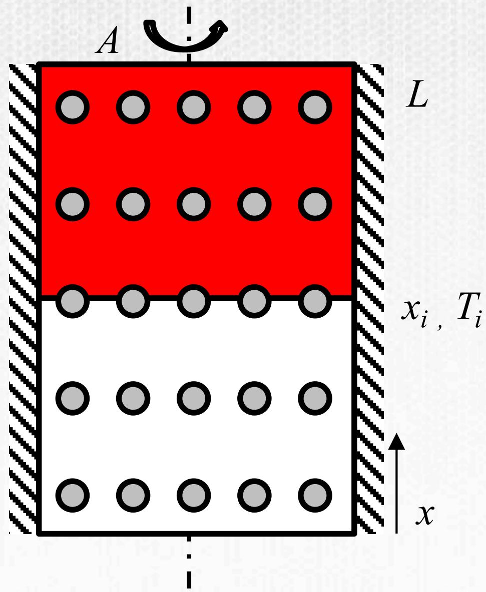
Sodium Pumping via Condensation within a Non-Wetting Porous Structure



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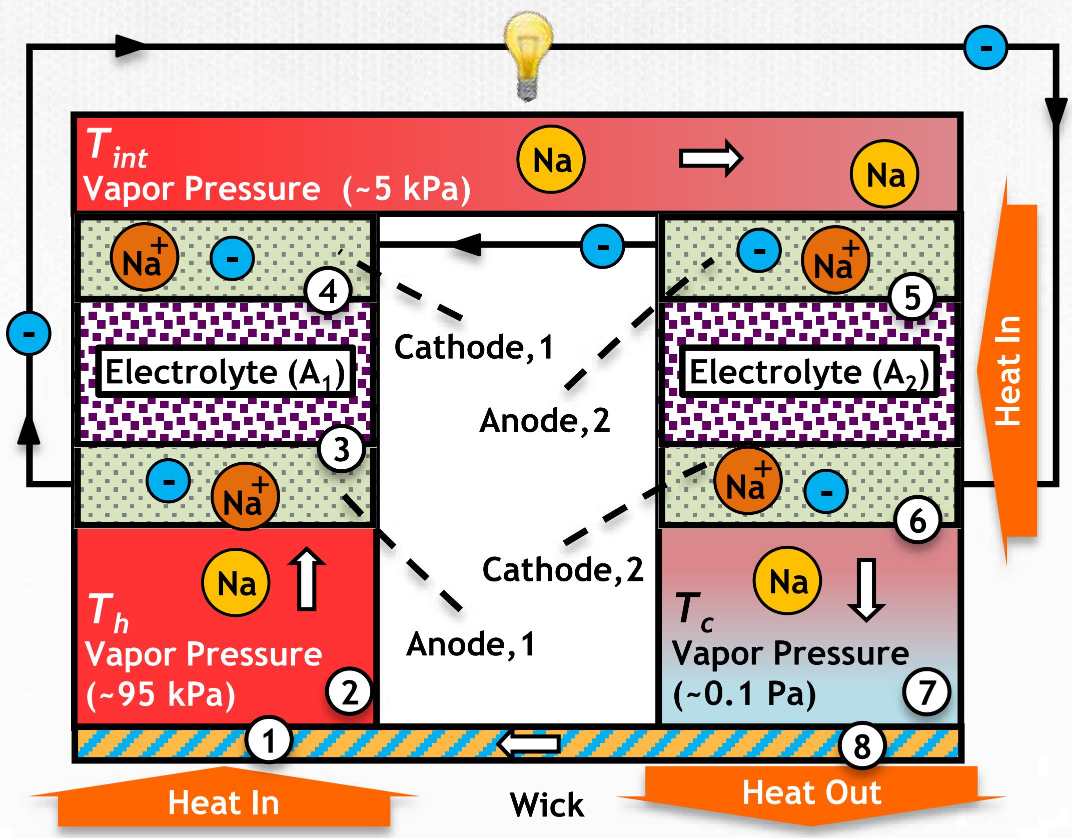
Scalable Thermal Energy Engineering Laboratory
Woodruff School of Mechanical Engineering

Motivation

- Liquid metals are used in applications with large heat transfer requirements (e.g. heat pipes, electrochemical energy conversion)
- Condensed sodium must be pumped into the evaporator to complete the Na-TEC thermodynamic cycle
- Low-temperature capillary pumping solutions in Na-TEC can be enabled with a non-wetting porous structure



Conservation of Mass

If mass transfer occurs by advection and diffusion, the two commonly used models are the advection-diffusion model (ADM) and the dusty-gas model (DGM).

Assume a binary mixture within a porous structure:

Conservation of mass

$$\varepsilon \frac{\partial \rho_i}{\partial t} + \nabla \cdot \left[\rho_i \underbrace{\left(-\frac{\kappa}{\mu} \nabla P \right)}_{\text{Advection}} - \underbrace{\rho \varepsilon D_{ij} \nabla \omega_i}_{\text{Binary diffusion}} \right] = 0$$

The permeability is given by the Blake-Kozeny expression $\kappa = \frac{D_p^2 \varepsilon^2}{150\left(1-\varepsilon^3\right)}$

To account for Knudsen diffusion, the permeability is modified by the Klinkenberg factor:

$$\kappa = \kappa_\infty \left(1 + \frac{D_{iK} \mu_i}{\kappa_\infty P} \right)$$

from kinetic theory:

$$\begin{cases} D_{iK} = \varepsilon \frac{4}{3} d_{pore} \left(2\pi RT \right)^{-1/2} \\ \mu_i = \rho d_{pore} Kn \left(2RT / \pi \right)^{1/2} \end{cases}$$

Effective Thermal Conductivity

- Due to the significant mismatch between the gas and the solid, use a parallel arrangement of thermal conductivities

$$k_{eff} = \left(k_s^{-1} + k_{gas}^{-1}\right)^{-1}$$

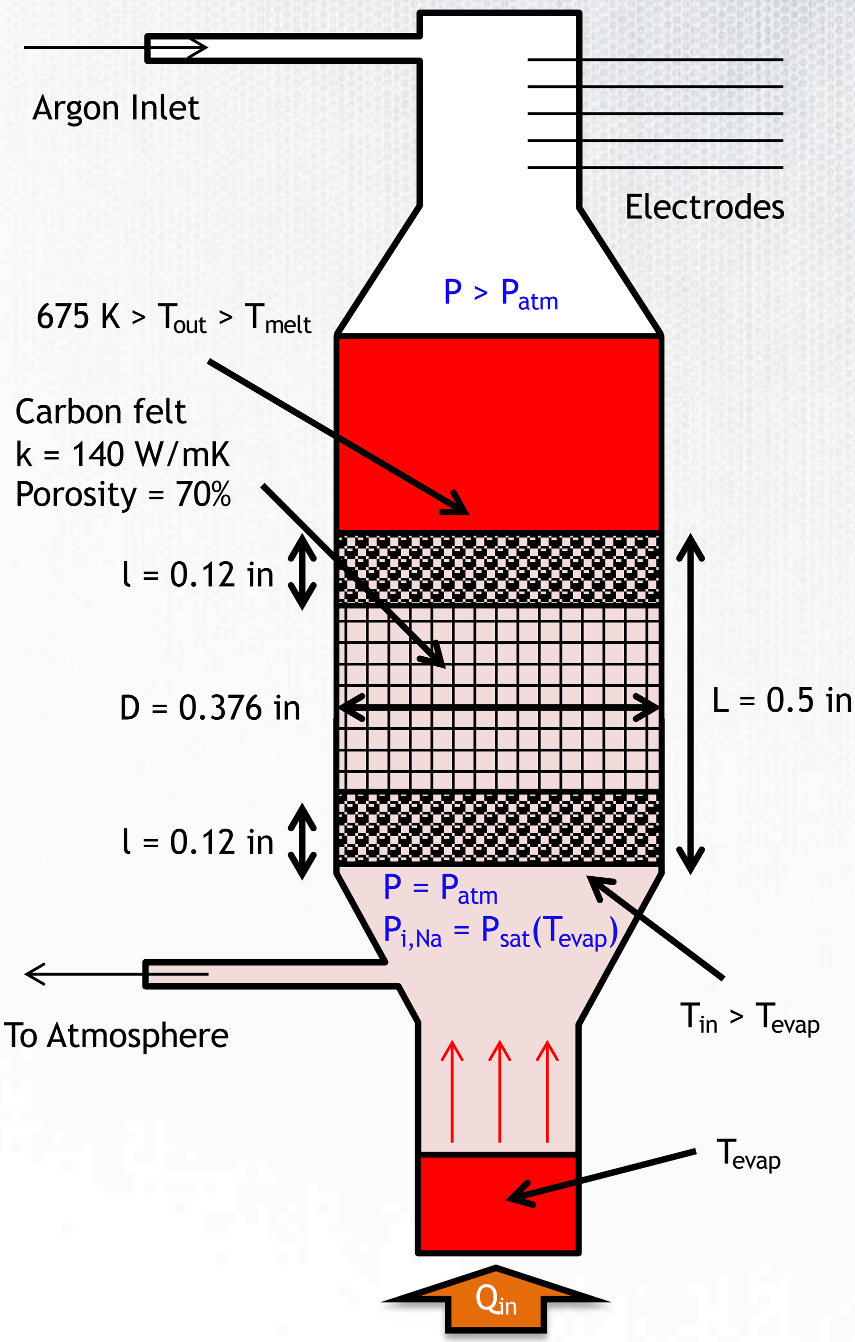
- Consider a binary mixture of monatomic gases [1] to find k_{gas}
- The porous solid thermal conductivity is enhanced by radiation between particles
- The packed bed is assumed to be pseudo-homogeneous with diffuse incident flux and a quasi-isotropic phase function [2]

$$k_s = k_c + k_r \quad \text{where} \quad k_r = \frac{16\sigma T^3}{3}\left(\frac{n^2}{\beta_r}\right) \Rightarrow Q = -k_s \frac{dT}{dx}$$

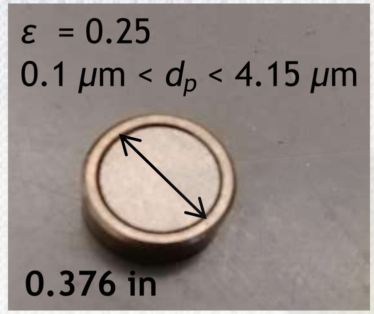
- The extinction coefficient can be extrapolated from previously gathered experimental data [2]

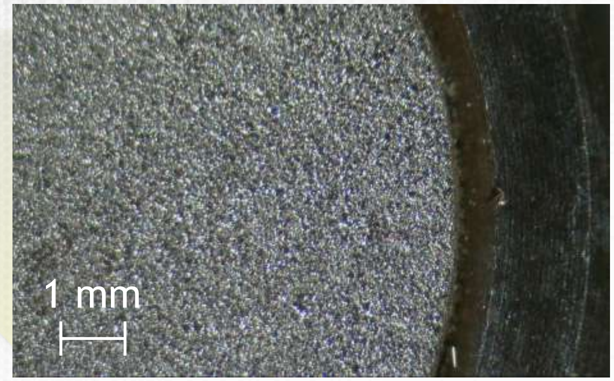
[1] Mason, Saxena, 1958
[2] Chen, Churchill, 1963

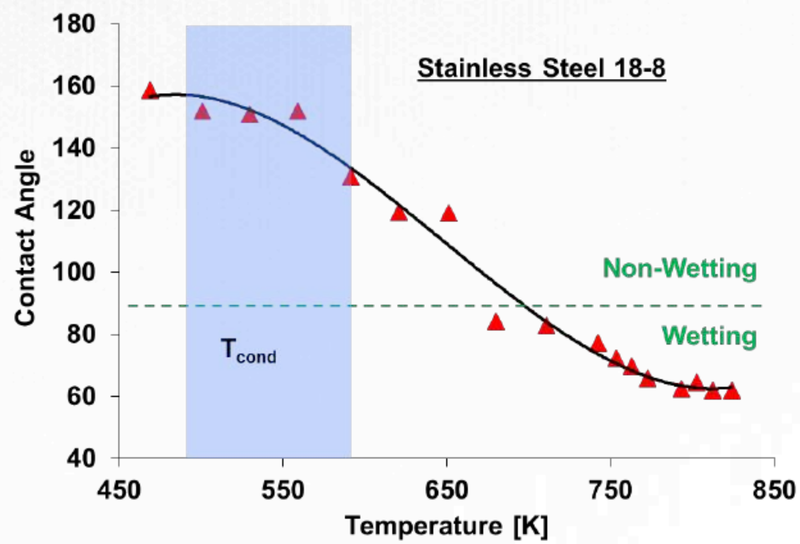
Gauge Pressure Experiment



SS 316 thermally pressed inside cylinder

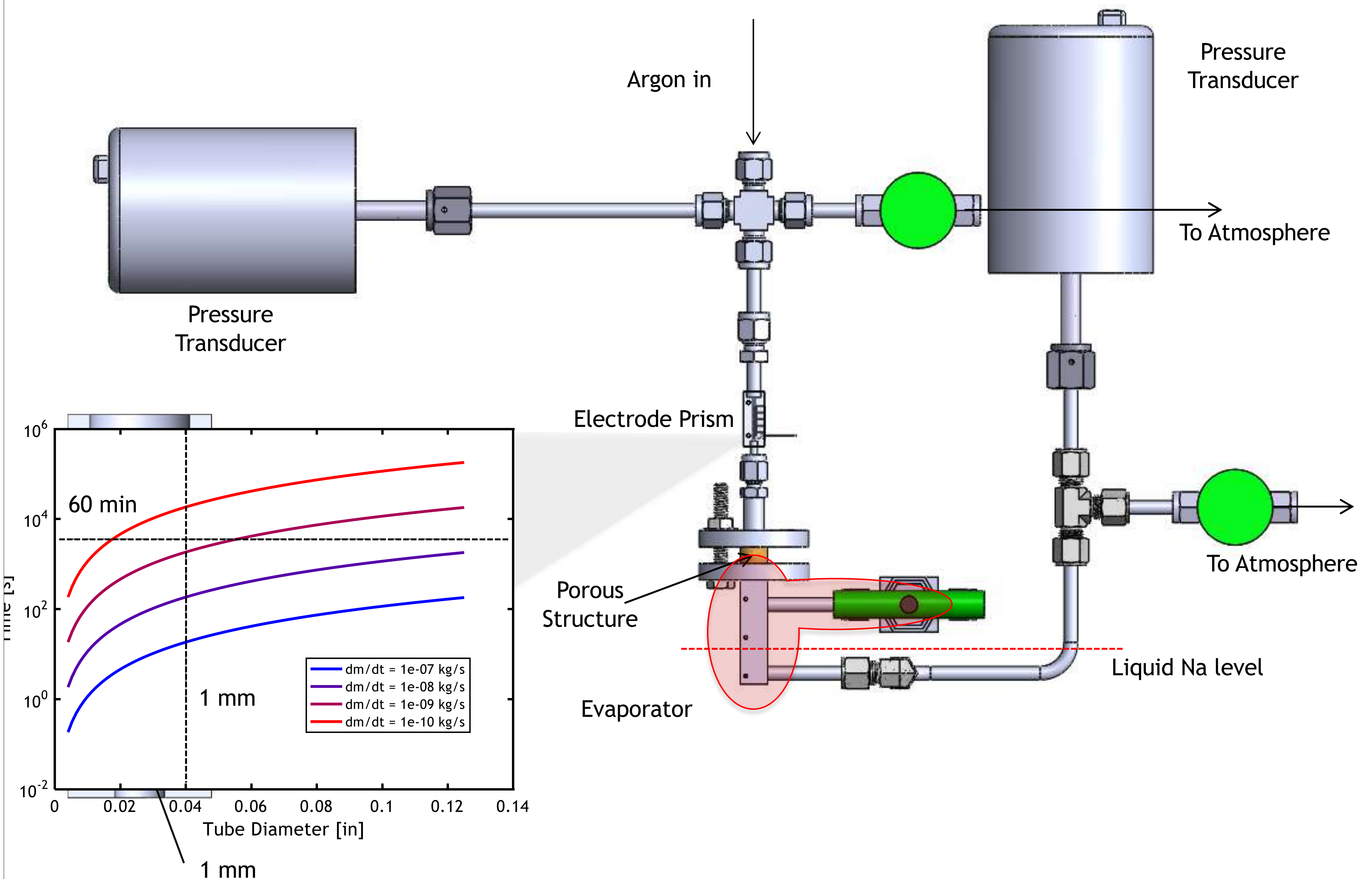




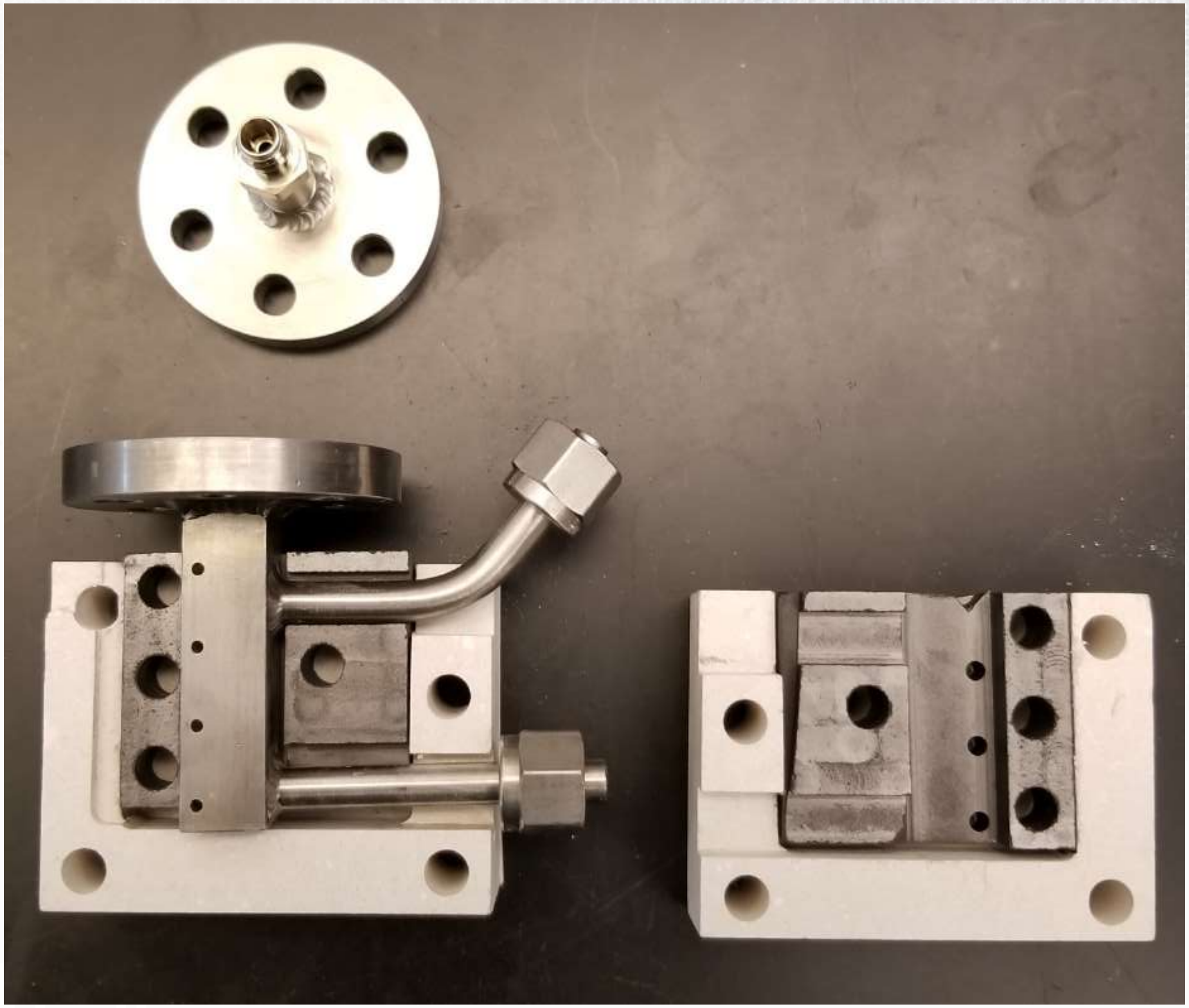


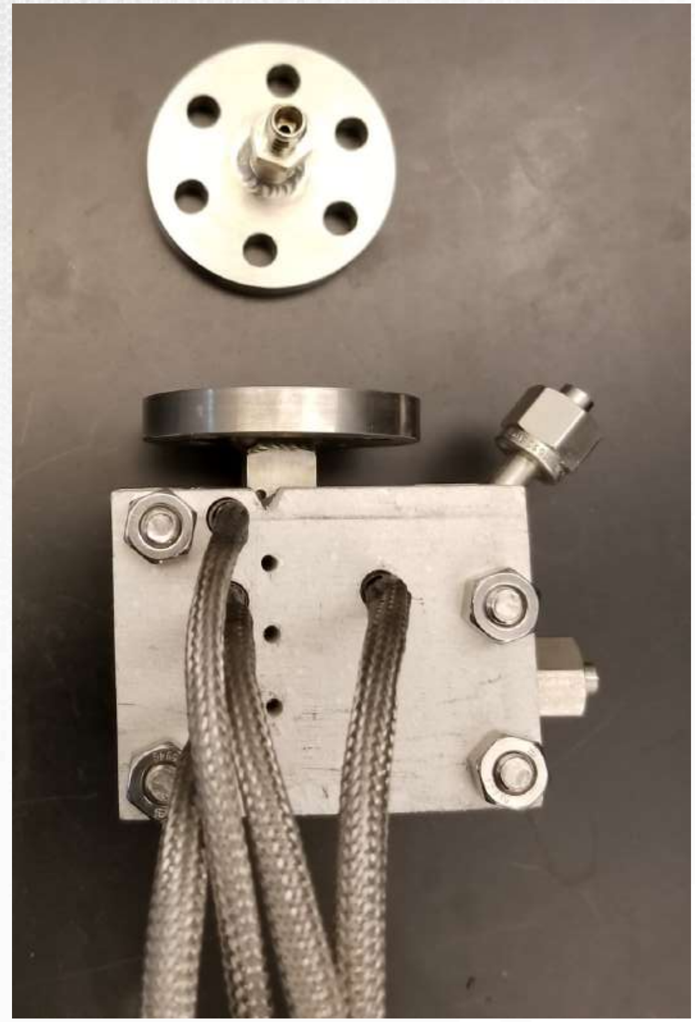
Taylor & Ford, *U.K. Atomic Energy Authority Report*, 1955

Experimental Design



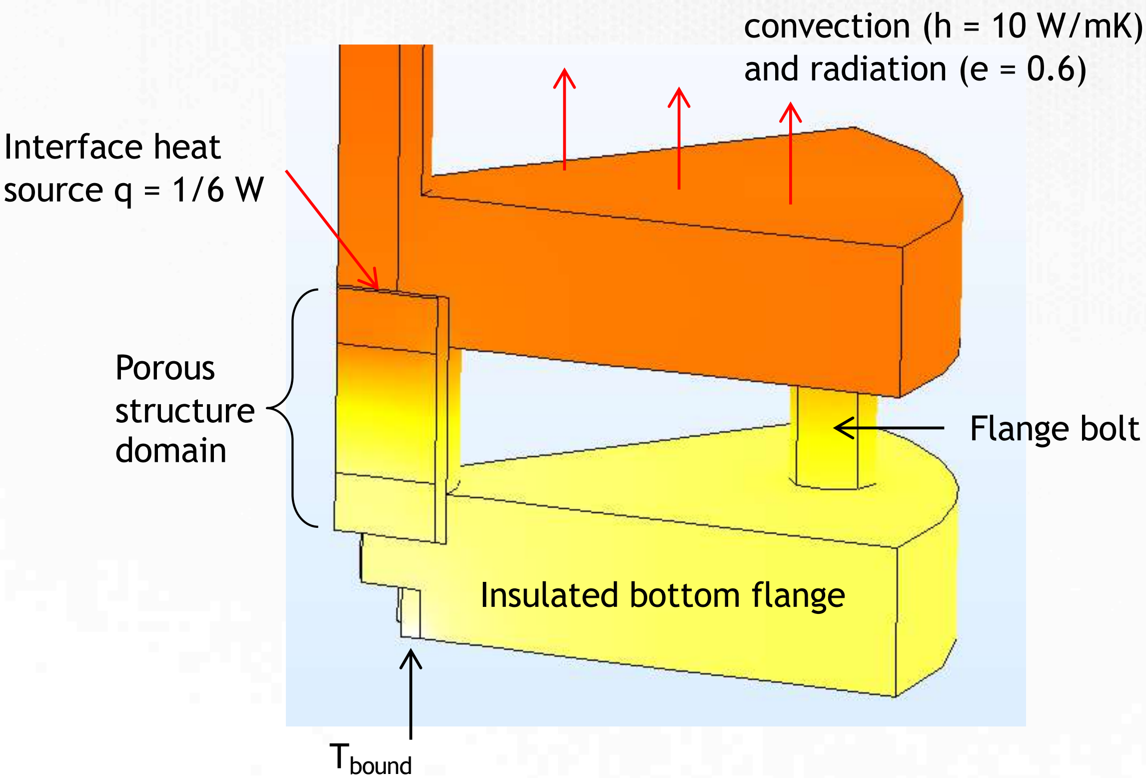
Evaporator Design

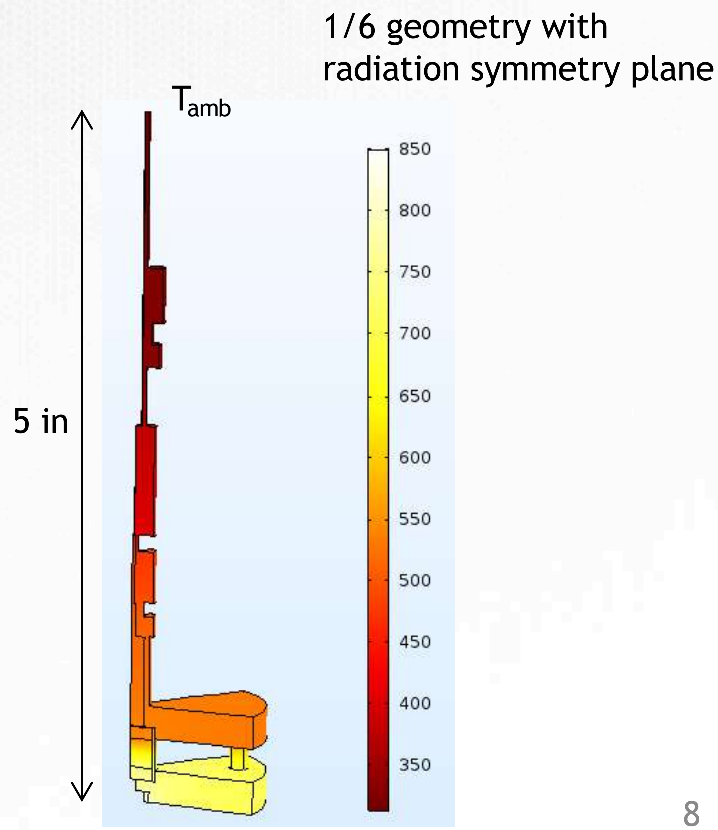




Thermal Profile

- To find temperature profile, use an quasi-axisymmetric 3D COMSOL model
  - Bottom of the flange is assumed to be isothermal (heat input)
  - Top of the geometry is set to ambient temperature (*i.e.* infinite fin)
  - Natural convection on external faces (use Churchill-Chu correlation)
  - Diffuse, gray radiation on internal and external boundaries





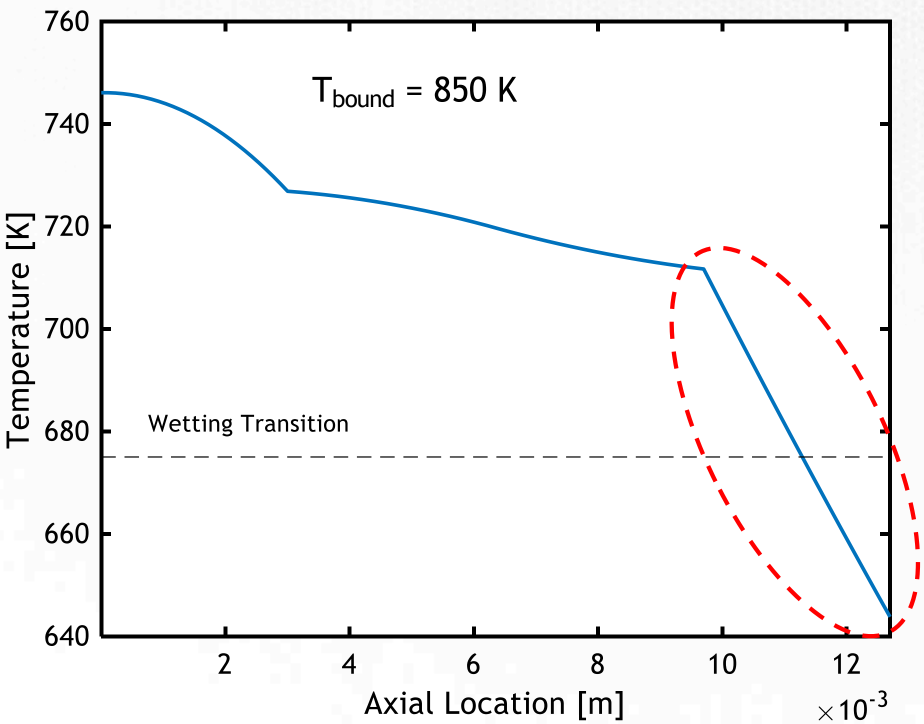
Maximum Mass Flowrate

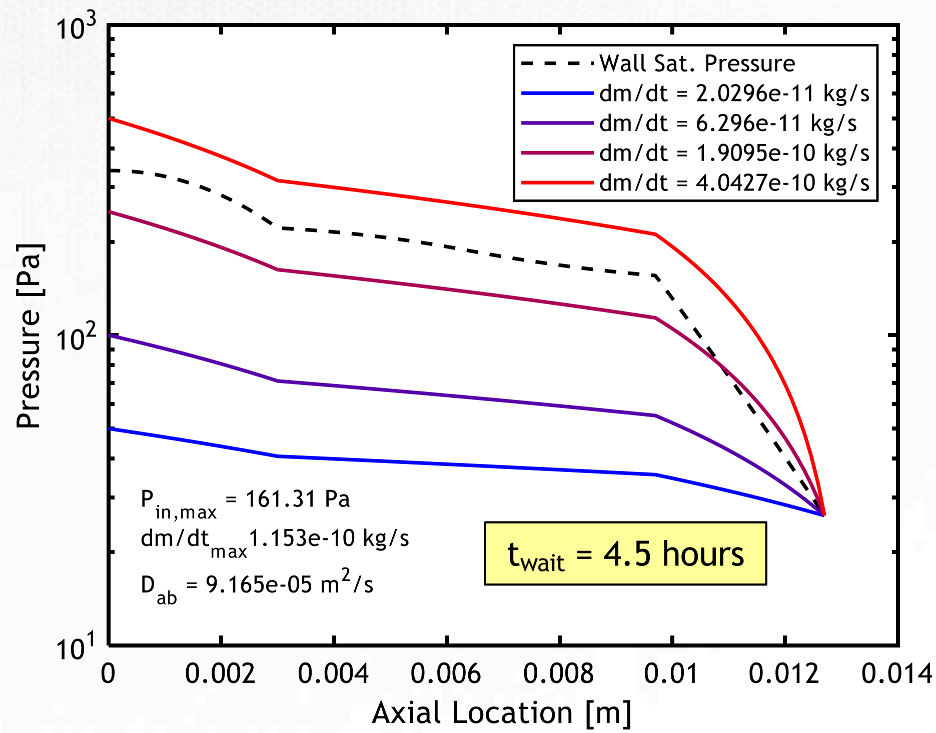
Consider a binary mixture of argon and sodium vapor. The argon does not penetrate the liquid sodium boundary in the evaporator or the porous structure.

Kelvin Equation at interface $$P(x_i) = P_{sat}(T_i)\exp\left(\frac{P_L}{\rho_l T_i \bar{R}}\right)$$

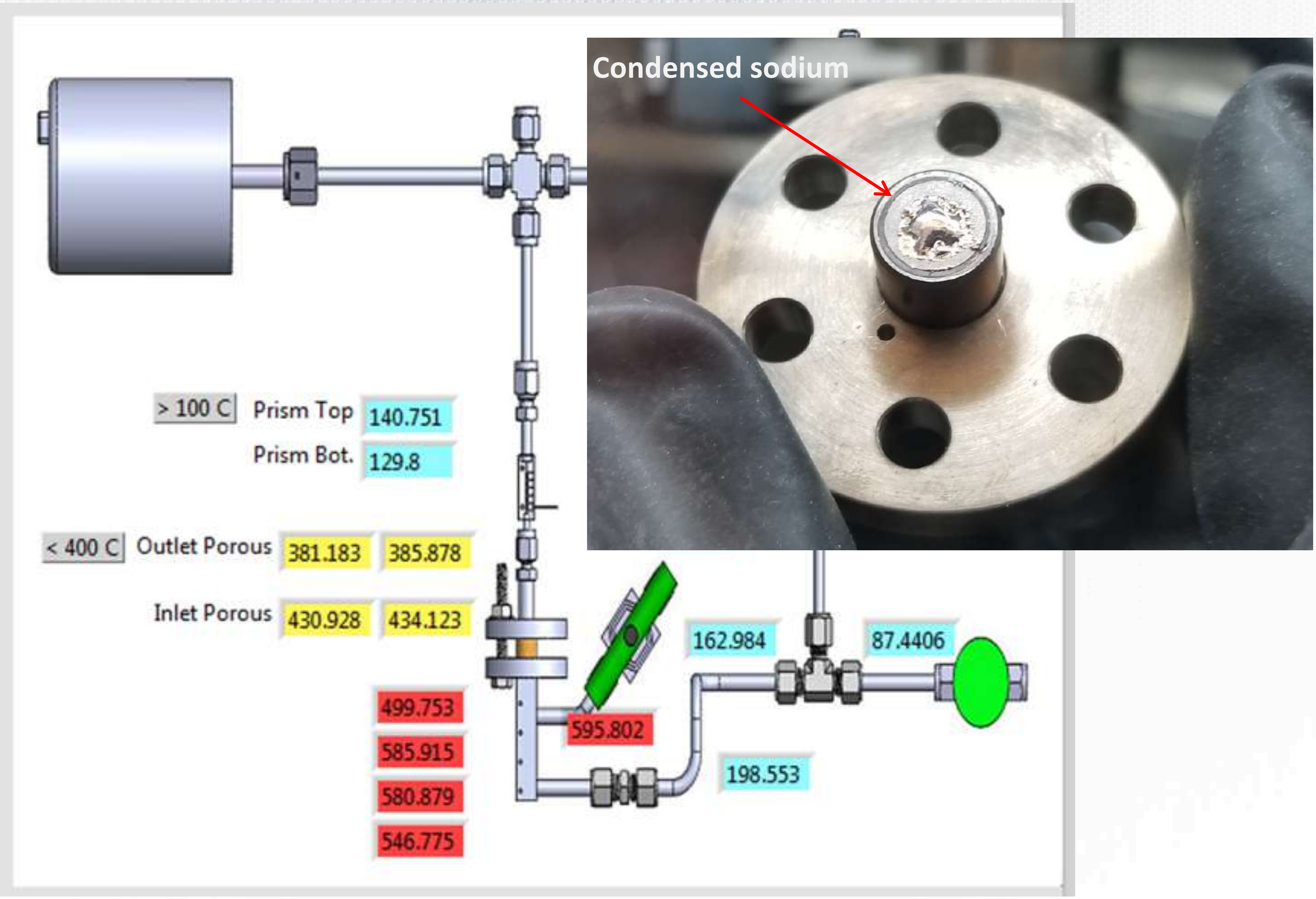
If $\omega_{Na} \ll 1$

use dilute gas approximation to neglect advection $$u = \frac{\rho_{Na}u_{Na} + \rho_{Ar}u_{Ar}}{\rho} = \omega_{Na}u_{Na}$$

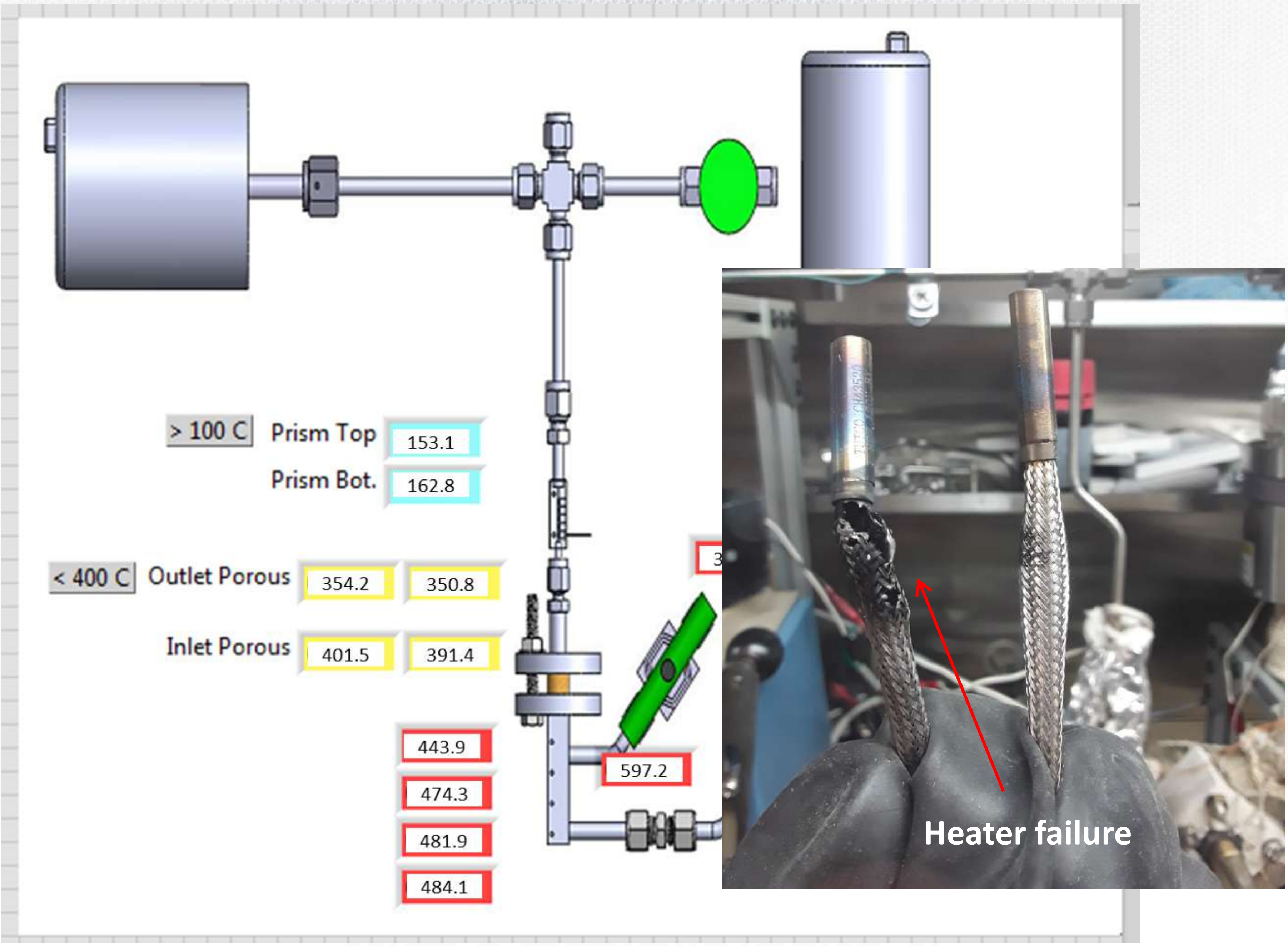




Experiment Attempt #1



Experiment Attempt #2



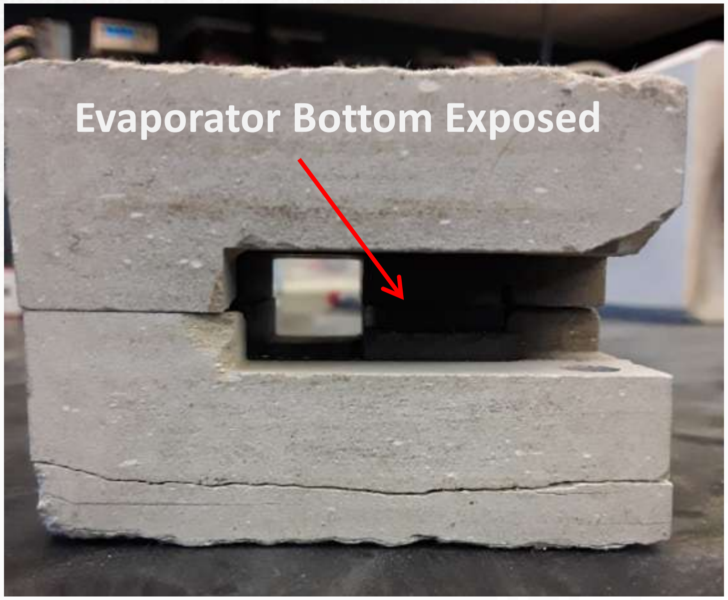
Summary and Future Work

Summary:

- Discussed transport model for combined advection/diffusion
- Introduced the experimental design used to demonstrate sodium pumping
- Described experimental modifications to achieve a successful run

Future Work:

- Continue experimental attempts while trying to improve the temperature profile
- Gather enough data points to construct a pump curve
- Validate experiment with conjugate heat transfer Comsol modeling



Acknowledgements

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