ANNUAL REPORT 2011

UIUC, August 18, 2011

Model of Argon Flow through UTN Refractory and Bubble Size Estimation

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Simulation of Argon Gas Flow through UTN

- Purpose of the study:
  - to gain insight into argon-steel two-phase flow in UTN and SEN, which greatly influences flow in the mold (especially asymmetric flow)
  - to obtain a reasonable initial bubble size distribution in the argon-steel two phase flow in UTN and SEN, which is needed to simulate argon-steel flow in the mold
  - to run parametric studies of gas injection on the flow pattern
  - to evaluate/design UTN geometry / material for optimal gas flow
- This work includes:
  - Description and validation of two models:
    - pressure-source model
    - porous-flow model
  - Simulation of argon flow through Dofasco UTN
    - Heat transfer analysis
    - Gas flow simulation using porous-flow model

Governing Equations
-- Pressure-Source Model

Darcy's Law: $\mathbf{v} = -K_D \nabla p$ **(1)**

Mass Conservation (or continuity): $\nabla \cdot (\rho \mathbf{v}) = 0$ **(2)**

Heat Conduction: $\nabla \cdot (k \nabla T) = 0$ **(3)**

Ideal Gas Law: $p = \rho R T$ **(4)**

Eqn (1) and (2) $\Rightarrow$ $\nabla \cdot (\rho K_D \nabla p) = 0$ $\Rightarrow$ $\nabla \rho \cdot (K_D \nabla p) + \rho \nabla \cdot (K_D \nabla p) = 0$

$$\Rightarrow \nabla \cdot (K_D \nabla p) = -\frac{1}{\rho}[\nabla \rho \cdot (K_D \nabla p)] \qquad \rho = \frac{p}{RT}$$

$$\Rightarrow \boxed{\nabla \cdot (K_D \nabla p) = -\frac{RT}{p}\left[\nabla\left(\frac{p}{RT}\right) \cdot (K_D \nabla p)\right] = \dot{S}}$$

pressure diffusion

Pressure source due to gas expansion

-- **For Pressure-Source Model**

- The **left hand side** of the final equation (in red box) is the standard diffusion term, while the **right hand side is in the form of a source term that accounts for the effect of gas expansion due to temperature and pressure gradient**.
- Add the source term into a FLUENT model of 3-D scalar diffusion (with pressure as the scalar) and solve coupled with a 3-D energy equation

Governing Equations
-- Porous Flow Model

Mass Conservation (or continuity): $\nabla \cdot (\rho \mathbf{v}) = 0$ **(1)**

Heat Conduction: $\nabla \cdot (k \nabla T) = 0$ **(2)**

Ideal Gas Law: $p = \rho R T$ **(3)**

Full Set of Navier-Stokes Equations for flow in porous media:

$$\nabla \cdot (\rho \mathbf{v}\mathbf{v}) \sim \frac{\rho V^2}{\Delta r} = \frac{0.3 \times 0.0073^2}{0.035} \approx 4.6 \times 10^{-4}$$

viscous resistance

Re ~2.3, C=0 for laminar flow

$$\underbrace{\frac{\partial(\rho \mathbf{v})}{\partial t}}_{0} + \underbrace{\nabla \cdot (\rho \mathbf{v}\mathbf{v})}_{0} = -\nabla p + \underbrace{\nabla \cdot (\mu \nabla \mathbf{v})}_{0} + \mathbf{F} - \left(\frac{\mu}{\alpha}\mathbf{v} + \underbrace{C\frac{1}{2}\rho|\mathbf{v}|\mathbf{v}}_{0}\right) \qquad \frac{\mu}{\alpha} = \frac{1}{K_D}$$

(steady state problem)

$$\nabla \cdot (\mu \nabla \mathbf{v}) \sim \frac{\mu V}{\Delta r^2} = \frac{8.1 \times 10^{-5} \times 0.0073}{0.035^2} = 4.8 \times 10^{-4}$$

inertial resistance

$$\Rightarrow \mathbf{v} = -K_D \nabla p$$

-- **Porous-Flow Model**

- Construct a complete set of 3-D Navier-Stokes equations, with the momentum equation simplified into equation (1), adopting the ideal gas law to relate density with pressure and temperature. Solve with FLUENT (porous-media flow module) with energy

Permeability (material property model)

Permeability Varying with Temperature:

Specific permeability, from ArcelorMittal for MgO or Alumina refractory: 0.8 – 1.2 x10^{-12} m^2

$$K_D = \frac{K_{DS}}{\mu(T)}$$

- $K_{DS} = 1.01\times10^{-12} m^2$ (constant specific permeability, from Z. Hashisho, '06)
- $\mu(T)$ (gas dynamic viscosity, as a function of local temperature)

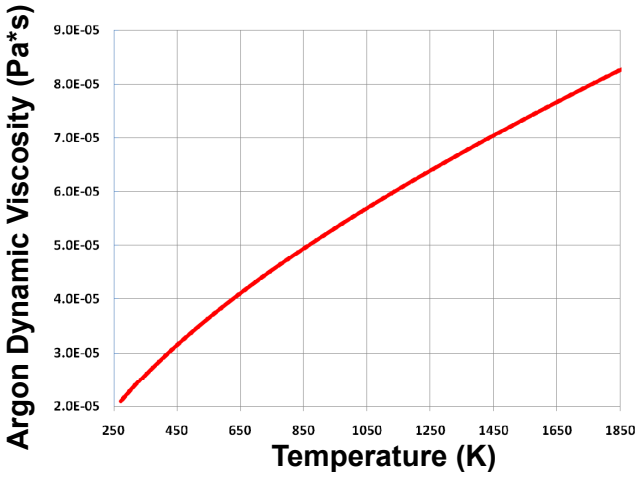
Viscosity Varying with Temperature:

$$\mu(T) = \mu_0 * 10^{\left(0.63842 \lg T - 6.9365/T - 3374.72/T^2 - 1.51196\right)}$$

Dawe '69*

$$\mu_0 = 2.228\times10^{-5} Pa\cdot s$$

Room temperature (20 C) argon viscosity



Ref:

*R. Dawe and E. Smith. Viscosity of Argon at High Temperatures. Science, Vol. 163, pp 675~676, 1969.

Model Validation --- 3D FLUENT Models

- Test Problem (2 cases)
  - 1-D problem of gas flowing through a porous medium,
  - cylindrical coordinate system,
  - heat conduction from heated inner surface (fixed at T1) to outer surface (fixed at T2)
  - gas injected into outer radial surface, and exits inner surface;
  - Effects of varying permeability and dynamic viscosity with temperature on pressure distribution are studied;
  - Both pressure and mass flow rate boundary conditions are tested in this simple problem, and three models are implemented for each of the cases.

B.C. for Case 1, fixed pressure:

$r=R_1$, $P=P_1$, $T=T_1$; $r=R_2$, $P=P_2$, $T=T_2$.

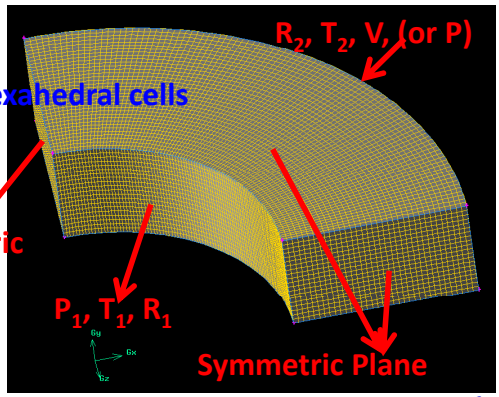
B.C. for Case 2, fixed gas mass flow rate:

$r=R_1$, $P=P_1$, $T=T_1$; $r=R_2$, $V=V_{inlet}$, $T=T_2$.

R_1 (m)	R_2 (m)	P_1 (Pa)	P_2 (Pa)
0.0375	0.0725	100000	200000

V_{inlet} (m/s)	T_1 (K)	T_2 (K)
0.0073	1800	1000

Total: 60000 hexahedral cells



1-D Test Problem – Matlab Solution

1-D numerical solution is obtained independently via a Matlab code to compare and validate solutions from FLUENT.

For the 1-D test problem, the equation above can be written as an ODE, together with the heat conduction equation for heat transfer process:

constant permeability, considering gas expansion

$$\begin{cases} P'' + \left(\frac{1}{r} - \frac{T'}{T}\right)P' + \frac{P'^2}{P} = 0 \\ \frac{1}{r}(rT')' = 0 \end{cases} \qquad P' = \frac{dP}{dr} \quad T' = \frac{dT}{dr}$$

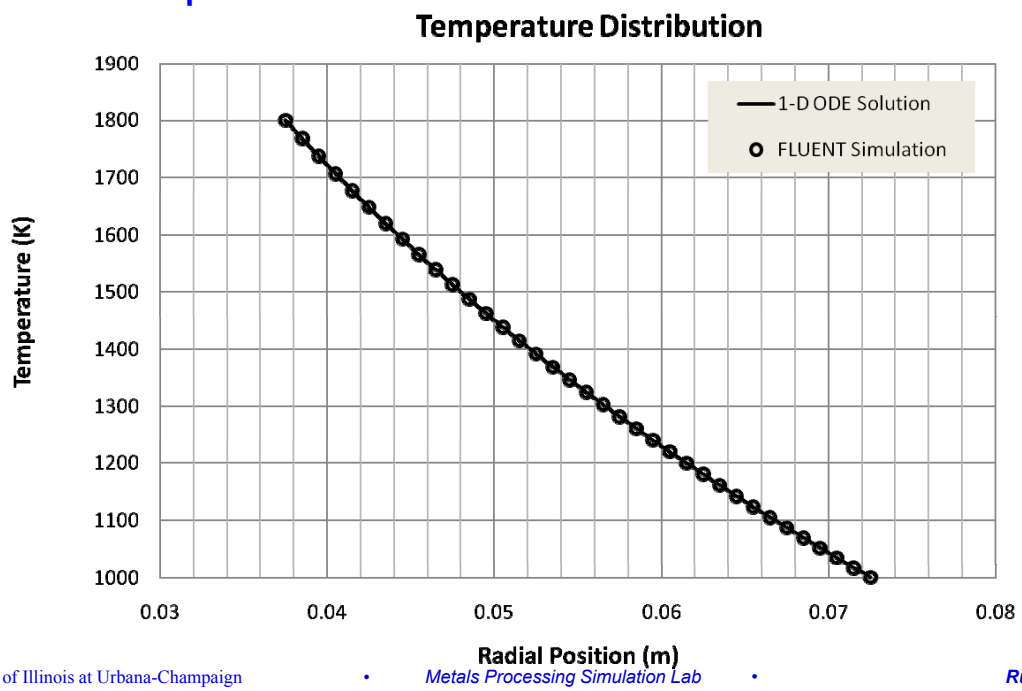
considering the thermal effects on both argon permeability and gas expansion

$$\begin{cases} P'' + \left(\frac{1}{r} - \frac{T'}{T} + \frac{K_D'}{K_D}\right)P' + \frac{P'^2}{P} = 0 \\ \frac{1}{r}(rT')' = 0 \end{cases} \qquad P' = \frac{dP}{dr} \quad T' = \frac{dT}{dr} \quad K_D' = \frac{dK_D}{dr}$$

Solver uses:
- **Implicit scheme**
- **TDMA method**
- **2nd central difference scheme**

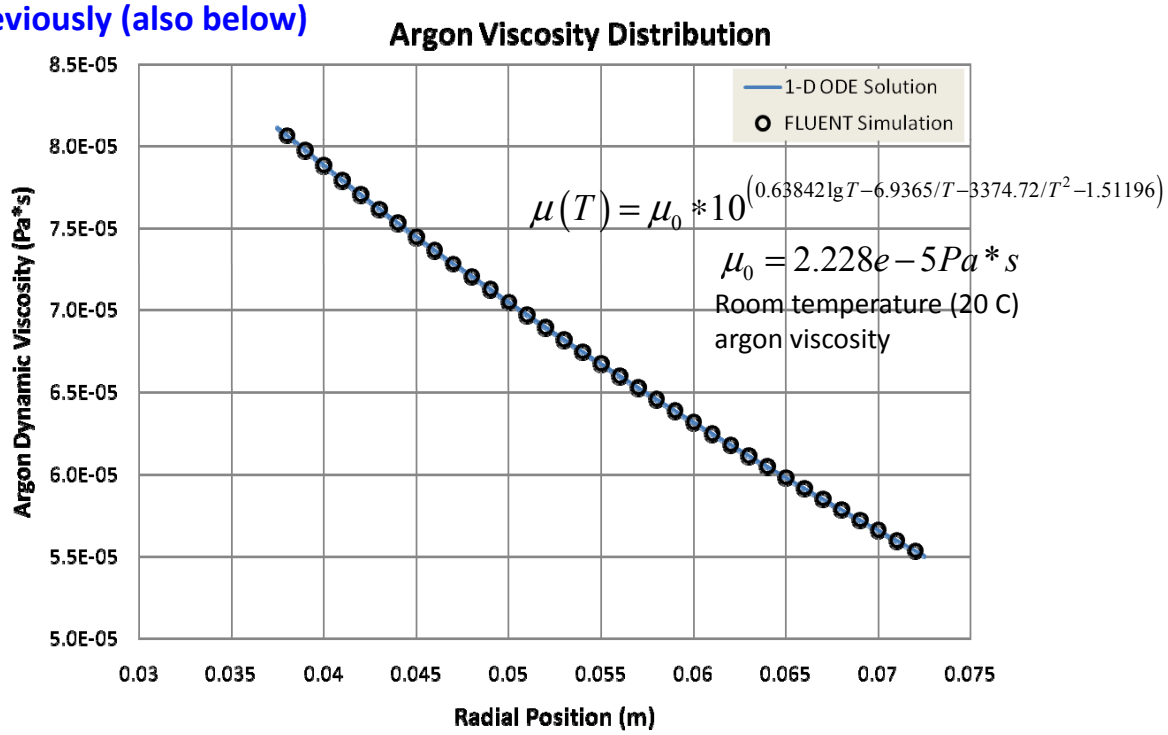
Heat Transfer Calculation – Temperature Profile

For this 1-D test problem, the heat conduction equation can be solved alone without coupling with any fluid flow equations (one-way coupling assumption). The resultant temperature distribution is shown below:



Argon Viscosity Profile

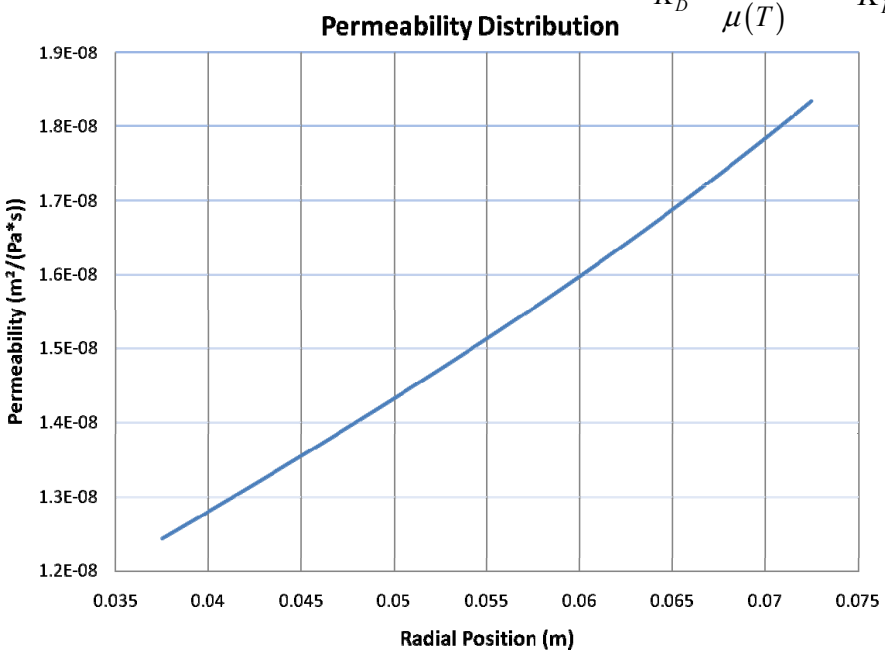
The argon viscosity is related to the local temperature via the correlation stated previously (also below)



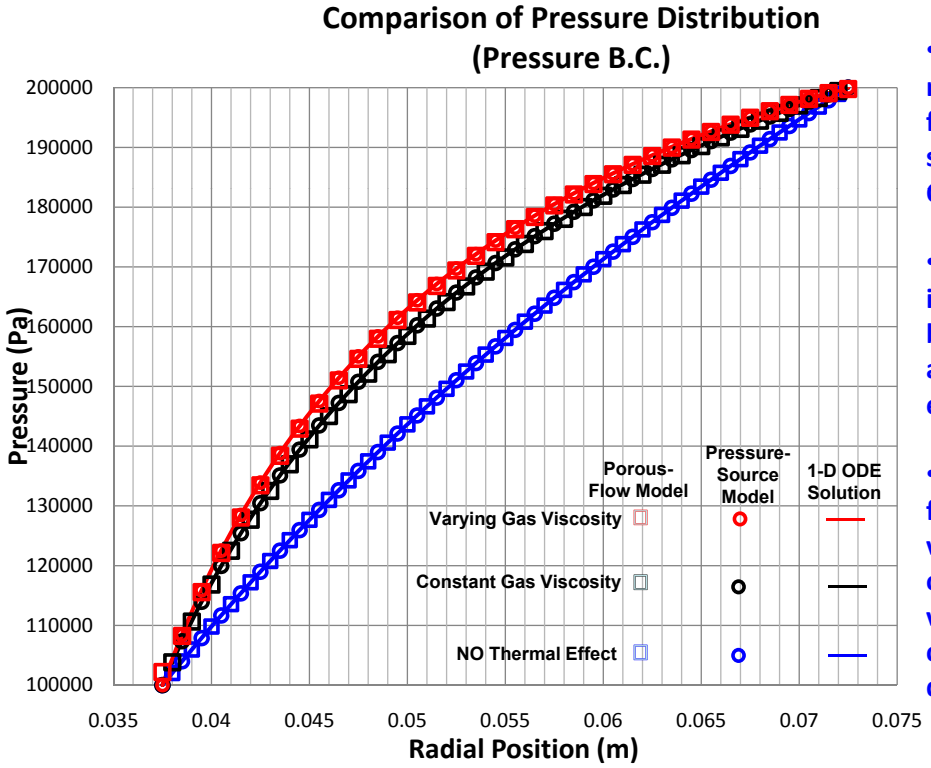
Permeability Profile for Argon Gas

The permeability for argon gas flowing through UTN refractory is determined by both the specific permeability, and the argon gas dynamic viscosity via the following relationship:

$$K_D = \frac{K_{DS}}{\mu(T)} \qquad K_{DS} = 1.01 \times 10^{-12} m^2$$

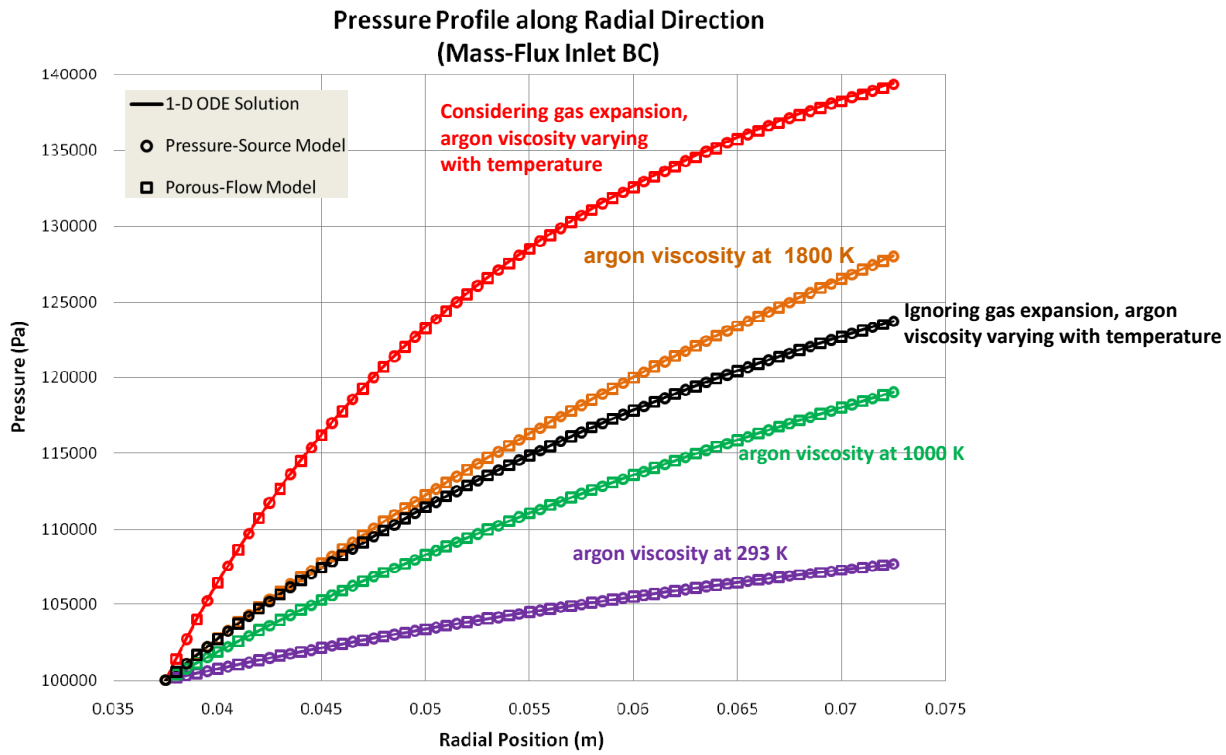


Model Validation CASE 1 —using Pressures as B.C.



- Both the pressure-source model and the porous-flow model match with solution from the 1-D ODE;
- Largest pressure gradient is found in the case with both gas expansion effect and varying viscosity effect
- The shape of the curve for the constant gas viscosity case is irrelevant of the value of the gas viscosity, as long as it is constant throughout the domain.

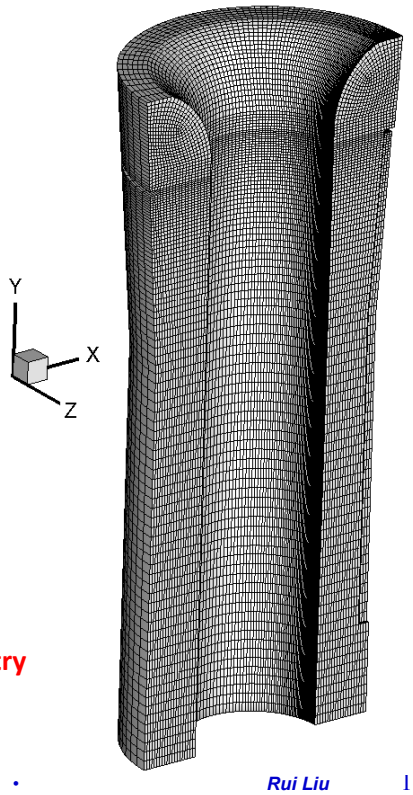
Model Validation CASE 2: -- using Mass Flow Rate as B.C.



Dofasco UTN Gas Flow Model – Assumptions

Specific permeability units: *1 centi-darcy = $9.869*10^{-15}$ m^2*
1 nPm = 10^{-13} m^2

Argon Flow Rate (SLPM)	Specific Permeability (npm)
1.0 (for half UTN)	10.1



- Porous-flow model is used in current simulation
- Heat transfer is modeled once, then the temperature field is exported to the porous-flow simulation as a fixed field, due to the assumption of one-way coupling between heat transfer and the fluid flow

Porous-flow model:

- Argon density varying with local pressure and temperature
- Argon viscosity varying with temperature
- one-way coupling with heat transfer
- half of the UTN is adopted as computation domain due to symmetry
- both circumferential and vertical gas injection slits are included

Total: 180,000 hexahedral cells

Heat Transfer Analysis

The heat transfer calculation for the real-world problem is more complicated than the previous test case, still the assumption is adopted that the heat transfer is not affected by the gas flow through the UTN refractory (true if the porosity is not large, maybe less than 50%). The following parameters are calculated/adopted:

-- heat transfer coefficients at both outer and inner bore surface;

$$h = \frac{Nu * K}{\mu} \qquad Nu = 5 + 0.015\,\mathrm{Re}^a\,\mathrm{Pr}^b \qquad \begin{cases} a = 0.88 - \left(\dfrac{0.24}{4+\mathrm{Pr}}\right) \\ b = \dfrac{1}{3} + 0.5\exp(-0.6\,\mathrm{Pr}) \end{cases}$$

(Sleicher-Rouse correlation)

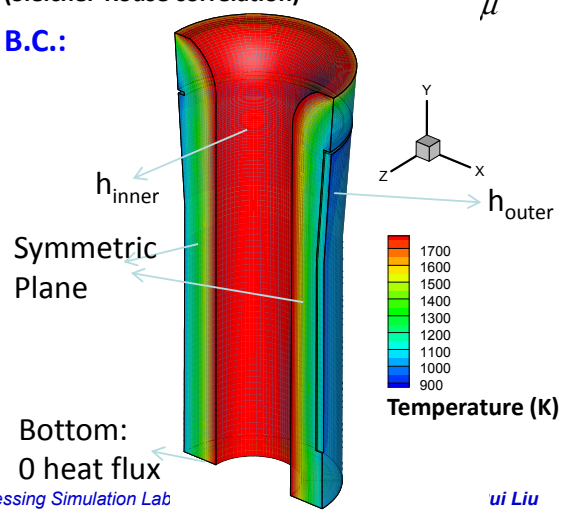
$$\mathrm{Pr} = \frac{\mu}{\rho\alpha}$$

inner bore diameter

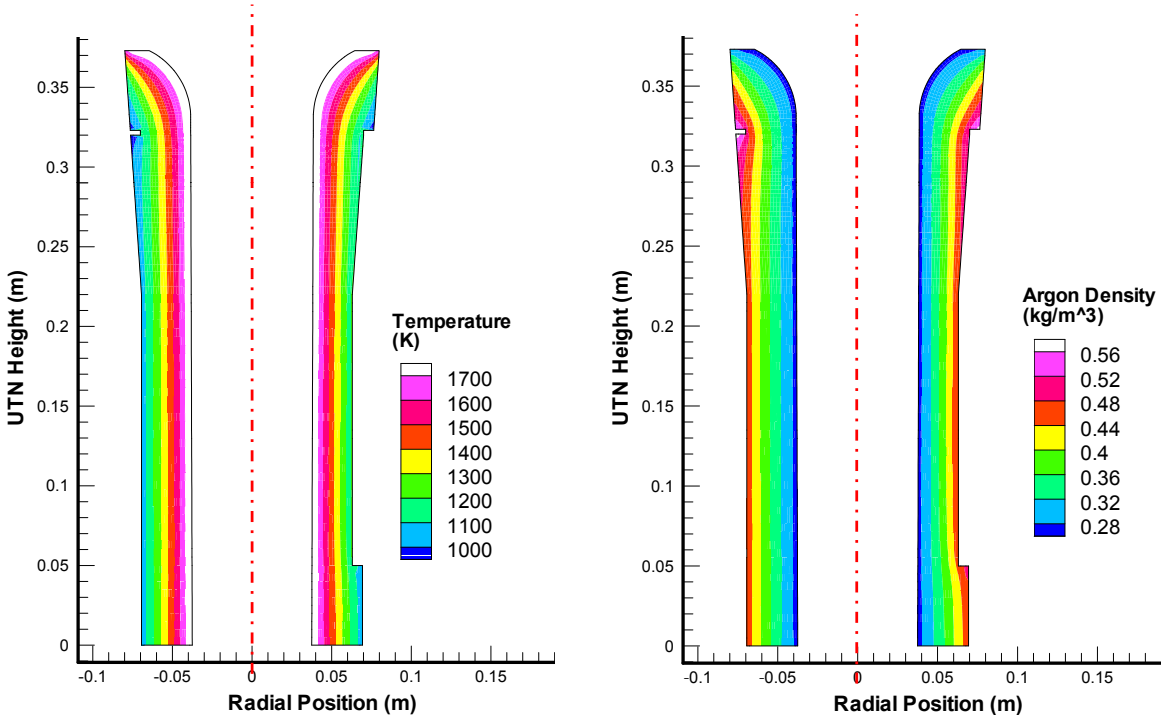
$$\mathrm{Re} = \frac{\rho U D}{\mu}$$

Parameters	Values
h_{inner} (W/m²K)	**$2.5*10^4$**
h_{outer} (W/m²K)	**10**
Heat conductivity K_s (W/mK)	**33**
μ (Pa*s)	**0.0056**
ρ (kg/m³)	**7200**
Average steel velocity U (m/s)	**1.6**

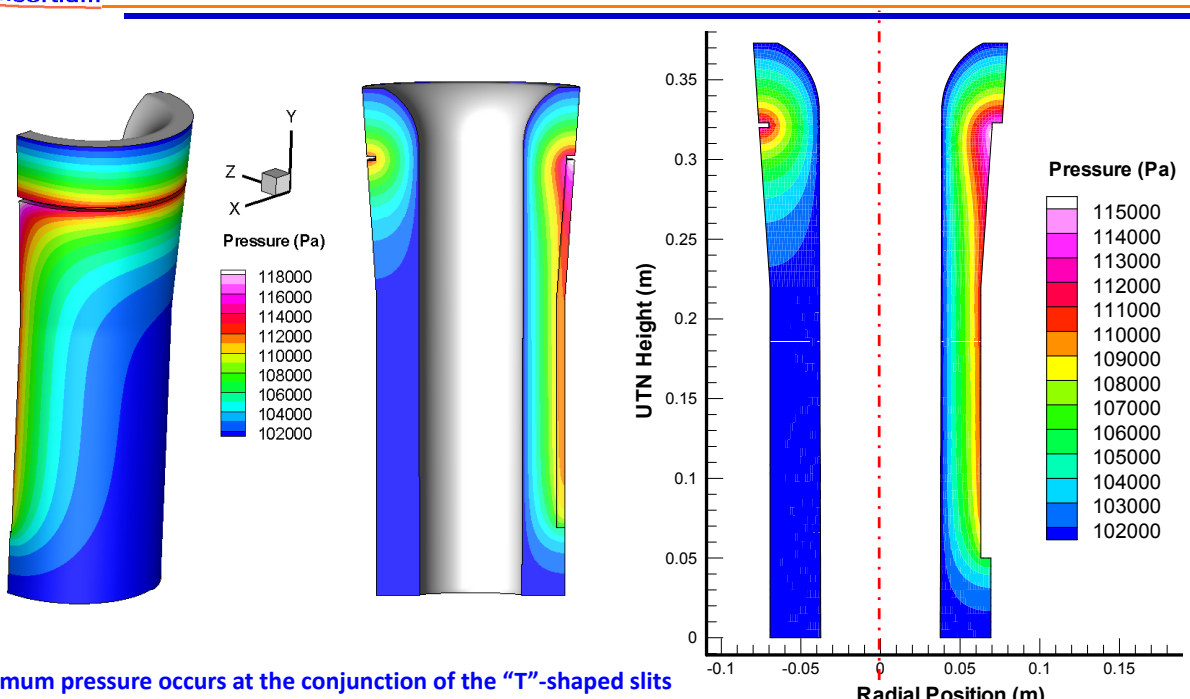
B.C.:



Temperature and Argon Density Distribution

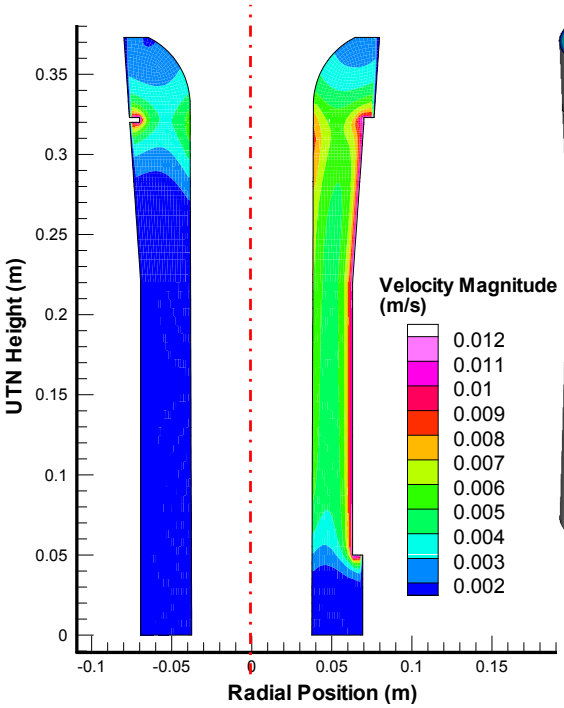


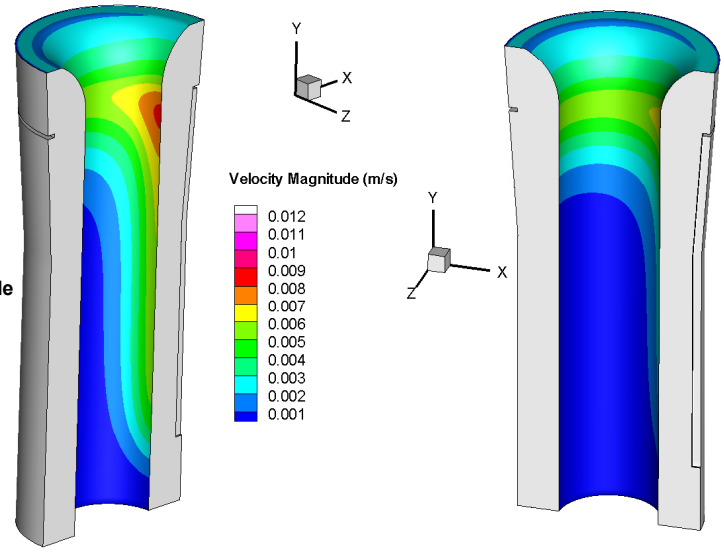
Pressure Distribution through UTN



- **Maximum pressure occurs at the conjunction of the "T"-shaped slits**
- **Obvious asymmetry of the pressure distribution is found through the UTN cross section, due to the asymmetric way of injecting gas into UTN**
- **For current case, the maximum pressure found in the domain is about 20 KPa, while the average pressure at the slits is approximately 12 KPa.**

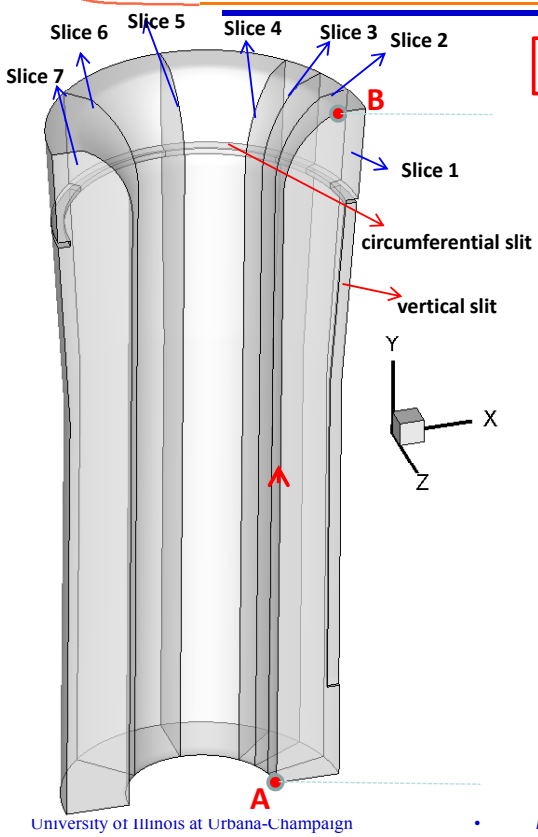
Average Velocity Contour at Inner Bore Surface

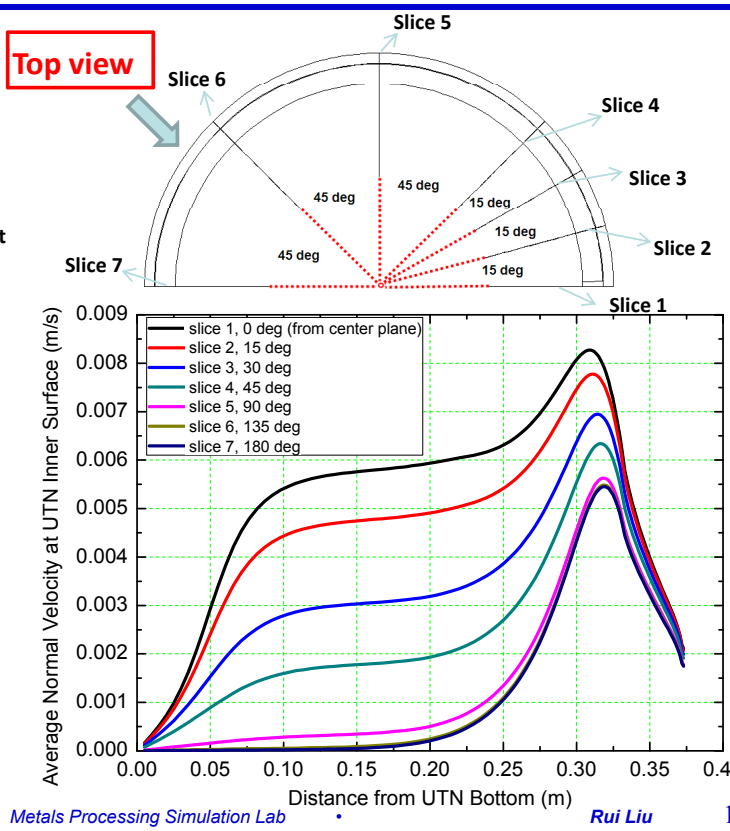




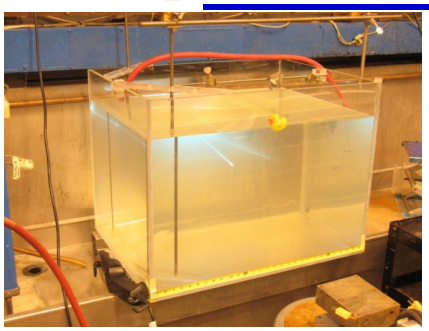
- Maximum velocity is found at the location corresponding to the conjunction point of the "T"-shaped slits;
- The average gas velocity entering the UTN inner surface corresponding to the circular slit is approximately 5~6 mm/s

Average Normal Velocity Profiles at Different Circumferential Locations



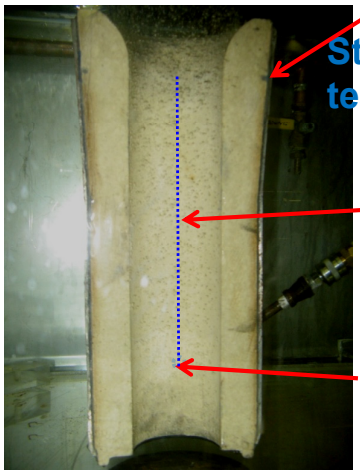


Validation via Static Test



water tank

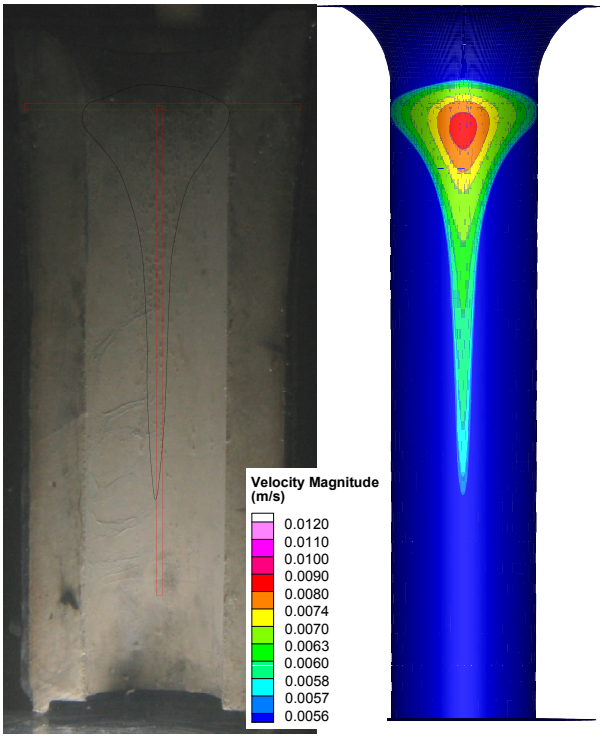
upper ring



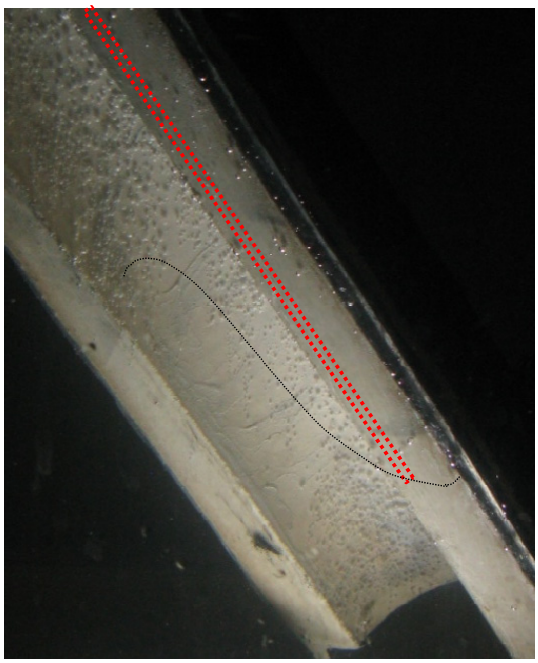
Static bubbling test

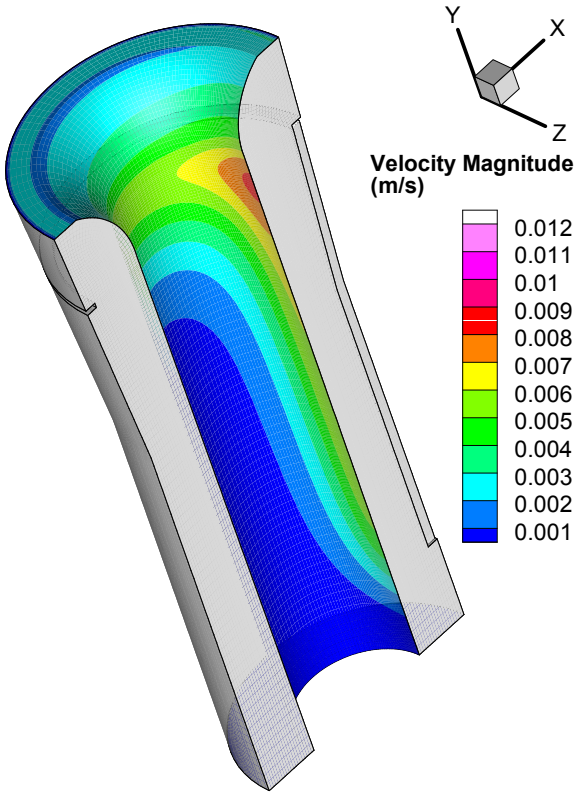
Vertical slit at outer surface

Gas injection point (at outer surface)

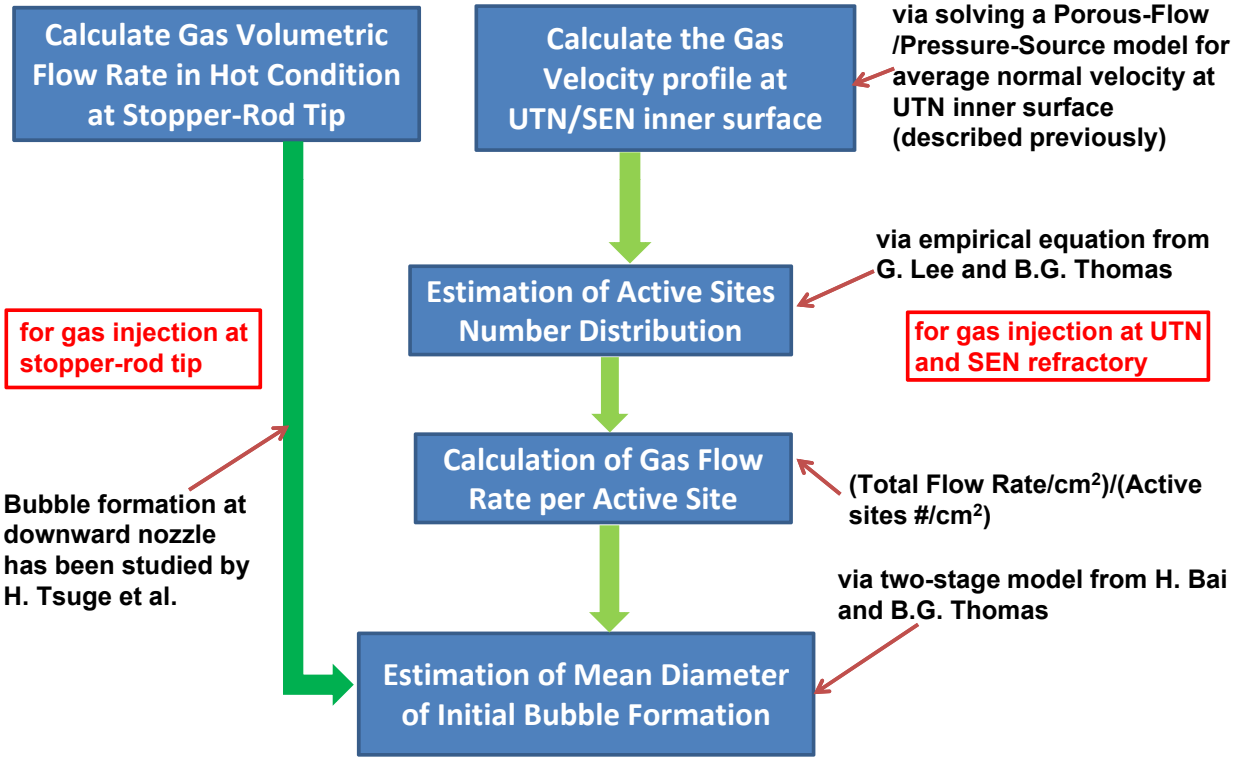


Comparison of Bubble Distribution on UTN Inner Surface

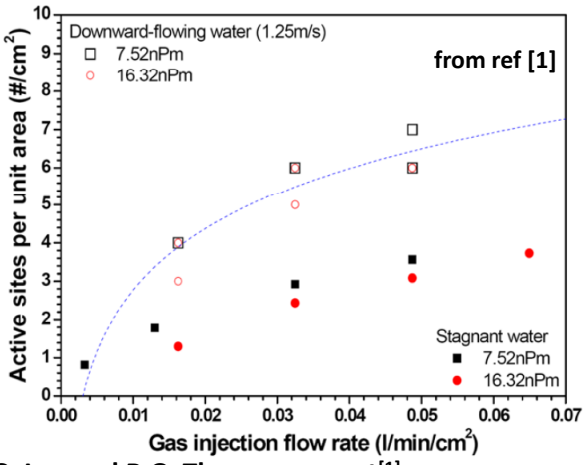


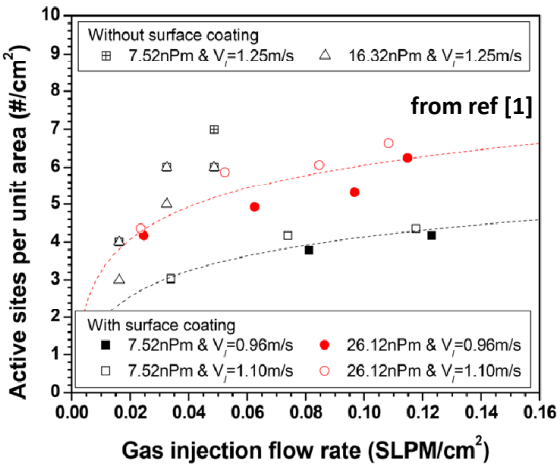


Methodology of Bubble Size Estimation in Argon-Steel System



Estimation of Active Sites Number in UTN/SEN Refractory





G. Lee and B.G. Thomas suggest[1]:

$$\text{Active sites per unit area}\,(\#/\text{cm}^2) = 7 \times \frac{Q_g^{0.2635} \times U^{0.85} \times P_{erm}^{0.3308}}{Radians(\theta)}$$

Where:

Q_g: the gas injection flow rate per cm² (LPM);

U: liquid superficial velocity (m/s);

P_{erm}: material permeability (npm);

ϑ: contact angle for wettability (rad)

So the number of active sites per cm² is:

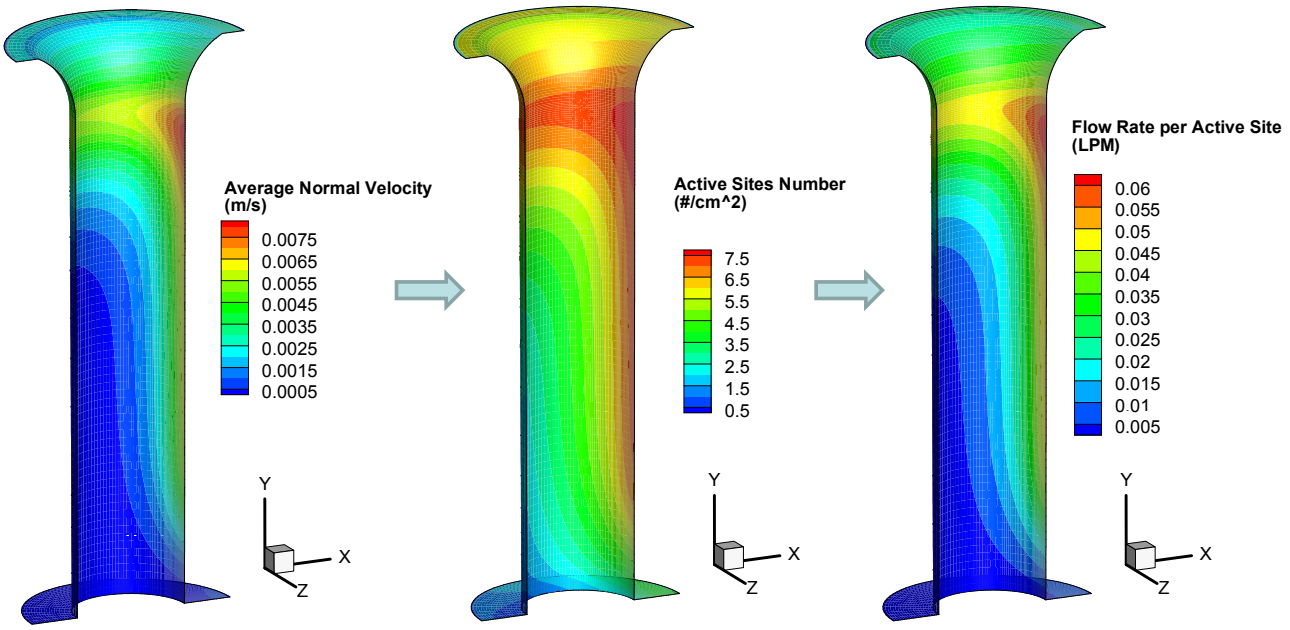
$$N_{site} = \frac{7 Q_g^{0.2635} U^{0.85} P_{erm}^{0.3308}}{\theta}$$

Ref:
[1] G. Lee, B.G. Thomas, et al., Met. Mater. Int., Vol. 16, No. 3 (2010), pp. 501~506

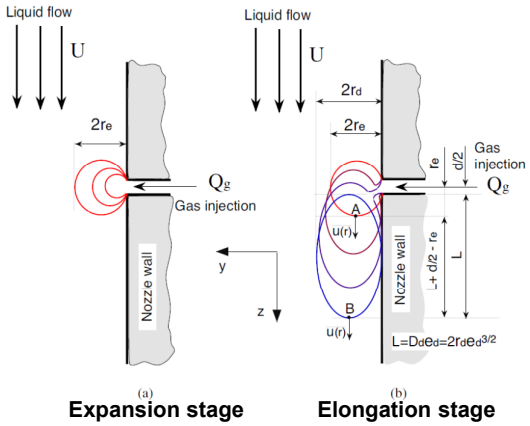
Calculation of Gas Flow Rate per Active Site

Adopting the active sites number correlation at UTN inner surface:

$$N_{site} = \frac{7 Q_g^{0.2635} U^{0.85} P_{erm}^{0.3308}}{\theta} \Rightarrow Q_{site} = \frac{Q_g}{N_{site}} = \frac{1}{7} \frac{Q_g^{0.7365} \theta}{U^{0.85} P_{erm}^{0.3308}}$$



Estimation of Mean Bubble Size using a Two-Stage Model



Expansion stage **Elongation stage**

--Figures from ref [2]

Active sites function as drilled holes where gas is injected. So based on the number of active sites and gas flow rate over an area, the gas flow rate per active site can be determined.

Ref:

[2] B. Hua and B. G. Thomas, Metall. Mater. Trans. B 32, 1143(2001).

Hua's two-stage initial bubble formation model[2]:

1.Expansion stage (solving for r, as r_e)

$$C_D \frac{1}{2} \rho_l \bar{u}^2 \pi r^2 = \frac{4}{3} \pi r^3 (\rho_l - \rho_g) g + \frac{1}{2} \pi r \sigma \sin\theta_o (\cos\theta_r - \cos\theta_a)$$

Drag coefficient: $C_D = \frac{24}{\mathrm{Re}_{bub}} (1 + 0.15 \mathrm{Re}_{bub}^{0.687}) + 0.42 / (1 + 4.25 \times 10^4 \mathrm{Re}_{bub}^{-1.16})$

Bubble Reynolds number: $Re_{bub} = \frac{\bar{u} D}{\upsilon}$

$$\bar{u} = \frac{1}{2r} \int_{y=0}^{y=2r} u dy = 1.3173 U \frac{r^{1/7}}{D_N^{1/7}}$$

Based on the 1/7th law in turbulent flow in the circular pipe

Contact angle function: $f_\theta = \sin\theta_o (\cos\theta_r - \cos\theta_a)$

$$f_\theta(U) = -0.06079 + 0.33109 U(m/s) + 0.078773 U(m/s)^2$$

Empirical correlation with liquid steel superficial velocity

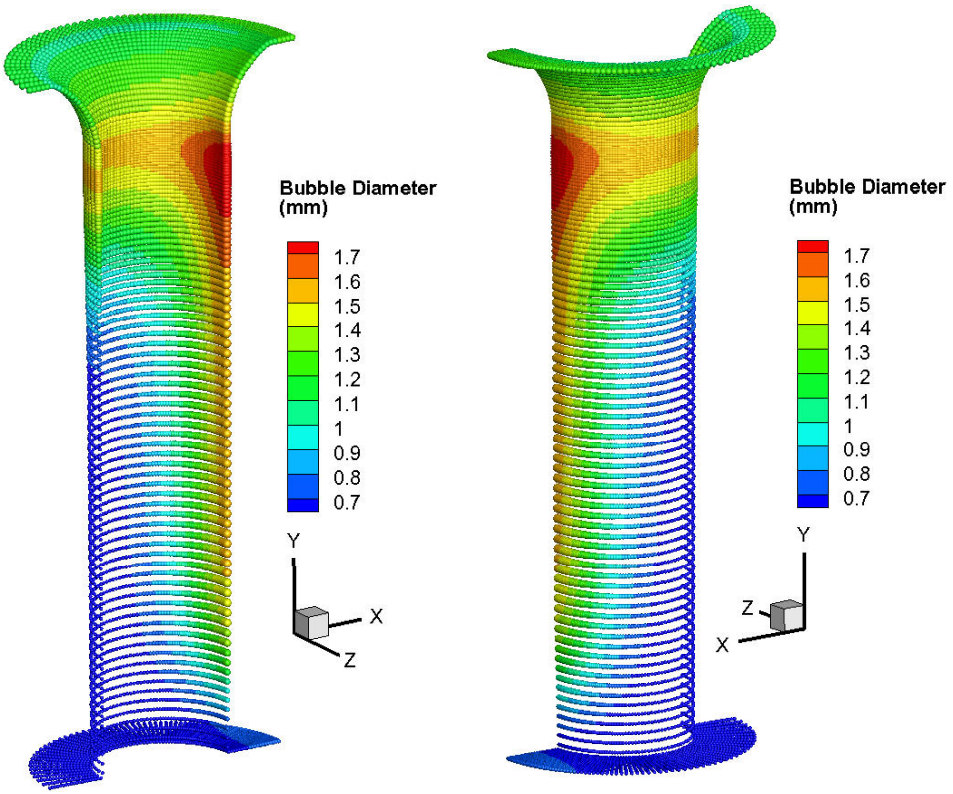
2.Elongation stage (solving for r_d)

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

$$a = \frac{e_d - 1}{r_d - r_e} \quad b = \frac{r_d - e_d r_e}{r_d - r_e} \quad e_d = 0.78592 + 0.70797 U(m/s) - 0.12793 U(m/s)^2$$

D_N :nozzle inner diameter (m)
ρ_l :liquid density (kg/m³)
ρ_g :gas density (kg/m³)
U :liquid steel superficial velocity (m/s)
σ :surface tension (N/m)
υ :kinematic viscosity of liquid steel (Pa*s)

Estimation of Bubble Size Distribution



Model Application: Gas Leakage Prediction

- **Parameters for this process:**
  - Casting speed: **40 ipm**
  - Mold width: **72 inches**
  - Mold thickness: **10 inches**
  - Submergence depth: **8 inches**
  - Dithering amplitude: **14 mm or 7 mm**
  - Dithering frequency: **0.4 Hz**
  - Total gas injection flow rate: **~20 SLPM**
  - Back Pressure: **19 psi**
  - SEN inner bore diameter: **80 mm**
  - Plate diameter: **75 mm**
  - SEN bottom shape: **Cup bottom**
- **Gas injection flow rate into the nozzle can be determined by modeling the hot system while considering leakage.**

Estimation of Gas Flow Rate Entering Nozzle

- Both argon flow rate and back pressure are measured, though one and only one of these two values is needed to define the problem
- Use back pressure as B.C. for the porous-flow model to calculate gas flow rate into the nozzle inside.
- Difference between measured total gas flow rate and calculated gas flow rate into the nozzle reveals the amount of gas leakage

Numerical Model set up:

Heat transfer model coupled porous flow model, with pressure at inner and outer bore surface as boundary conditions.

B.C. fixed pressure: $r=R_1, P=P_1, T=T_1$; $r=R_2, P=P_2, T=T_2$.

R_1 (m)	R_2 (m)	P_1 (Pa)	P_2 (Pa)	T_1 (K)	T_2 (K)
0.04	0.0875	84672	131000	1832	1200

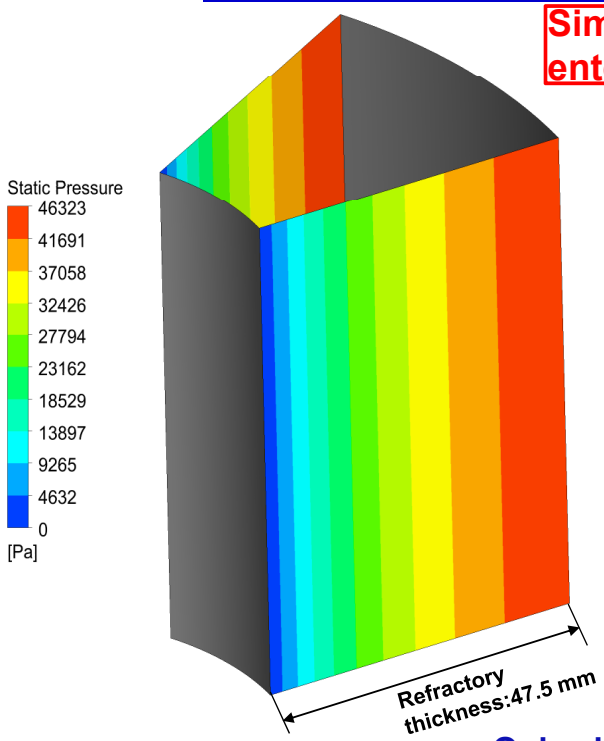
Refractory (specific) permeability (m^2): $1.01*10^{-12}$

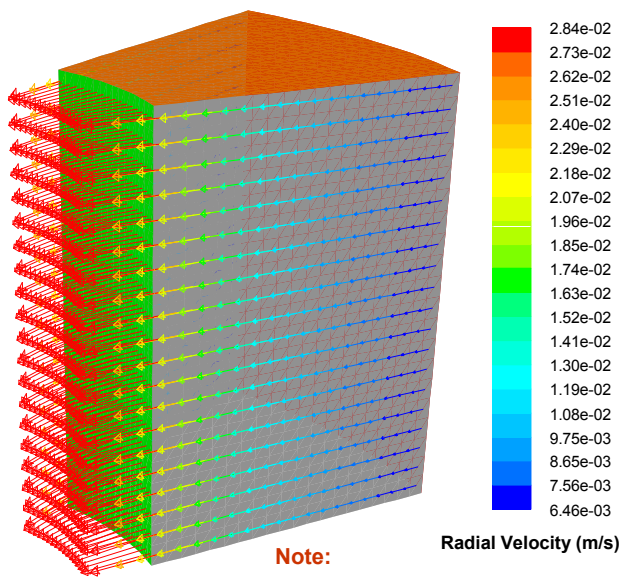
Argon dynamic viscosity (Pa*s): $\mu(T) = \mu_0 * 10^{(0.63842 \lg T - 6.9365/T - 3374.72/T^2 - 1.51196)}$

Room temperature (20 C) argon viscosity $\mu_0 = 2.228 \times 10^{-5} Pa*s$

Pressure/Velocity Distribution of Gas Flowing Through Heated UTN Wall

Simulation suggests 30 LPM argon entering nozzle (hot condition)





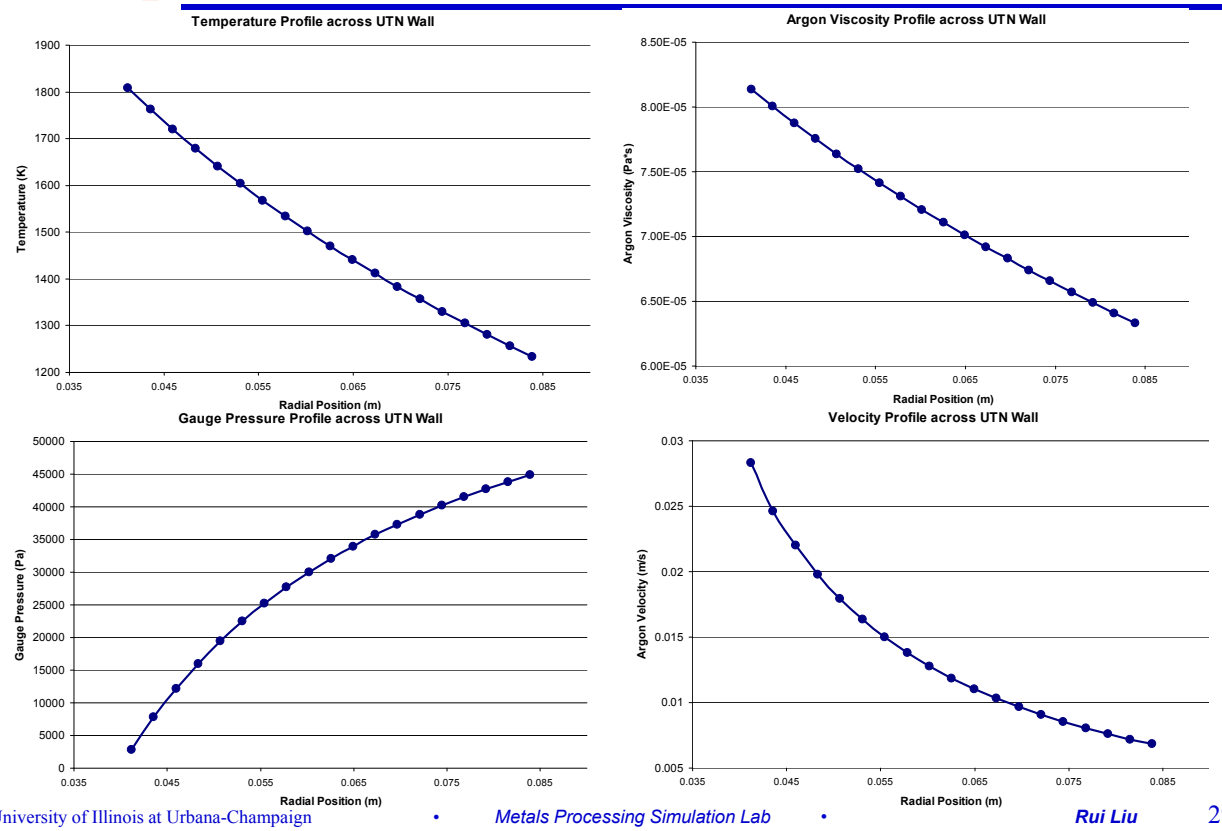
Note:

contour is just for velocity vectors

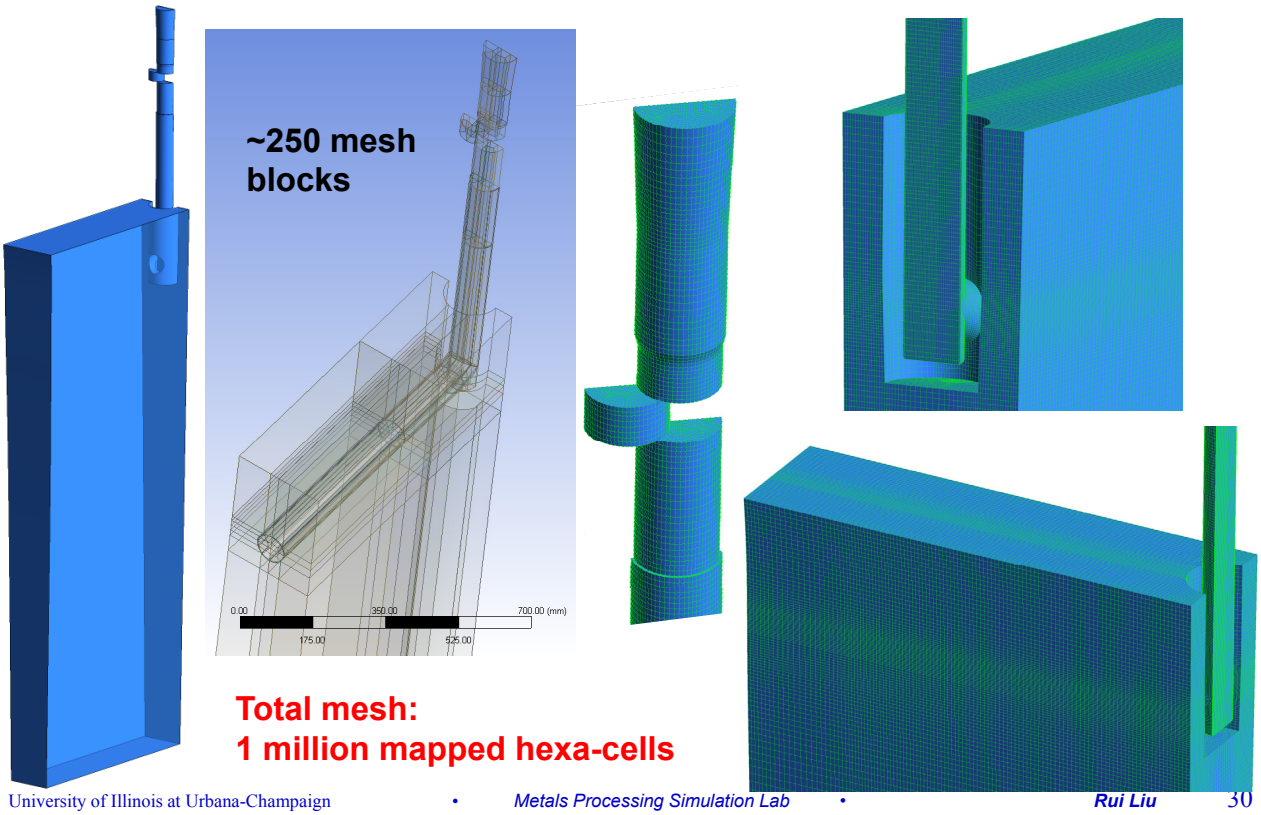
Only about 25% of the total gas enters the nozzle

Note: pressure shown in the contour is the gauge pressure

Temperature and Viscosity Profiles

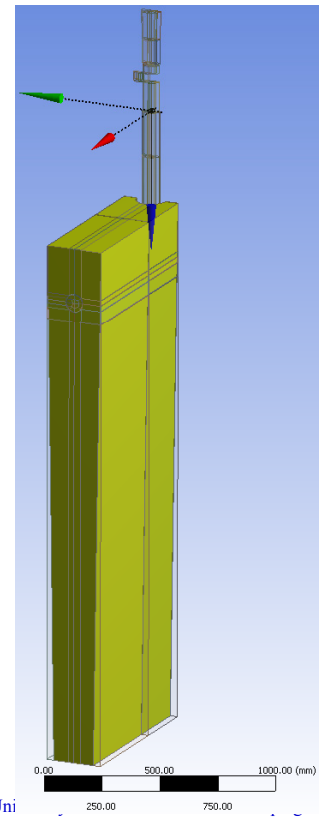


Geometry and Mesh



Total mesh:
1 million mapped hexa-cells

Computation Details



Models and Schemes	Name
Turbulence Model	k-epsilon with std. wall functions
Multiphase Model	Eulerian Model
Advection Discretization	1st order upwinding

B.C.:	Meniscus	Domain Outlet
	No-slip wall	Pressure outlet

Bubble size: 2.4 mm **Time step:** 0.05 sec

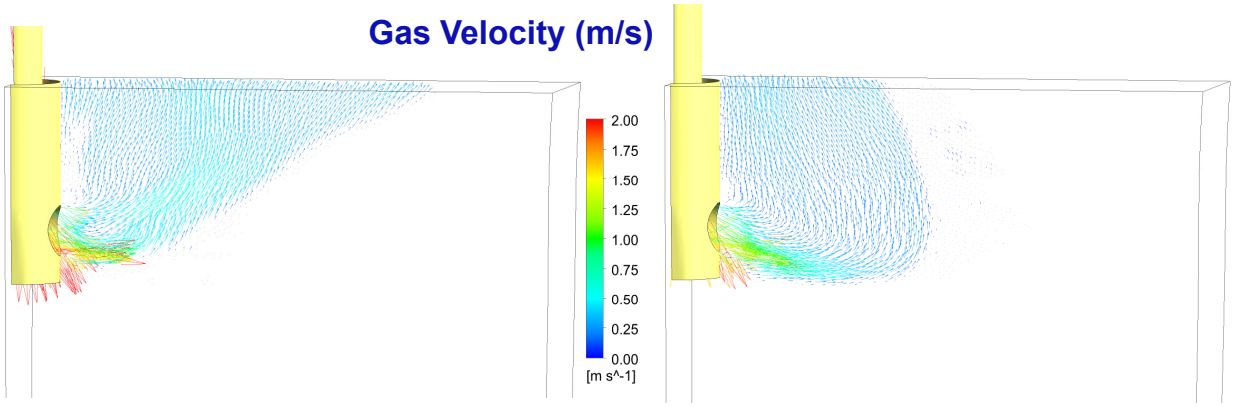
Total mesh: 1.0 million mapped hexa- cells

Sources and Sinks:

Mass and momentum sinks are utilized for solidification of liquid steel adjacent to shell, and escape of argon gas adjacent to meniscus

Half mold was used as computational domain.

Argon Flow Pattern at Center Plane between Wide Faces



Gas taking liquid steel to meniscus (buoyancy force dominated flow)

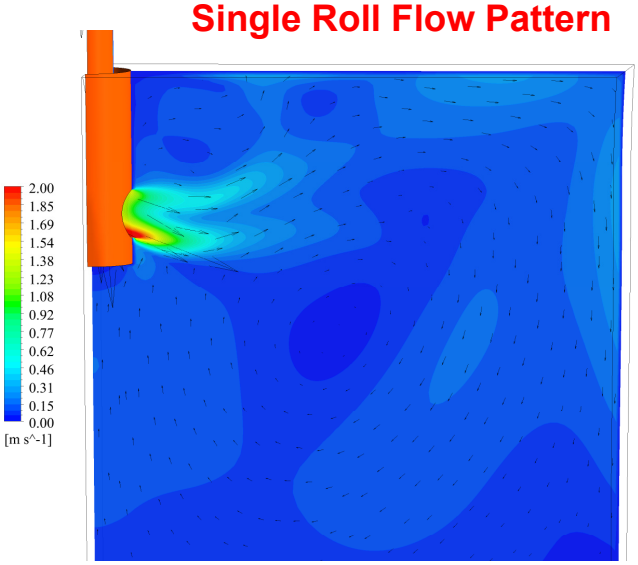
120 LPM argon flow rate (hot) (20 SLPM with no leakage)

Gas taken by liquid steel jet once coming out of ports, then rising to meniscus

30 LPM argon flow rate (hot) (20SLPM with 75% leakage based on porous flow model results)

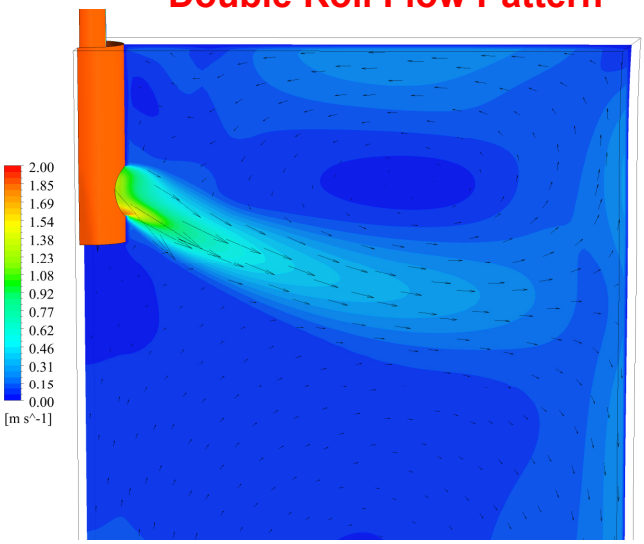
Liquid Steel Flow Pattern at Center Plane between Broad Faces

Single Roll Flow Pattern



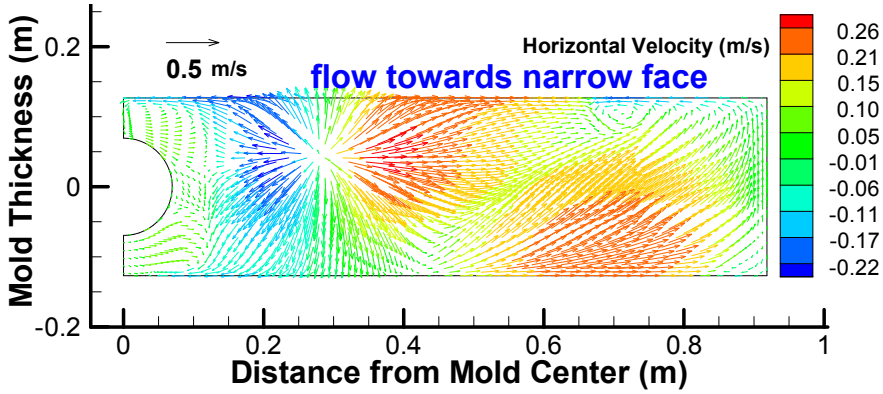
120 LPM argon flow rate (hot) (20 SLPM with no leakage)

Double Roll Flow Pattern



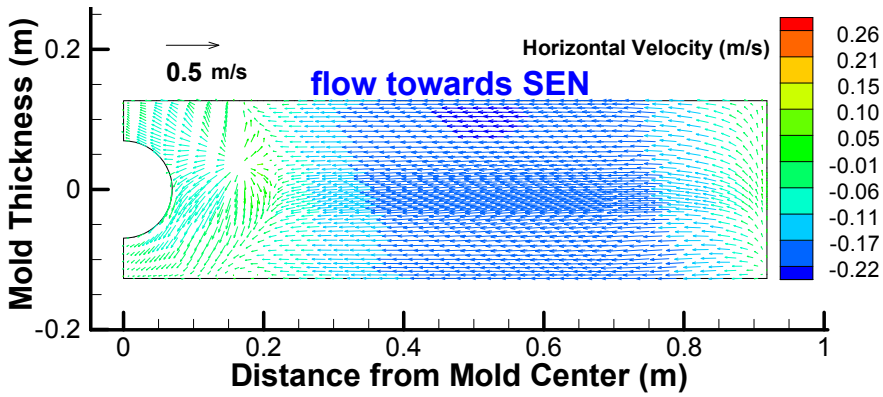
30 LPM argon flow rate (hot) (20SLPM with 75% leakage based on porous flow model results)

Steady State Flow Patterns at Different Gas Injection Rate



Single Roll Flow Pattern

120 LPM hot argon flow rate (no leakage)



Double Roll Flow Pattern

30 LPM hot argon flow rate (75% leakage)

Conclusions

- **Nice matches are achieved among the 1-D ODE solutions, pressure-source model and porous-flow model for the test problems, with the following factors considered:**
  - **expansion of heated gas**
  - **argon viscosity change with temperature**
- **Validated models of argon flow through heated UTN can be utilized to predict:**
  - **asymmetry of gas distribution at UTN inner surface, for design optimization purpose**
  - **initial bubble size combined with bubble size models (by H. Bai and G. Lee)**
  - **argon gas leakage, which greatly changes flow pattern**

Acknowledgements

- **Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Tata Steel, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech, Posco, SSAB, ANSYS-Fluent)**
- Hongbin Yin, Bruce Forman and Yong Lee from ArcelorMittal global R&D at East Chicago
- Other graduate students in Metals Processing Simulation Lab