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Argon Gas Flow through Nozzle Refractories

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Acknowledgements

- Continuous Casting Consortium at UIUC (Accumold, Algoma, Corus, Labein, LWB Refractories, Nucor, Mittal Riverdale, Postech)
- COMSOL, Inc. (FEMLab 3.0)
- Other Graduate students, Kun Xu, Francois Harvengt, Julien Nuttin
- R. Nunnington & D. Griffin, LWB (data)

Reasons for Argon Gas Injection into Nozzles

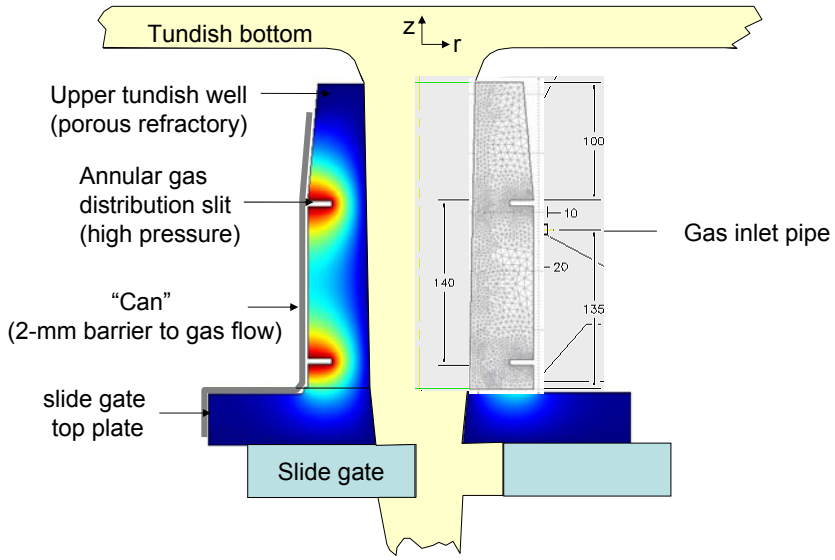
- Argon reduces air aspiration and reoxidation by increasing pressure inside nozzle and replacing air aspiration with argon
- Film of gas forms on nozzle walls to prevent inclusion attachment
- Inclusions attach to bubbles, which carry them away
- Gas increases flow turbulence, dislodging inclusions from nozzle walls
- Argon retards chemical reactions with nozzle walls
- Argon bubble buoyancy changes flow pattern in nozzle and especially in mold

Objectives

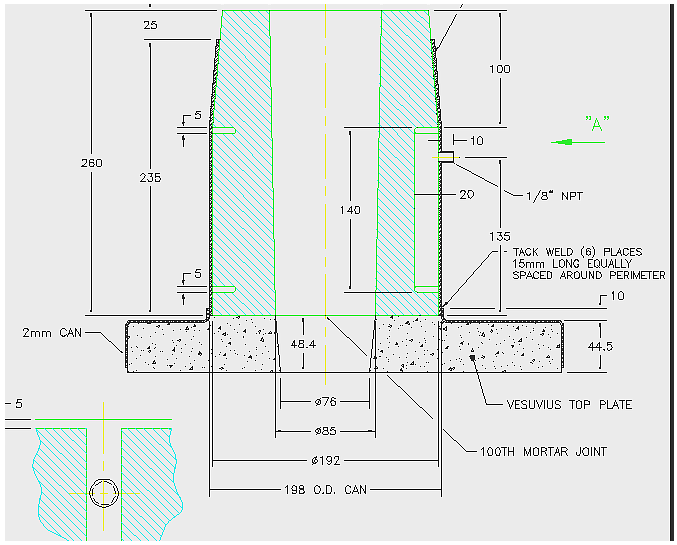
Determine steady argon gas velocity and bubble size distribution exiting nozzle walls and effects of:

- Nozzle thermal conductivity
- Gas sealing at nozzle – top plate junction
- Gas inlet pressure (back pressure)
- Nozzle refractory permeability
- Nozzle refractory geometry:
  - Nozzle shape
  - Number of argon slits
  - Slit location (single slit)

Nozzle domain "2-slit base case"



2-slit nozzle geometry



Governing Phenomena & equations (axisymmetric FEM model of nozzle)

- Temperature Distribution in nozzle wall

$$\frac{k}{r}\frac{\partial T}{\partial r}+\frac{\partial}{\partial r}k\frac{\partial T}{\partial r}=0$$

- Effects of pressure and temperature on gas expansion

$$PV = nRT$$

- Gas diffusion through porous refractory

$$\frac{K_D}{P}\left(\frac{\partial P}{\partial r}\right)^2-\frac{K_D}{T}\left(\frac{\partial T}{\partial r}\right)\left(\frac{\partial P}{\partial r}\right)+\frac{\partial}{\partial r}K_D\frac{\partial P}{\partial r}+\frac{K_D}{r}\frac{\partial P}{\partial r}++\frac{\partial}{\partial z}K_D\frac{\partial P}{\partial z}+\frac{K_D}{P}\left(\frac{\partial P}{\partial z}\right)^2=0$$

Base Conditions

Inlet pressure	P_{in}	200 kPa
Pressure at nozzle inside wall & ambient	P_∞	101 kPa
Specific permeability	K_p	10.1 nPm = 10.1 x10^{-7} mm²
Dynamic Viscosity	μ	7.42 x10^{-5} MPa.s = kg/(m-s)
Permeability (K_p/ μ)	K_D	1.3612 x10^{-8} m²/(Pa.s)
Thermal conductivity	k	2.6 or 18 W/mK
Heat transfer coefficient (nozzle exterior)	h	40 W/m²K

Note: keeping inlet pressure constant results in variable gas flow rate (depending on conditions and properties of nozzle)

Properties of Fired Doloma Tundish Nozzle

- Composition (wt%) 55.9 CaO; 38.9 MgO; 0.6 Al2O3; 0.9 SiO2; 0.9 Fe2O3; 2.8 ZrO2
- Bulk Density (g/cc)2.92
- Porosity 14.4%
- Permeability 10.1 nPm
- Thermal Conductivity 2.6 W/mK @1100°C
- Specific Heat 0.25 kcal/Kg °C @1100 °C

Solving equations using conventional FEM (Femlab 3.0)

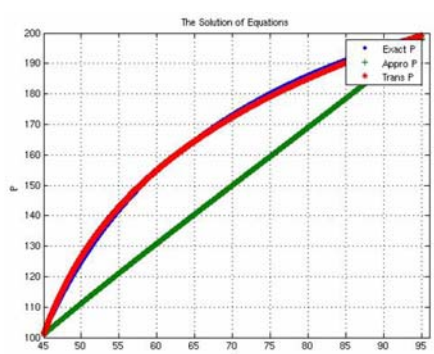
Adjust radii to account for temperature and pressure:

$$\frac{r_2'}{r_1'} = \left(\frac{r_2}{r_1}\right)\left(\frac{T_1}{T_2}\right)\left(\frac{P_2}{P_1}\right) \qquad r_1' = \frac{r_2 - r_1}{\left(\frac{r_2}{r_1}\right)\left(\frac{T_1}{T_2}\right)\left(\frac{P_2}{P_1}\right) - 1} \qquad r_2' = \frac{(r_2 - r_1)\left(\frac{r_2}{r_1}\right)\left(\frac{T_1}{T_2}\right)\left(\frac{P_2}{P_1}\right)}{\left(\frac{r_2}{r_1}\right)\left(\frac{T_1}{T_2}\right)\left(\frac{P_2}{P_1}\right) - 1}$$

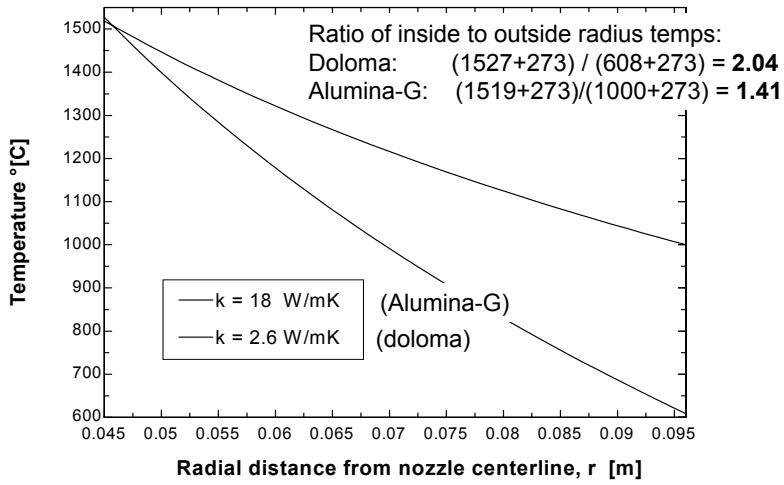
Solve simple axisymmetric equation:

$$\frac{\partial}{\partial r} K_D \frac{\partial P}{\partial r} + \frac{K_D}{r}\frac{\partial P}{\partial r} + \frac{\partial}{\partial z} K_D \frac{\partial P}{\partial z} = 0$$

Validate approach using 1-D analytical solution:
- Approximate result (appro) is very close to exact.
- Ignoring the thermal and pressure expansion effects (trans) is different



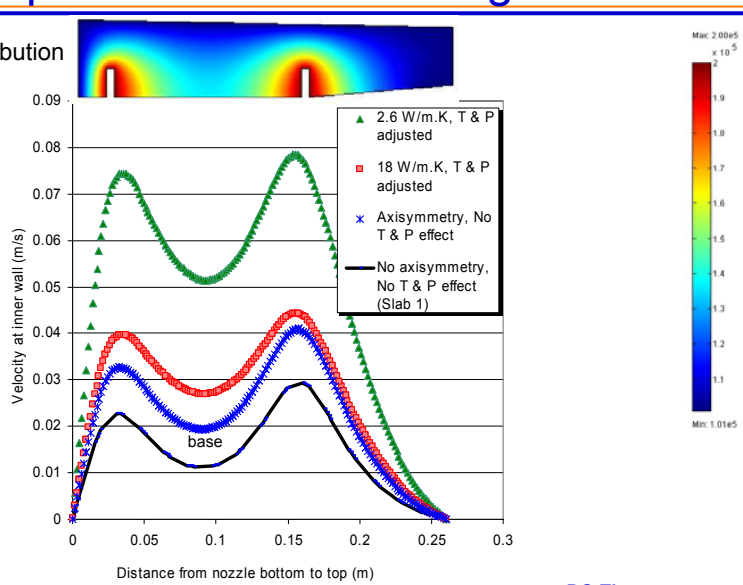
Temperature Profile Through Nozzle Wall



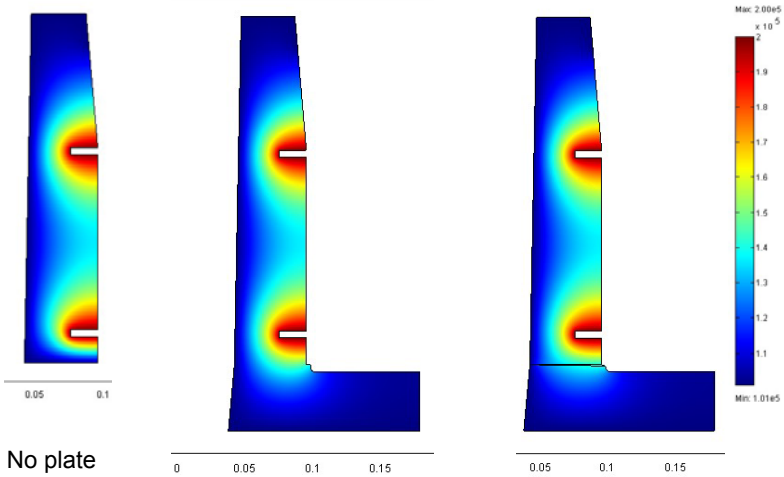
h=40 W/m²K

Importance of temperature and pressure variation on gas flow

Pressure Distribution (Pa)



Effect of Slide-gate Top Plate

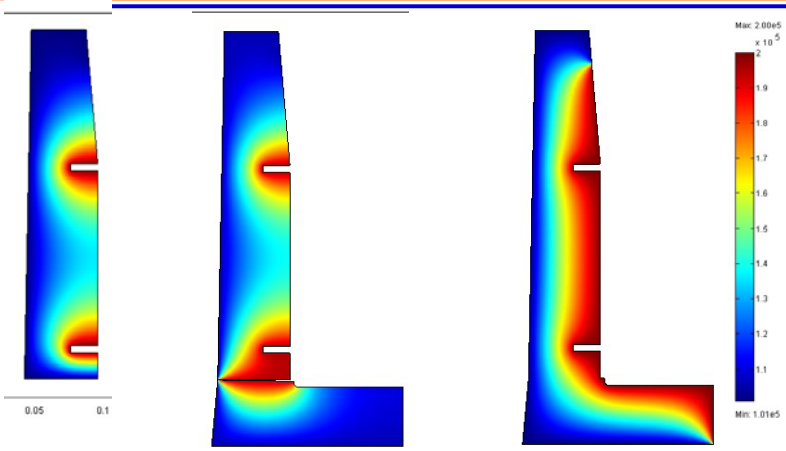


No plate (max leakage from bottom)

Top plate with no gap (min bottom leakage)

Top plate with high-permeability wedge-gap (realistic leakage)

Effect of Leakage



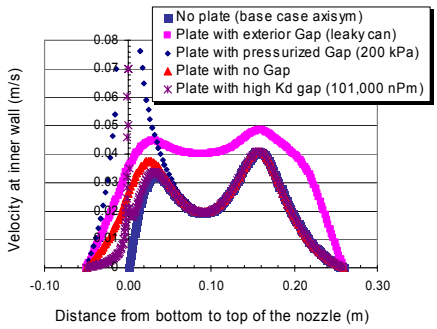
No plate (no leakage to side)

Top plate with gap pressurized to 200kPa (from partial side leakage)

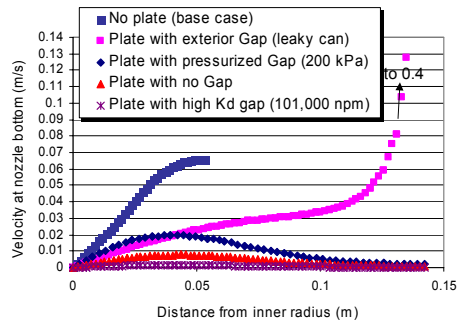
Leakage all along exterior side between nozzle and can (from can thermal distortion)

Effect of Slide gate - top plate

Gas Flow into Steel

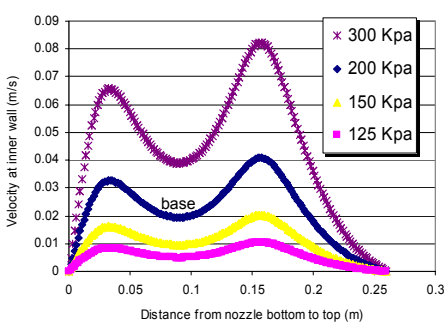


Gas Flow into Gap

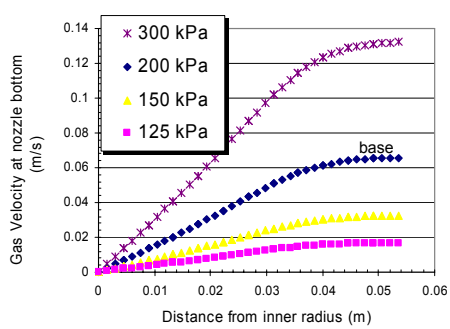


Effect of Inlet Pressure

Gas Flow into Steel



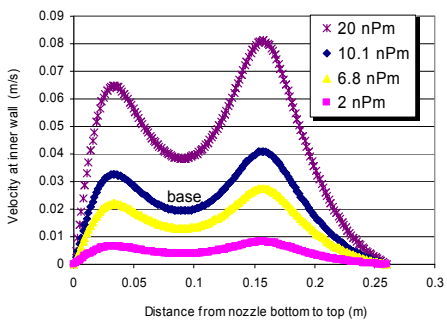
Max Gas Flow into Gap



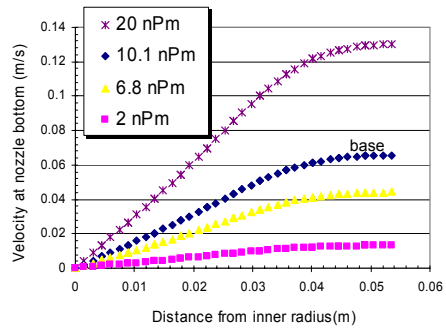
2-slit nozzle, base conditions, no T or P adjustment

Effect of Refractory Permeability

Gas Flow into Steel



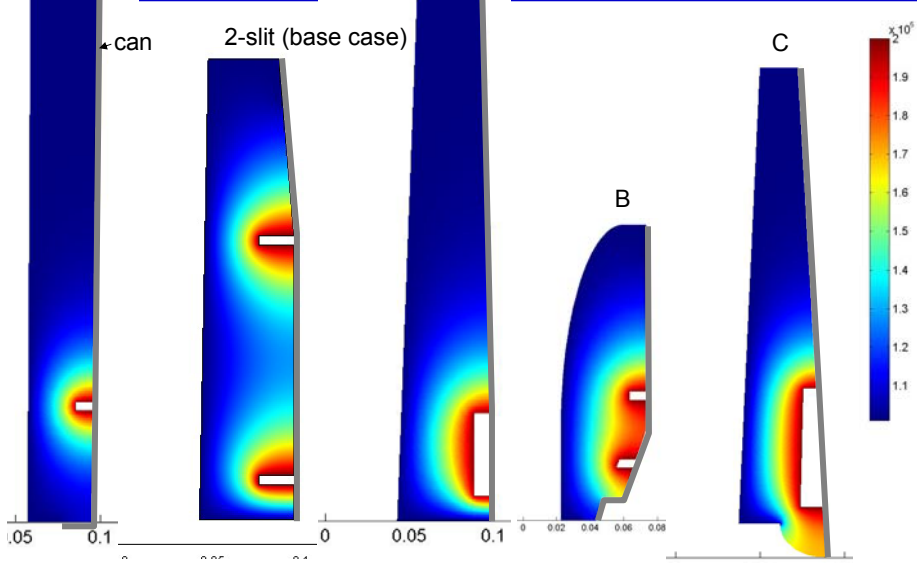
Max Gas Flow into Gap



2-slit nozzle, base conditions, no T or P adjustment

Pressure distribution

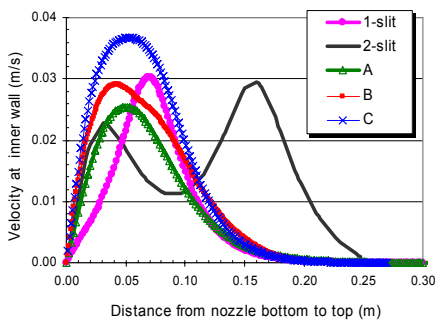
Effect of nozzle geometry



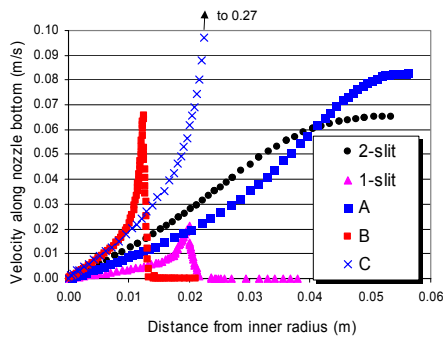
base conditions, no axisymmetry, no T or P adjustment

Effect of Nozzle Geometry

Gas Flow into Steel

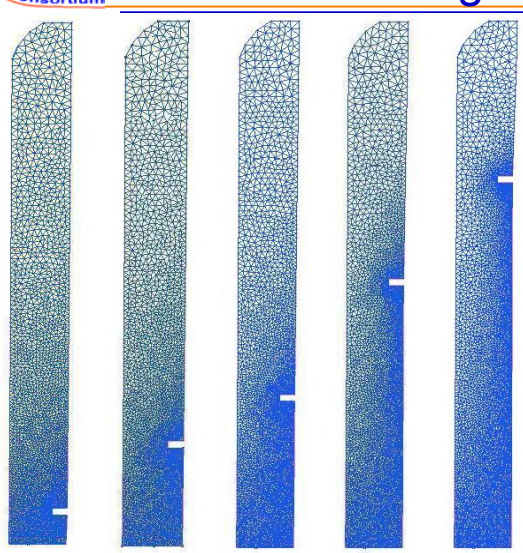


Max Gas Flow into Gap



base conditions, no axisymmetry, no T or P adjustment

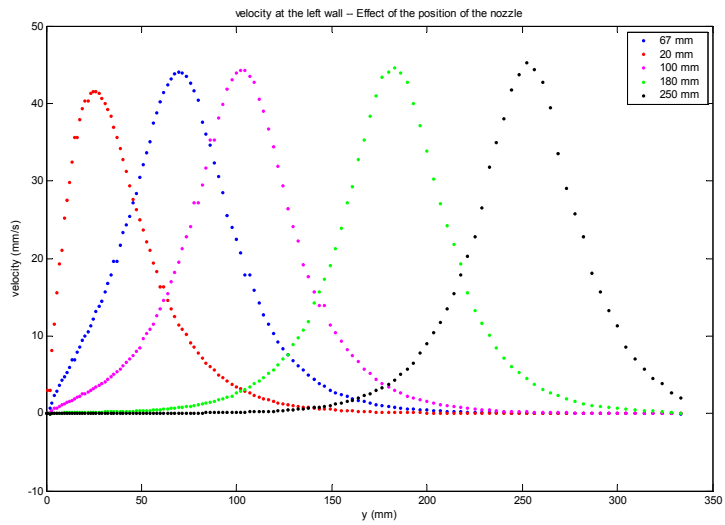
Effect of location of annular gas-inlet slit



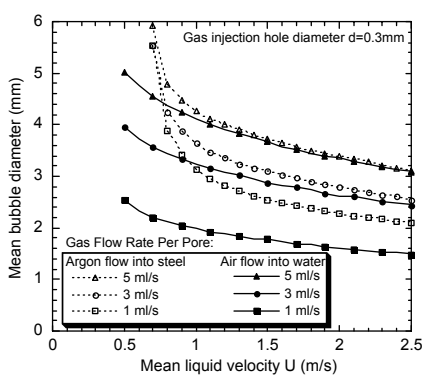
h = 20 mm h = 67 mm h = 100 mm h = 180 mm h = 250 mm

1-slit nozzle geometry
base conditions
no axisymmetry,
no T or P adjustment

Effect of slit location on gas flow profile



Bubble size distribution

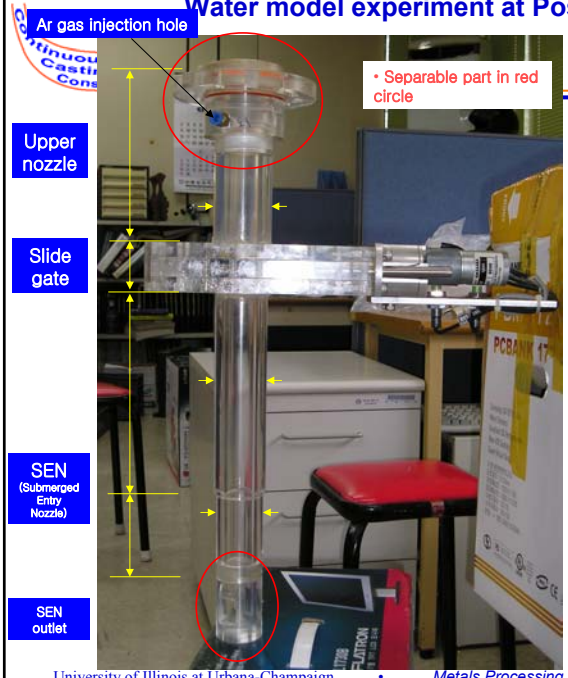


Bubble diameter entering nozzle depends on:
- vertical steel velocity
- gas flow rate per site (pore or hole)

H. Bai & Thomas, Met Trans B, 2001

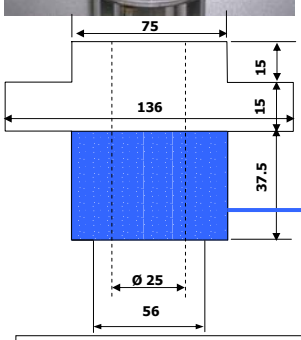
- Depends on number of "active sites" in nozzle wall (to determine flow rate / pore)
- Should conduct experiments to measure this

Water model experiment at Postech – Gogi Lee



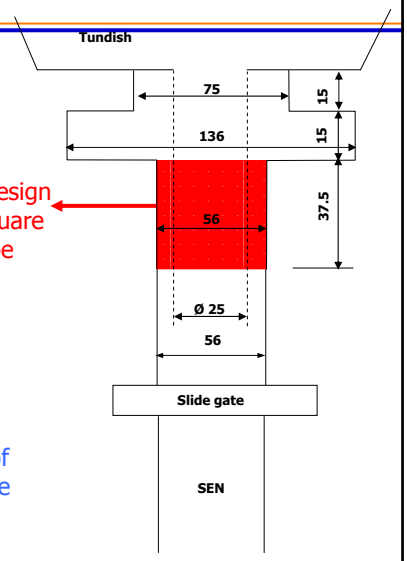
- Dimension of each part
- Especially, the dimension of upper nozzle and slide gate and outlet part is need in detail

New 3rd part of top UTN



Remove of round tube

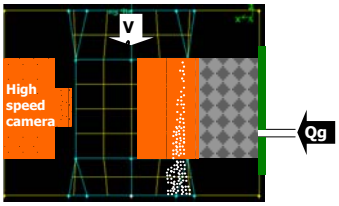
New design for square tube



Planned water model experiments

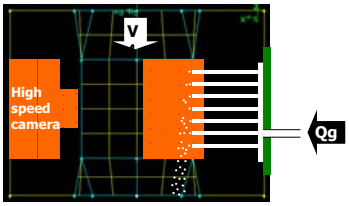
Variables:

1. gas flow rate (Qg, ℓ/min)
2. liquid flow rate (Vℓ, m3/sec)
3. hole shape (porous refractory vs. machined holes)
4. manufacturing variations in porous refractory



< porous refractory >

Observe the bubble sizes according to permeability of refractory



< machined holes >

Observe the bubble sizes according to hole spacing

Conclusions

- Model of argon gas flow through nozzle refractory has been developed, including important expansion effects from temperature and pressure changes
- Gas exits nozzle wall into steel with a profile that is closely associated with the annular slit where gas is injected
- Significant gas will leak into gap between nozzle bottom and top plate if there are leaks
- Thermal expansion of can would cause leakage that greatly changes gas flow rate and profile
- Gas flow increases with increasing inlet pressure or decreasing refractory permeability