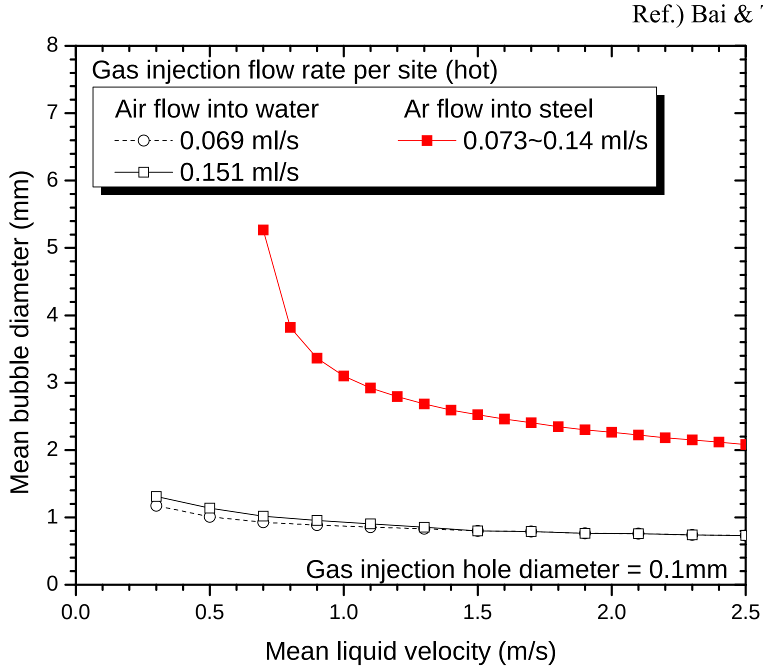
$$Mean\ gas\ flow\, rate\ per\ site = \frac{Total\ gas\ flow\, rate}{Mean\ active\, sites}$$

Bubble size prediction model: $5.2692 \frac{\pi U}{Q_g D_N^{1/7}} \int_{r_e}^{r_d} \left(r^{15/7} (ar + b)^{3/2} + \frac{a r^{22/7}}{2} (ar + b)^{1/2} \right) dr = 2 r_d e_d^{3/2} + \frac{d}{2} - r_e$

Ref.) Bai & Thomas, Met. Trans., 2001

Comparison of Estimated Ar Bubble Size between Steel Caster and Water Model using the Bai's Prediction

Ref.) Bai & Thomas, Met. Trans., 2001

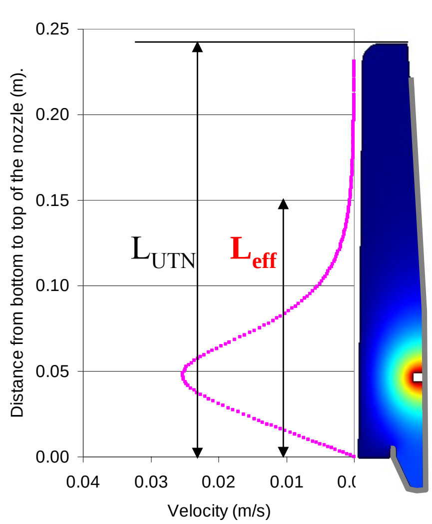


Conclusions

- Investigation of Ar bubble size in water model nozzle using porous refractory
  - Micro texture of the porous refractory greatly affects injected gas behavior in stagnant flow
  - Active sites in downward-flowing flow are about two times compare with stagnant measurement
  - Although matching different dimensionless groups at the same time is impossible, the similarity of mean gas flow rate per site between water model and steel caster is good
  - Bubble size variations increase with increasing gas flow rate and increasing bubble diameter
  - Mean bubble size increases with increasing gas flow rate and decreasing liquid velocity
  - The match of mean bubble size between the previous model prediction by Bai and the experimental data is reasonably good

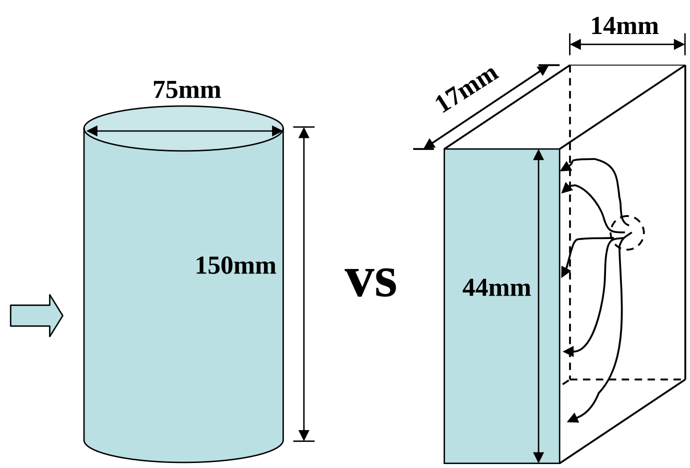
Appendix 1. Surface Area Ratio

Effective length of UTN considered distribution of Ar gas velocity



Distribution of Ar gas velocity

B. G. Thomas & Z. Hashisho, CCC Annual Report, 2005



Cylinder-like refractory in actual plant

Surface area (A_S) = 353.4cm^2

Rectangular refractory fixed in water model

Surface area (A_W) = 6.2cm^2

Appendix 2. Calculation of Gas Density

ρ_g *is density of gas*

$$\rho_g = \frac{weight(m)}{volume(V)} \qquad (1)'$$

Ideal gas eqution is $PV = nRT$ $\qquad (2)'$

Combining Eqs.(1)'&(2)' *gives*

$$\rho_g = \frac{mP}{nRT}$$

1) Steel-Ar system

$$\therefore \frac{(\rho_{Ar})_{1833K}}{(\rho_{Ar})_{std}} = \left(\frac{P}{P_{std}}\right)\left(\frac{T_{std}}{T_{1833K}}\right) = \left(\frac{P_{std} + \rho_S \cdot g \cdot H_S}{P_{std}}\right)\left(\frac{273}{1833}\right)$$

$$= 1.679 * \left(\frac{1}{6.714}\right) \approx \frac{1}{4} = 0.25$$

$$\therefore (\rho_{Ar})_{1833K} = 0.25 * (\rho_{Ar})_{std} = 0.446\, kg/m^3$$

∴ Ar volume expansion coefficient relative to STP = 4

2) Water-air system

$$\frac{(\rho_{Air})_{273K}}{(\rho_{Air})_{std}} = \left(\frac{P}{P_{std}}\right)\left(\frac{T_{std}}{T_{273K}}\right) = \left(\frac{P_{std} + \rho_W \cdot g \cdot H_W}{P_{std}}\right)\left(\frac{273}{273}\right)$$

$$= 1.032$$

$$\therefore (\rho_{Air})_{273K} = 1.032 * (\rho_{Air})_{std} = 1.331\, kg/m^3$$

Table. Properties used in calculation

Standard pressure	P_{std}	101325	Pa
The Density of the liquid (kg/m^3)			
Density of water	ρ_W	1000	kg/m^3
Density of steel	ρ_S	7020	kg/m^3
The Density of the gas (kg/m^3, STP)			
Density of Ar gas	ρ_{Ar}	1.783	kg/m^3
Density of air gas	ρ_{Air}	1.29	kg/m^3
The height of steel in tundish	H_s	1.0	m
The height of water in tundish	H_w	0.33	m

$$\therefore (\rho_{Ar-hot}) = 0.446\, kg/m^3$$

$$\therefore (\rho_{air-out}) = 1.331\, kg/m^3$$