CCC Annual Report

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Gas Flow Through Upper Tundish Nozzle Refractory and Bubble Size Evolution Inside SEN

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OUTLINE

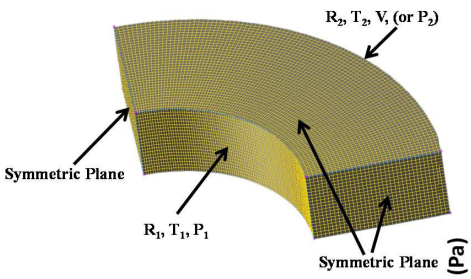
- **PART 1: UTN porous gas flow model**
  - **Review of previous model**
  - **Model updates:**
    - **Realistic pressure distribution on UTN inner surface**
    - **Bubble formation threshold for gas pressure**
    - **One-way passing pressure boundary condition**
  - **Effects of back pressure effects**
  - **Effects of gas leakage at UTN bottom**
- **PART 2: Bubble size study in a water model**
  - **Bubble size distributions in SEN**
  - **Evolution of gas volume fraction down the SEN**

Development and Validation of Gas Porous Flow Models – Review

3-D Coupled Eqns.:

$$\begin{cases} \nabla\cdot\left(K_D\nabla p\right) = -\dfrac{RT}{p}\left[\nabla\left(\dfrac{p}{RT}\right)\cdot\left(K_D\nabla p\right)\right] \\ \nabla\cdot\left(k\nabla T\right) = 0 \end{cases}$$

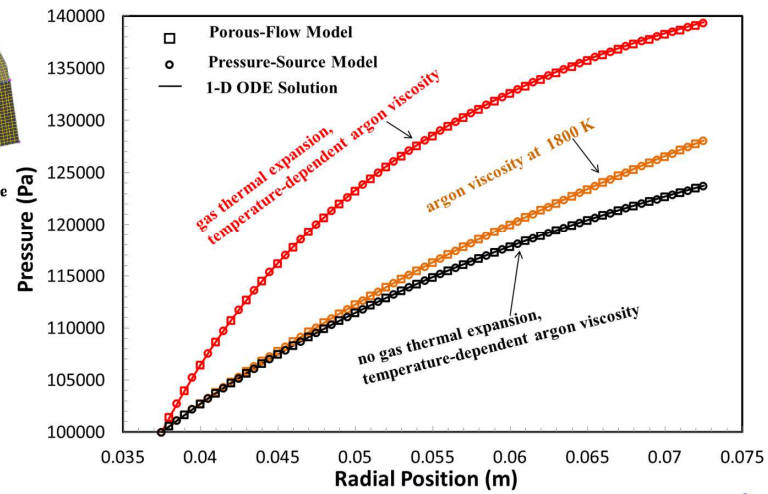
R. Liu and B.G. Thomas, *Proc. AISTech 2012 Conf.* (Atlanta, GA), p2235, (2012)



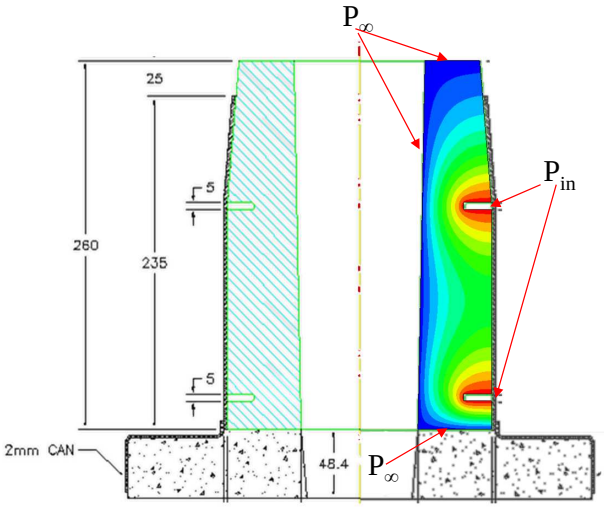
R_1 (m)	R_2 (m)	P_1 (Pa)	T_1 (K)	T_2 (K)	V (m/s)
0.0375	0.0725	100000	1800	1000	0.0073

1-D Simplified Eqns.:

$$\begin{cases} P'' + \left(\dfrac{1}{r} - \dfrac{T'}{T} + \dfrac{K_D'}{K_D}\right)P' + \dfrac{P'^2}{P} = 0 \\ \dfrac{1}{r}\left(rT'\right)' = 0 \end{cases}$$



Schematic and Parameters for the Base Case



Inlet pressure	P_{in}	200 kPa (abs.)
Pressure at nozzle inside wall & ambient	P_∞	101 kPa (abs.)
Specific permeability	K_p	10.1 nPm = 10.1 x10^{-7} mm²
Dynamic Viscosity*	μ	7.42 x10^{-5} Pa.s (at 1280C)
Permeability (K_p/ μ)	K_D	1.36x10^{-8} m²/(Pa.s) (at 1280C)
Thermal conductivity	k	18 W/mK
Heat transfer coefficient (nozzle exterior)	h	40 W/m²K

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

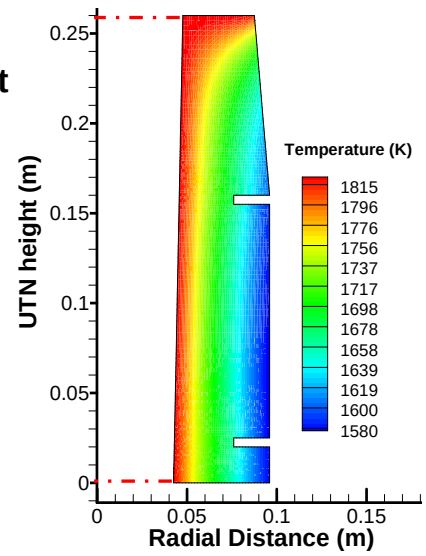
$$* \quad \mu(T) = \mu_0 * 10^{\left(0.63842\lg T - 6.9365/T - 3374.72/T^2 - 1.51196\right)}$$

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

Room temperature (20 C) argon viscosity

Scenarios for the Base Case

- **Further Factors to consider:**
  - **Hydrostatic pressure profile with steel velocity (Bernoulli's eqn.)**
  - **Bubble formation pressure threshold at pore (due to surface tension)**

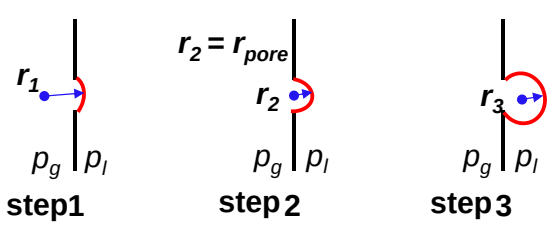


- **Scenarios:**
  1. **Base case parameters, with porous flow model, constant gas viscosity, constant pressure**
  2. **Base case parameters, but with temperature-dependent gas viscosity**
  3. **Consider liquid steel pressure distribution at UTN inner surface (using Bernoulli's Eqn)**
  4. **Same with case 3, but consider bubbling pressure threshold due to surface tension**

Pressure Threshold for Bubble Formation

- **In order for gas to intrude into the liquid and form bubbles, surface tension effects have to be considered:**

Bubble expanding stage (assume bubbles expand slowly in equilibrium):



$r_1 > r_2$

$r_3 > r_2$

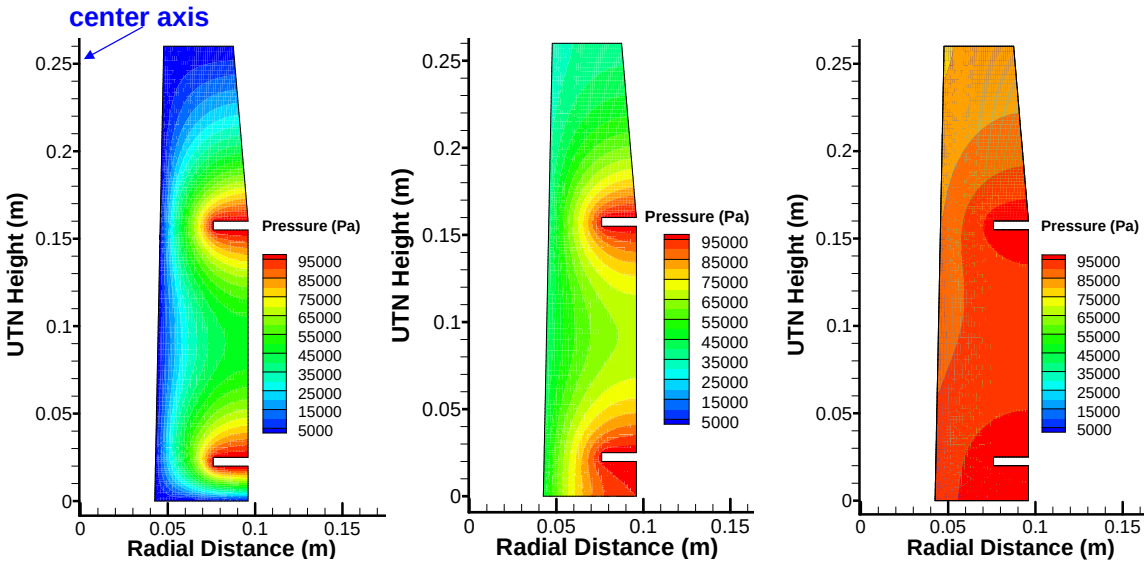
$$p_g - p_l = \sigma\kappa \qquad \kappa = \frac{2}{r} \quad \Rightarrow \quad p_g = p_l + \frac{2\sigma}{r} \quad \Rightarrow \quad \boxed{\begin{array}{l} p_{g2} > p_{g1} \\ p_{g2} > p_{g3} \end{array}}$$

Pressure threshold for bubble formation:

$$\boxed{p_g = p_l + \frac{2\sigma}{r_2} = p_l + \frac{2\sigma}{r_{pore}}}$$

Parameters used in current study: $\boxed{\sigma = 1.2\, N/m \quad , \quad r_{pore} = 200\,\mu m}$

Pressure Distributions – Base Case Scenarios

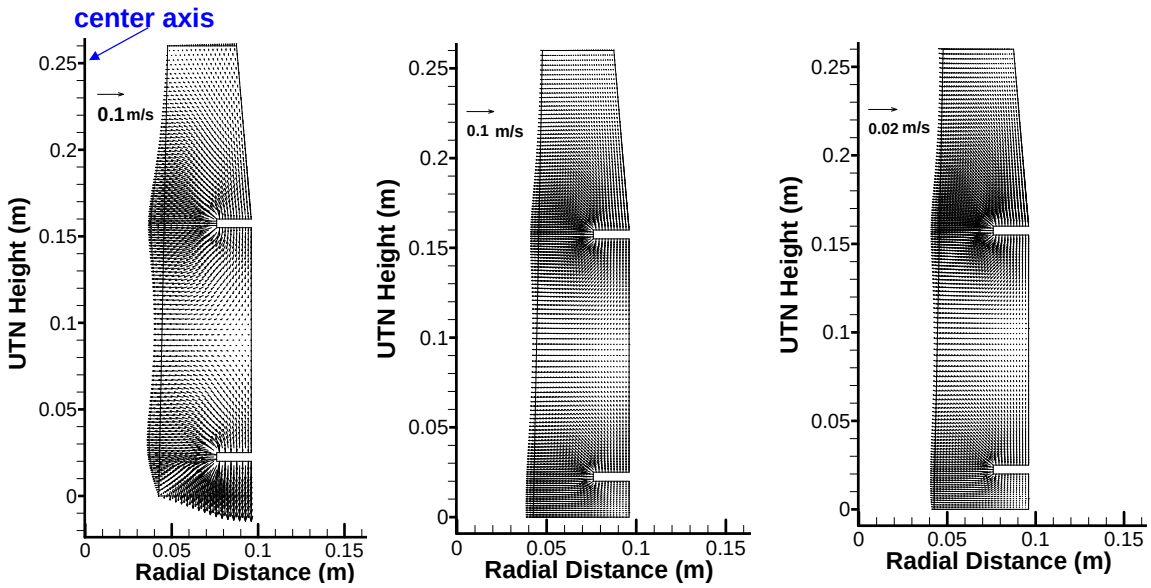


bottom leakage, constant liquid pressure

bottom sealed , Bernoulli-based pressure

bottom sealed , Bernoulli-based pressure , and bubbling threshold

Velocity Distributions – Base Case Scenarios

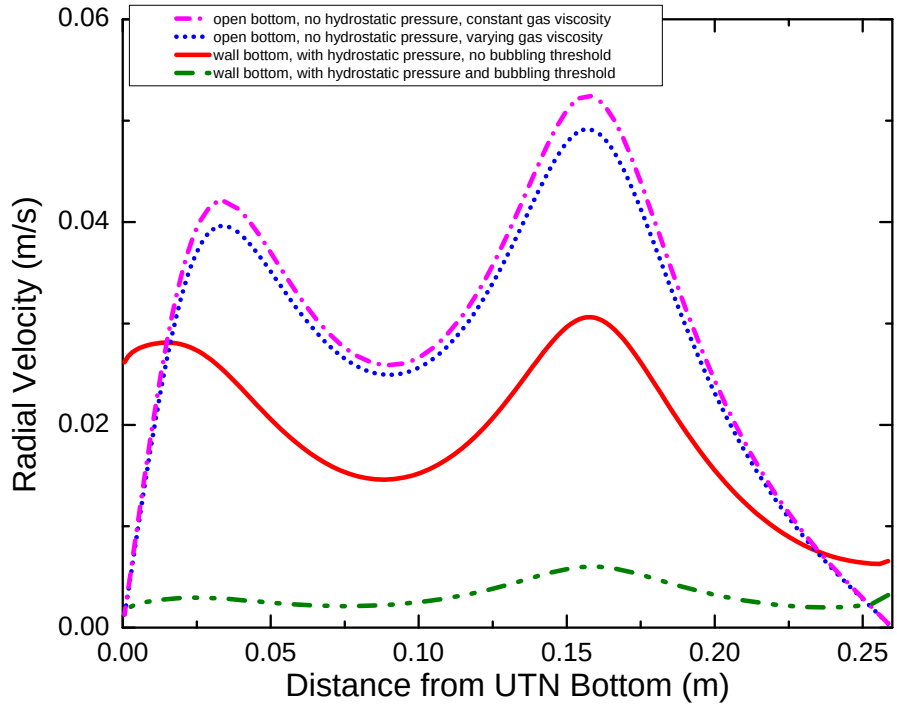


bottom leakage, constant liquid pressure

bottom sealed , Bernouli-based pressure

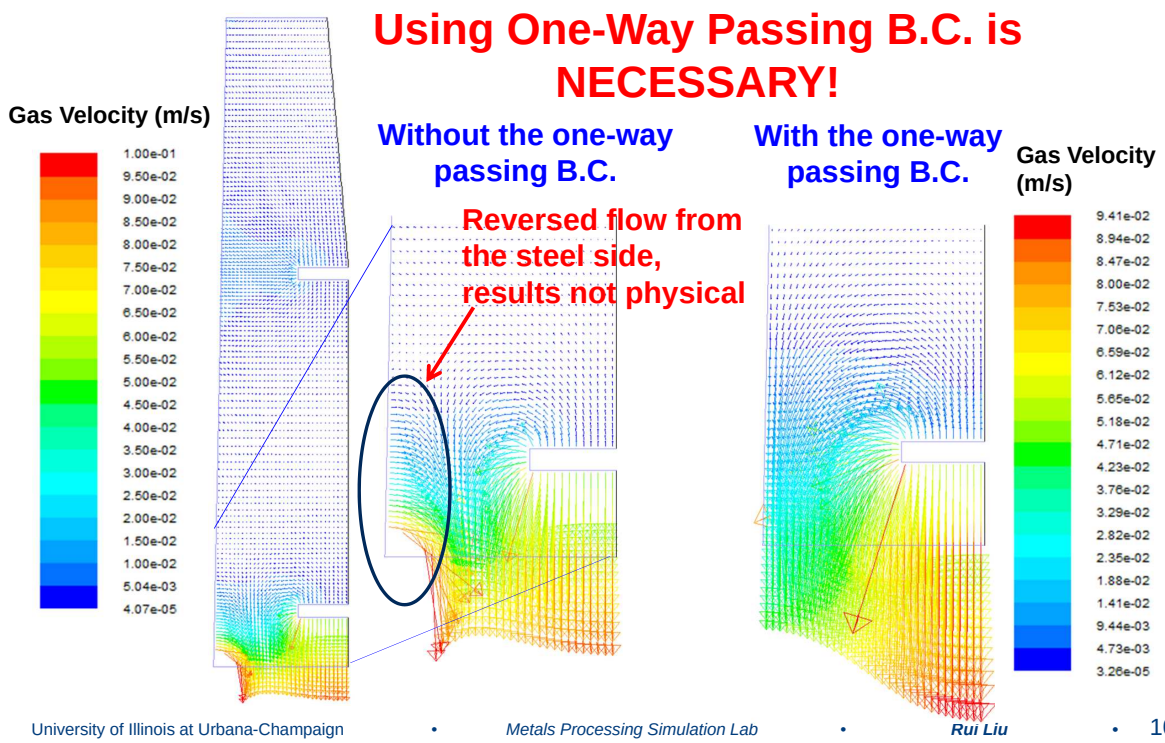
bottom sealed , Bernouli-based pressure , and bubbling threshold

Radial Velocity Distributions

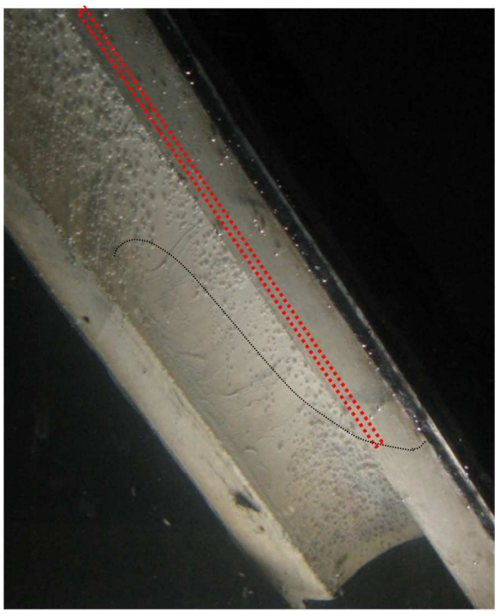


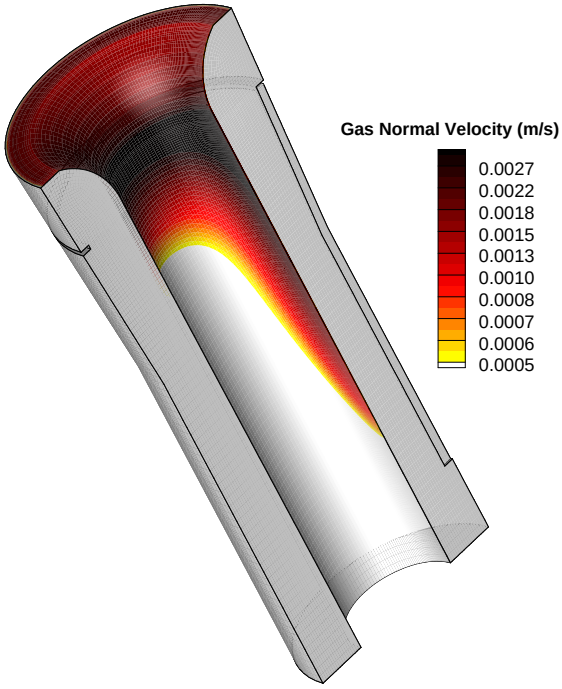
Effect of One-Way Passing Pressure B.C.

Using One-Way Passing B.C. is NECESSARY!

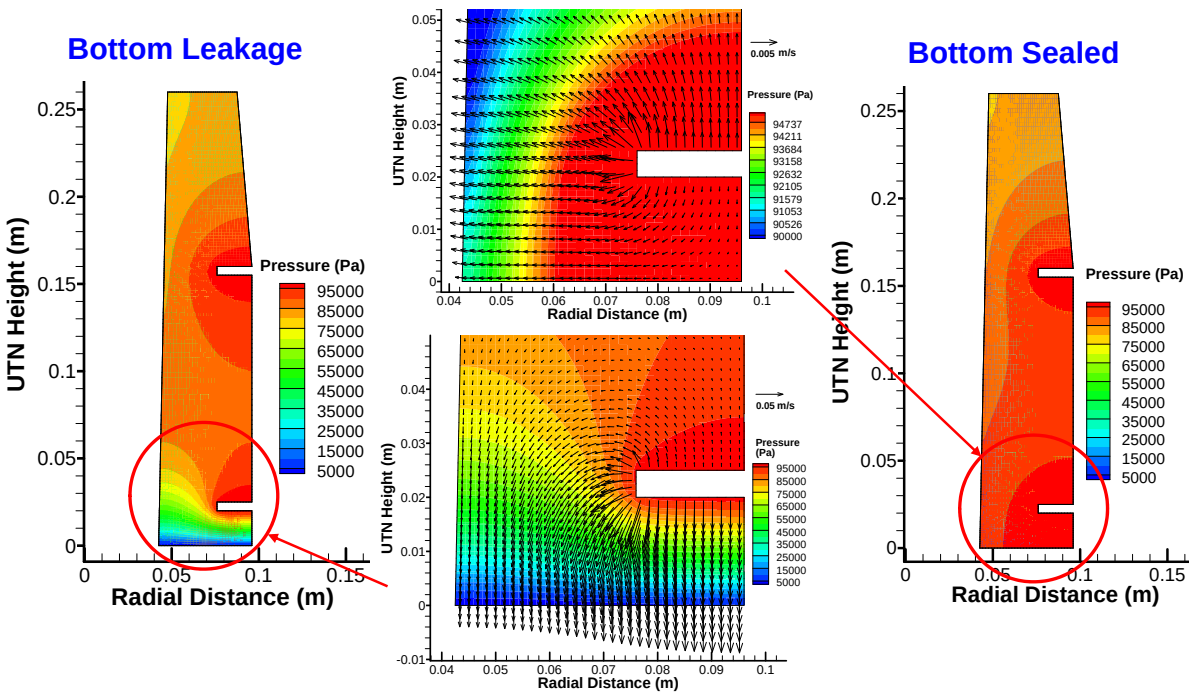


Model Validation with Static Bubbling Test





Pressure Distribution – Bottom Leakage vs. Sealed



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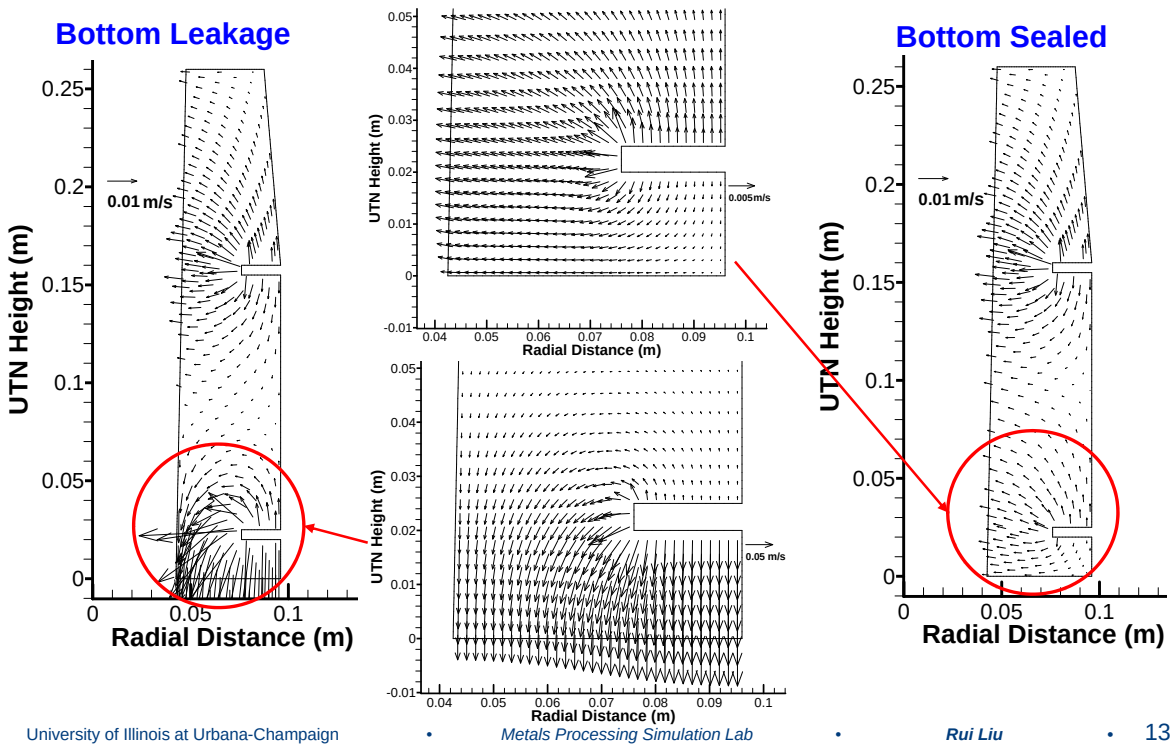
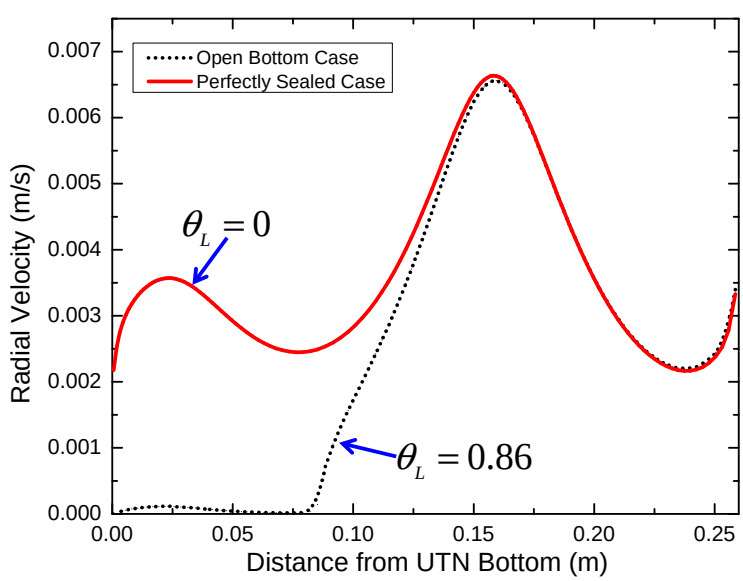


Evaluation of UTN Gas Injection – Bottom Leakage vs. Sealed



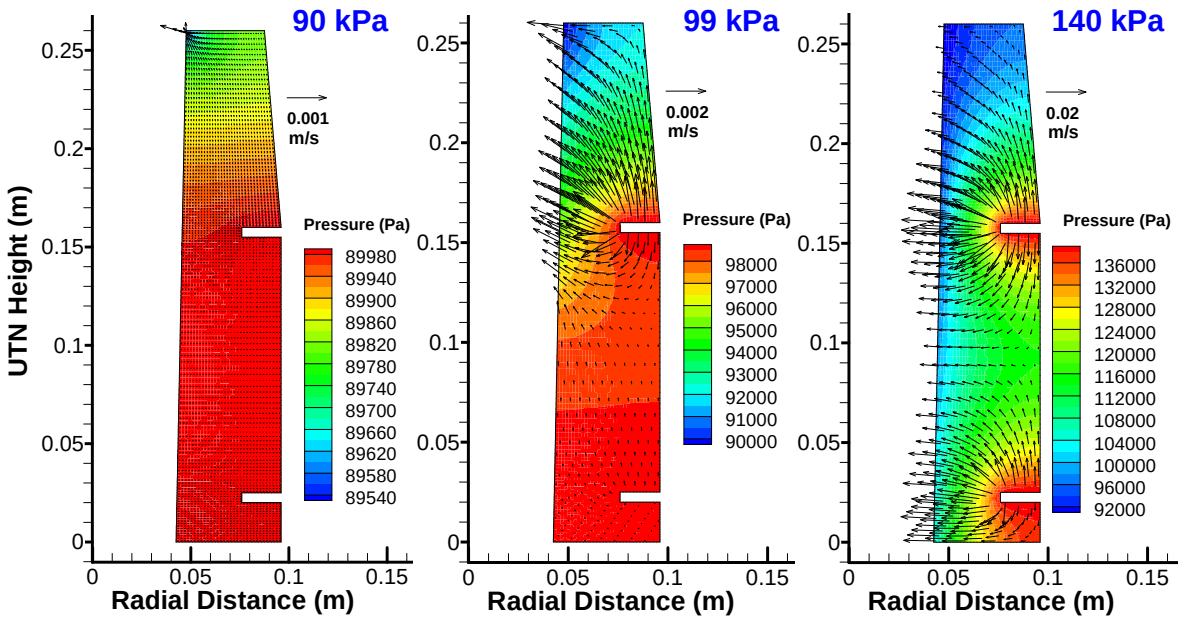
DEFINE:

Gas Leakage Rate

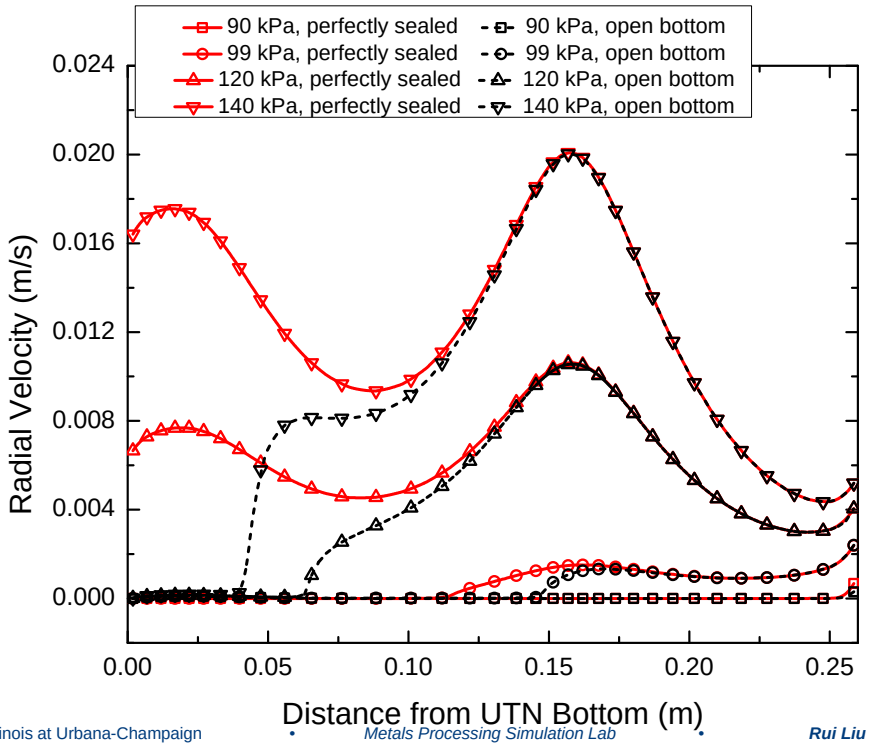
$$\theta_L = 1 - \frac{\dot{m}_{in}}{\dot{m}_{total}}$$

- **Possible gas leakage through UTN bottom does not affect much gas deliver through the upper slit**
- **An 86% gas leakage is found in current case with the complete open-bottom case**

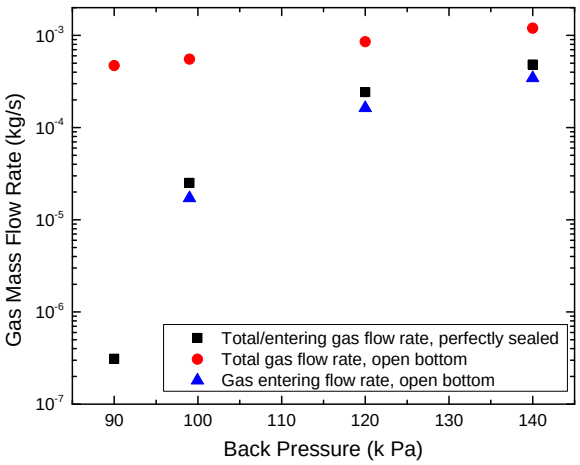
Effects of Back Pressure on Gas Velocity Distributions in Refractory

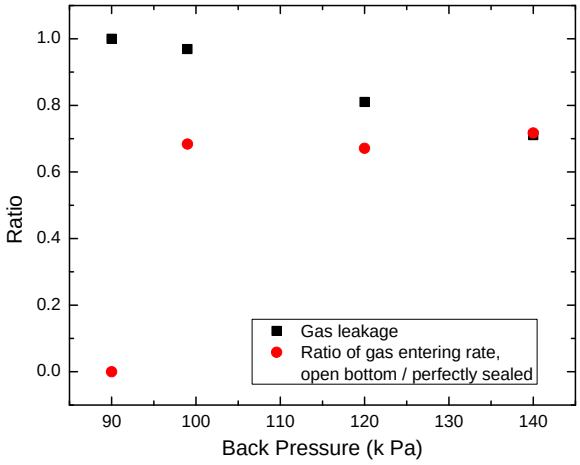


Effects of Back Pressure and Sealing on Gas Radial Velocity Distributions



Effects of Back Pressure on Gas Mass Flow Rate and Leakage Ratio



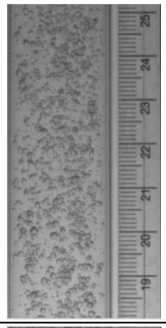
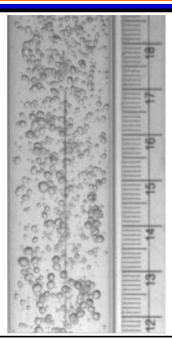
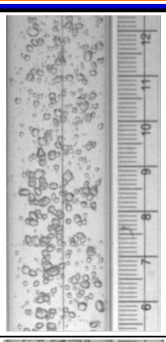
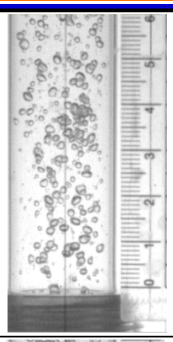
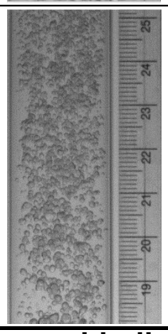
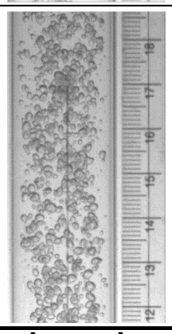
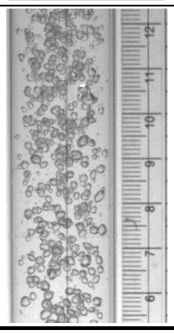
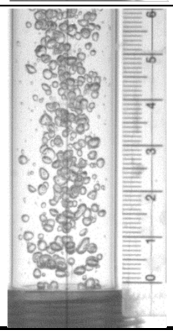


- **For both open-bottom and perfectly-sealed cases, gas mass flow rates increase with increasing back pressure**
- **For open-bottom cases, with different back pressures in this work, gas leakage ratio decreases with increasing back pressure, but all above 70%, with ratio of gas entering rate also remaining 70% between open-bottom and perfectly sealed cases**

Part 1: Conclusion – UTN Porous Gas Flow Model

- **UTN porous gas flow model has been improved to incorporate realistic conditions, including:**
  - **Liquid steel pressure distribution on UTN inner surface**
  - **Bubble formation gas pressure threshold**
  - **One-way passing pressure boundary condition to eliminate unphysical reversed gas flow on UTN surface**
- **Parametric studies on gas injection back pressure reveal:**
  - **For both open-bottom and perfectly sealed cases, gas flow rates increases with increasing back pressure;**
  - **Open-bottom cases leaks more than 70% of the gas under normal pressure conditions (14~21 psi)**
  - **Upper slit in open-bottom cases maintains a gas entering ratio of ~70% compared with the perfectly sealed case**

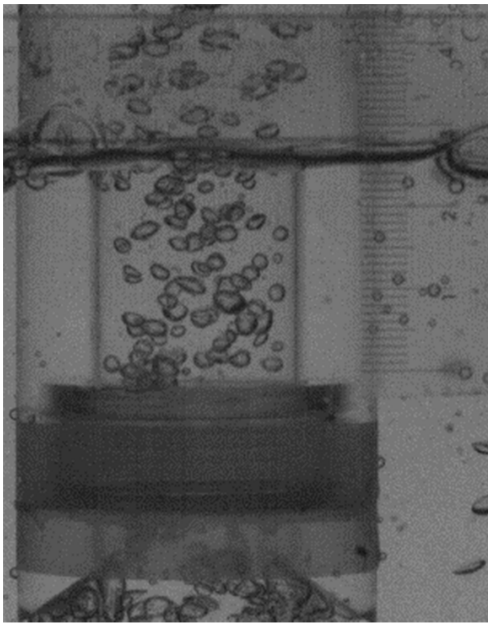
Bubbles Moving Down in the SEN

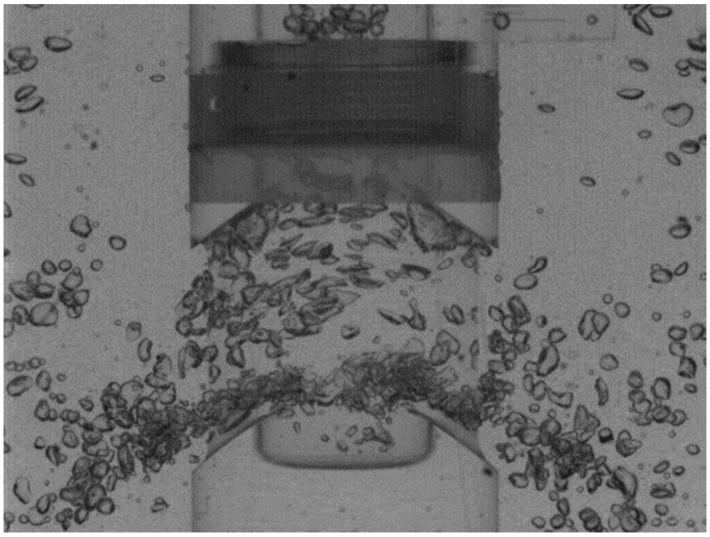
35 LPM (Water)_ 0.8 SLPM (Argon)				
35 LPM (Water)_ 1.6 SLPM (Argon)				

- Bubbles look bigger with distance down the nozzle
- Perhaps: bubbles coalesce; or else larger bubbles accumulate with time

Bubble Size Change Near Nozzle Exit

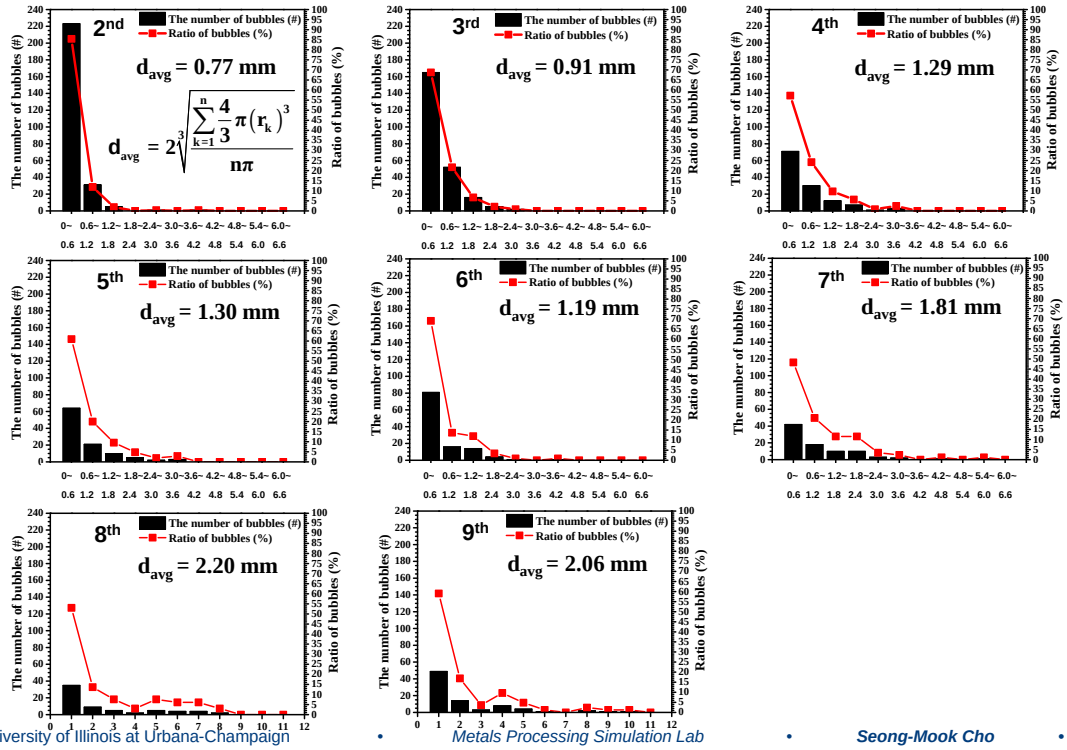
"35LPM (Water)_1.6SLPM (Argon)"





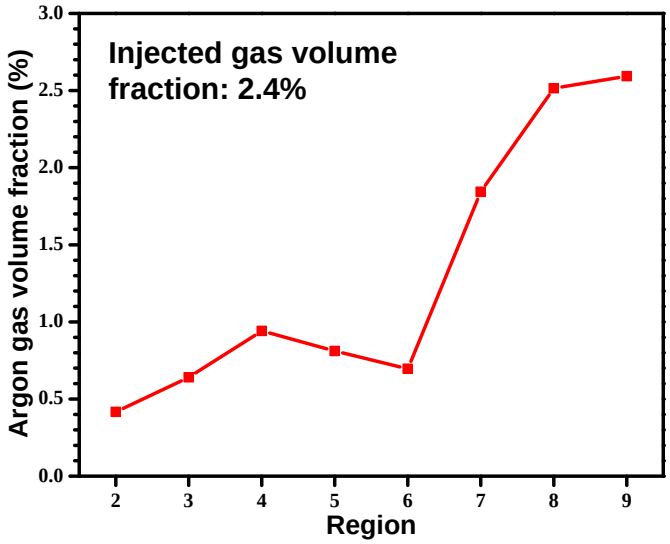
- Bubbles smaller at the nozzle bottom
- Bubbles coalesce at the top region of nozzle port (stagnant flow region)

Argon Bubble Size Distribution through the Nozzle 35 LPM (Water)_0.8 SLPM (Argon)



$$d_{avg} = 2\sqrt[3]{\frac{\sum_{k=1}^{n}\frac{4}{3}\pi\left(r_k\right)^3}{n\pi}}$$

Gas Volume Fraction Evolution



- **Bubble accumulation ?**
- **Calculating drift flux of bubble is needed to obtain gas void fraction considering argon and water superficial velocities, and bubble size.**

Part 2: Conclusion – Bubble Size Distribution in SEN

- **Average bubble size is smaller in SEN upper regions, but larger in lower SEN regions**
- **Small gas bubbles appear at SEN bottom, but large bubbles are found close to SEN port upper region**
- **Measured gas volume fraction increases in general along the downward SEN direction, but still smaller than the superficial gas volume fraction**

Acknowledgments

- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Magnesita Refractories, Nippon Steel, Nucor Steel, Postech/ Posco, Severstal, SSAB, Tata Steel, ANSYS/ Fluent)
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