Interfacial and Transport Property Measurements of Liquid Sodium within a Porous Structure

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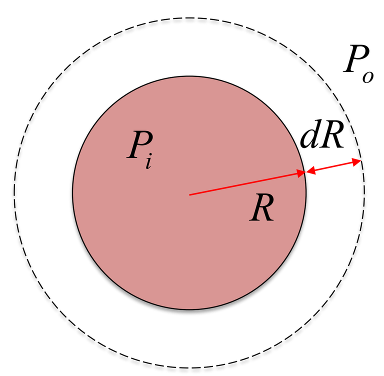
Project Objectives and Goals

The transfer of liquid sodium from a low-pressure condenser to a high-pressure evaporator is necessary to complete the thermodynamic cycle of a Na-TEC. A unique sodium capillary pump for the Na-TEC is proposed, whereby low-pressure sodium vapor is condensed within a non-wetting porous sample. The curvature created at this non-wetting condensation interface supplies a directed force upon the liquid sodium that effectively "pushes" it towards a high pressure region, rather than a traditional capillary wick that "pulls" the liquid. An experimental set-up is used to measure the temperature-dependent Laplace pressure generated at the phase change interface and the permeability of the porous structure.

Background

Considering the interface between two fluids, the work required to displace the interface by *dR* is given by:



$$\delta W = P_i dV - P_o dV - \sigma dA_s$$

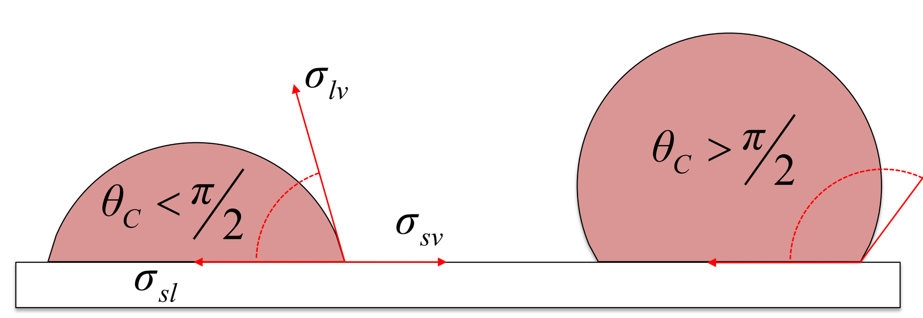
For a sphere at equilibrium:

$$\left(P_i - P_o\right)\left(4\pi R^2 dR\right) = \sigma\left(8\pi R dR\right)$$

Laplace Pressure:

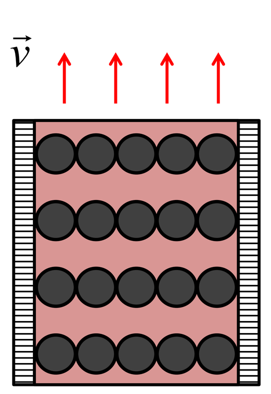
$$P_i - P_o = \Delta P = 2\kappa_{12}\sigma$$

where $\kappa_{12} = \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \rightarrow \left(\frac{1}{R}\right)_{sphere}$



Young-Dupree Equation $\quad \sigma_{sv} = \sigma_{sl} + \sigma_{lv}\cos\theta_C$

Momentum conservation for transport through a porous medium is governed by the classical Darcy law. Assuming laminar flow in the pores, the permeability is described by the Carman-Kozeny expression [1]



Darcy Law: $\quad \vec{v} = -\frac{\kappa}{\mu}\nabla P$

Carman-Kozeny Equation: $\quad \kappa = \frac{D_p^2\varepsilon^2}{150\left(1-\varepsilon^3\right)}$

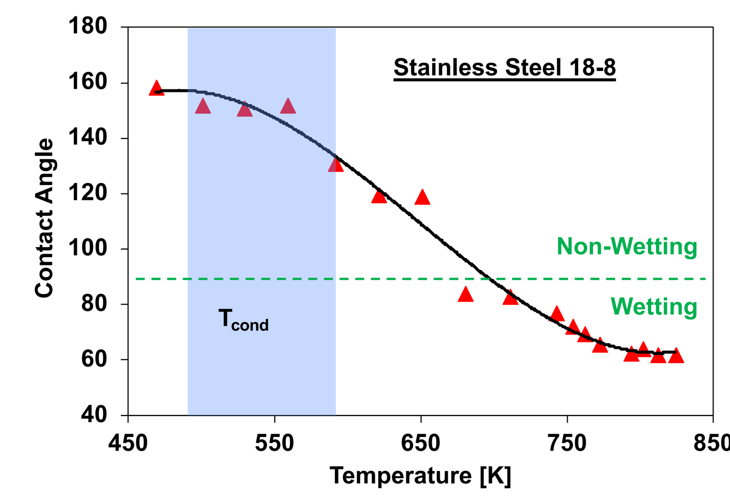
Particle Diameter: $\quad D_p = d_p\left(\frac{2\varepsilon}{3\left(1-\varepsilon\right)}\right)$

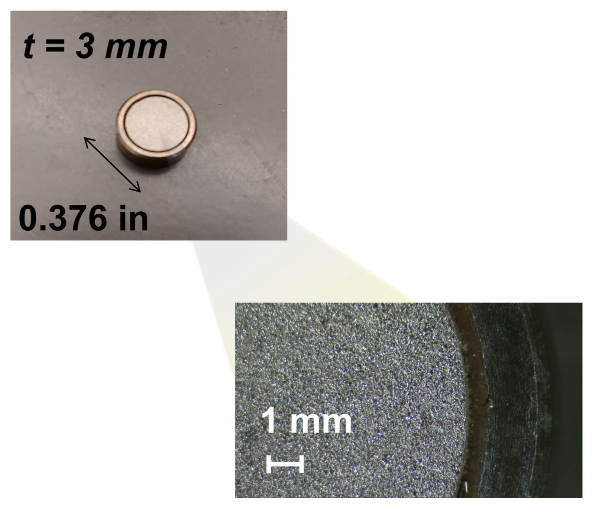
Assuming the pores are cylindrical tubes, the Laplace pressure is a function of contact angle:

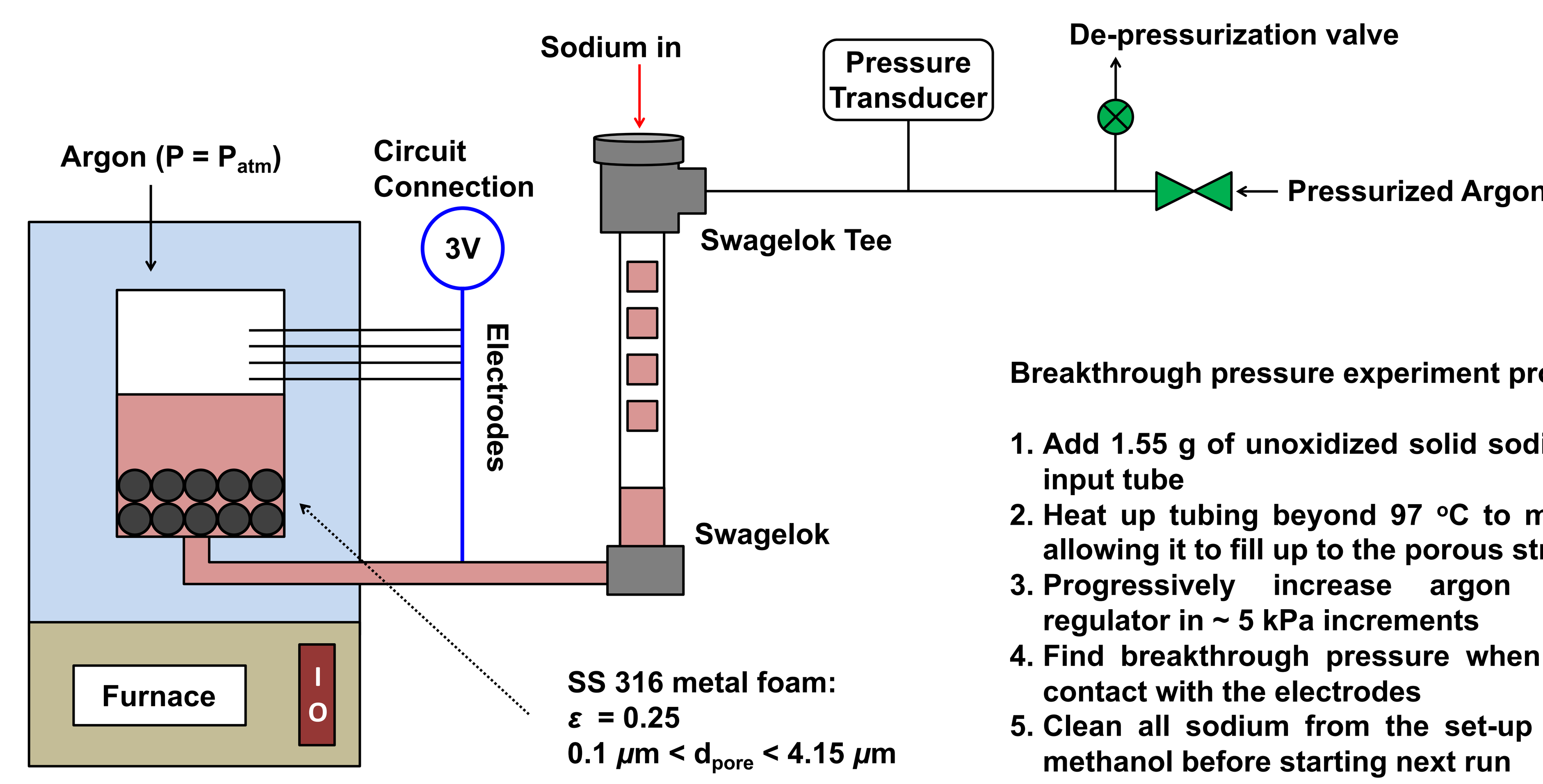
$$P_L = \frac{4\sigma_{lv}}{d_p}\cos\left(\pi - \theta_C\right)$$

Experimental Setup

- For pumping, it is necessary to use a material that is non-wetting to liquid sodium
- Stainless steel can be used up to ~ 400 C, at which point it enters a transition regime from non-wetting to wetting dynamics [2]
- A porous, commercially available (GKN), SS-316 coupon is thermally press fit within a SS bearing
- The pore effective diameter is < 4.15 μm, including at the boundary between the coupon and the bearing



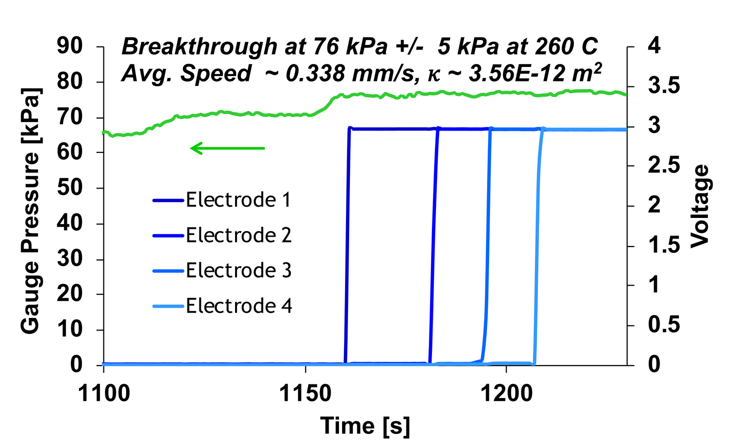


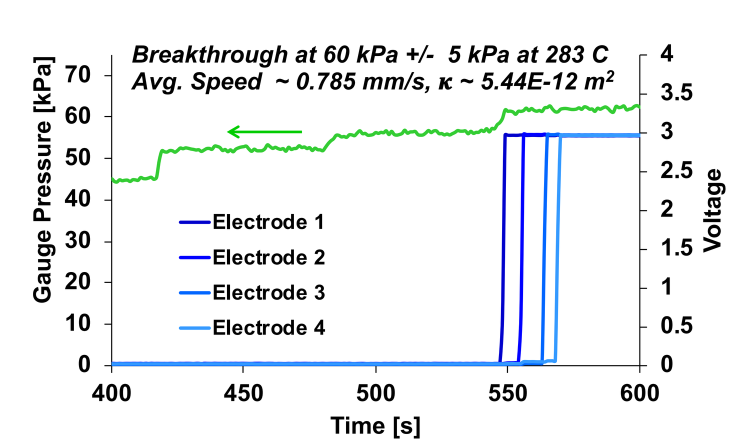


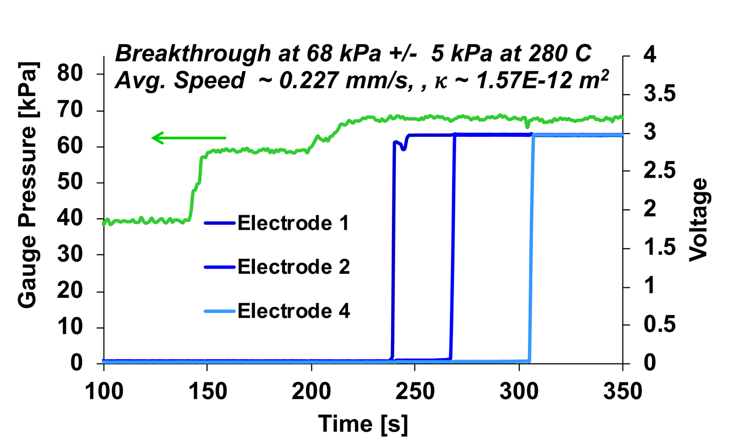
Breakthrough pressure experiment procedure:

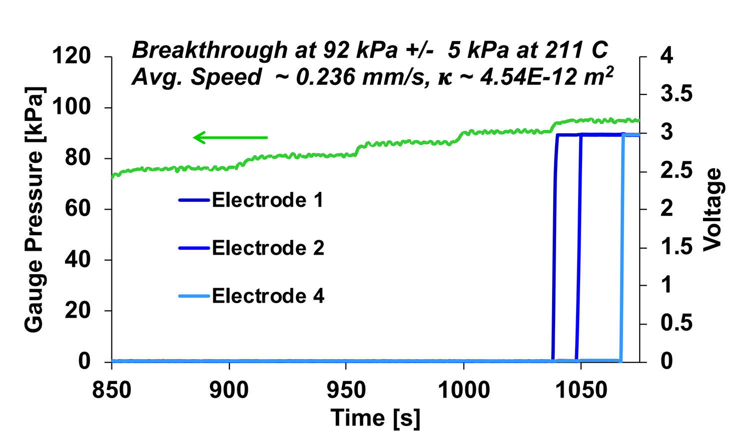
1. Add 1.55 g of unoxidized solid sodium through the input tube
2. Heat up tubing beyond 97 °C to melt the sodium, allowing it to fill up to the porous structure
3. Progressively increase argon pressure with regulator in ~ 5 kPa increments
4. Find breakthrough pressure when sodium makes contact with the electrodes
5. Clean all sodium from the set-up by rinsing with methanol before starting next run

Data and Results









Run	Breakthrough Pressure [kPa]	Velocity [mm/s]	Permeability [$\times 10^{12}$ m^2]	Furnace Temp. [°C]
1	95	0.369	3.89	300
4	97	0.206	2.17	300
5	133	0.139	--	300
6	85	0.549	5.79	300
7	30	--	--	300
8	76	0.338	3.56	300
9	76	0.379	4.00	300
10	72	0.144	1.52	300
11	68	0.227	1.57	300
12	57	0.391	4.12	300
13	65	0.406	4.28	300
14	67	0.340	2.36	300
15	60	0.785	5.44	300
16	92	0.182	3.49	250
17	92	0.236	4.54	250
18	100	0.253	4.94	250
19	91	0.276	--	250

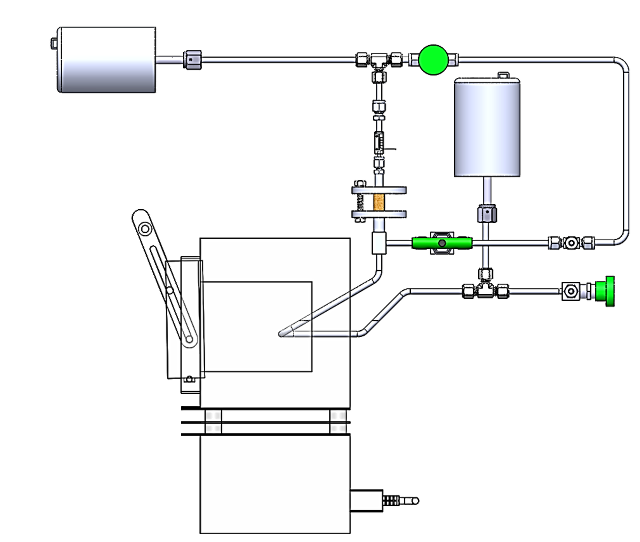
Failed Run

Conclusion

After attempting to run this experiment with a few different configurations, the set-up described herein is robust and reliable as evidenced by 15 successful runs shown in the results. The breakthrough pressure is a proxy for the interfacial pressure at the liquid sodium, porous structure, interface. The measurements are consistent for each temperature. Any variability in the magnitude is attributed to the distribution in pore diameter (0.1 μm < d_{pore} < 4.15 μm). As expected, the mean breakthrough pressure is higher at 250 C than at 300 C. This occurs because the contact angle is reduced as temperature increases. The permeability measurements are all within the same order of magnitude, but they vary significantly (+/- 50% from the mean). More experimental trials need to be run in order to properly characterize the porous sample permeability. One issue that might be exacerbating these inconsistencies is residual sodium methoxide leftover in the tubing infrastructure after cleaning out the sodium with methanol.

Future Studies

- Run breakthrough experiments at different temperatures to characterize the temperature-dependent Laplace pressure
- Measure the permeability of the porous samples more consistently across future trials
- Use this experimental set-up to measure the transport properties of different pore sizes and different materials (Cu, Al etc.)
- Perform contact angle measurements of sessile sodium drops on stainless steel 316
- Develop condensation transport model using property measurements from the breakthrough experiments
- Use information from these measurements to build an experiment (pictured in the right) to demonstrate the sodium capillary pumping



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Publications

1. A. Limia, J.M. Ha, P. Kottke, A. Gunawan, A. Fedorov, S.W. Lee, and S. Yee, *A Dual Stage Sodium Thermal Electrochemical Converter (Na-TEC),* Journal of Power Sources, (2017).
2. A. Limia, P. Kottke, A. Fedorov, and S. Yee, *Thermal Modeling and Efficiency of a Dual-Stage Sodium Heat Engine*, Applied Thermal Engineering, (2018).

References

[1] R.B. Bird, W. Stewart, E. Lightfoot, *Transport Phenomena*, Wiley, (2002).
[2] J. Taylor, S. Ford, *Solid Metal-Liquid Metal Interactions Studies. Part II. Contact Angle Relationships for Sodium on Solids,* United Kingdom Atomic Energy Authority, (1955).