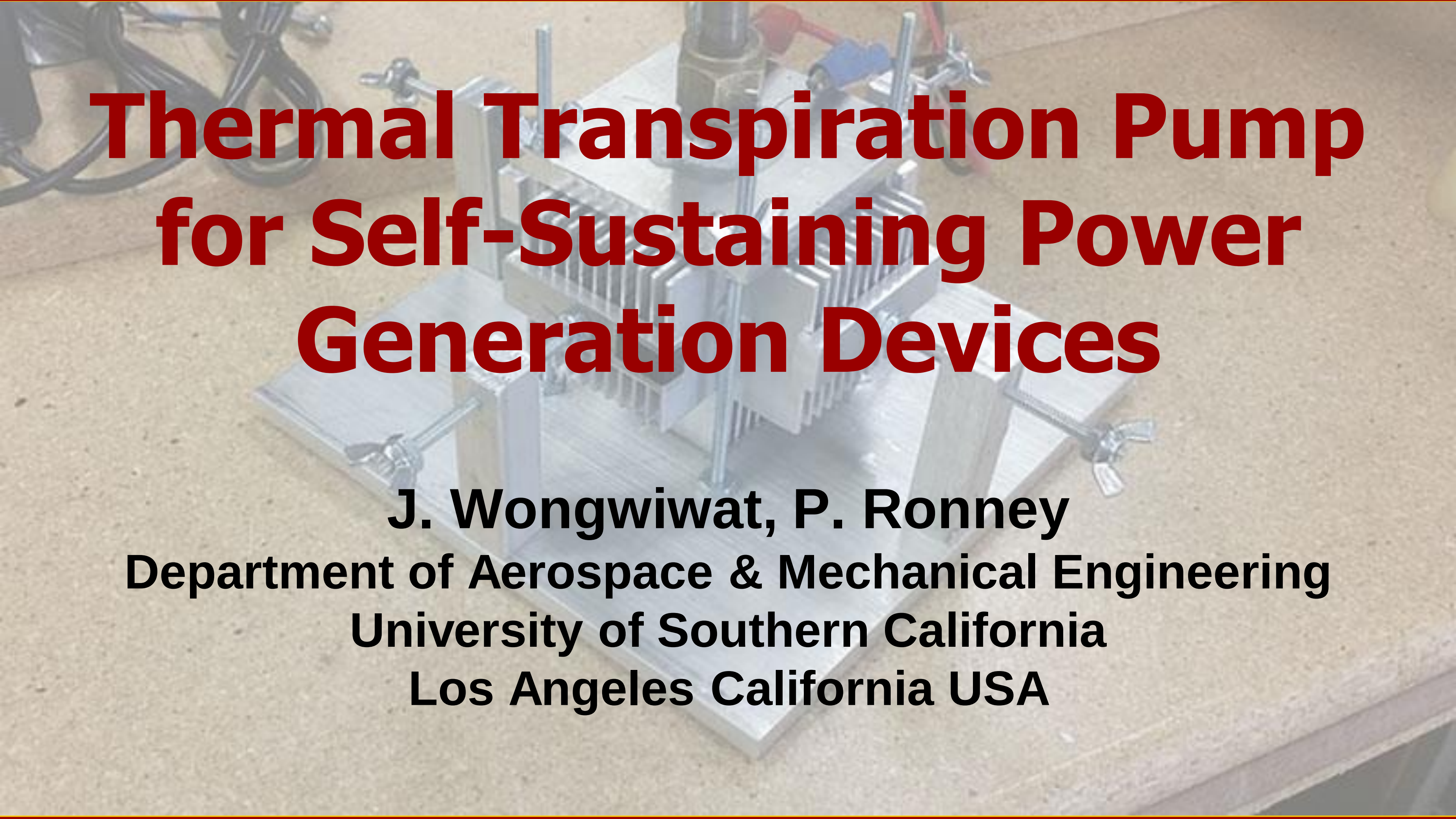


Thermal Transpiration Pump for Self-Sustaining Power Generation Devices

J. Wongwiwat, P. Ronney

Department of Aerospace & Mechanical Engineering

University of Southern California

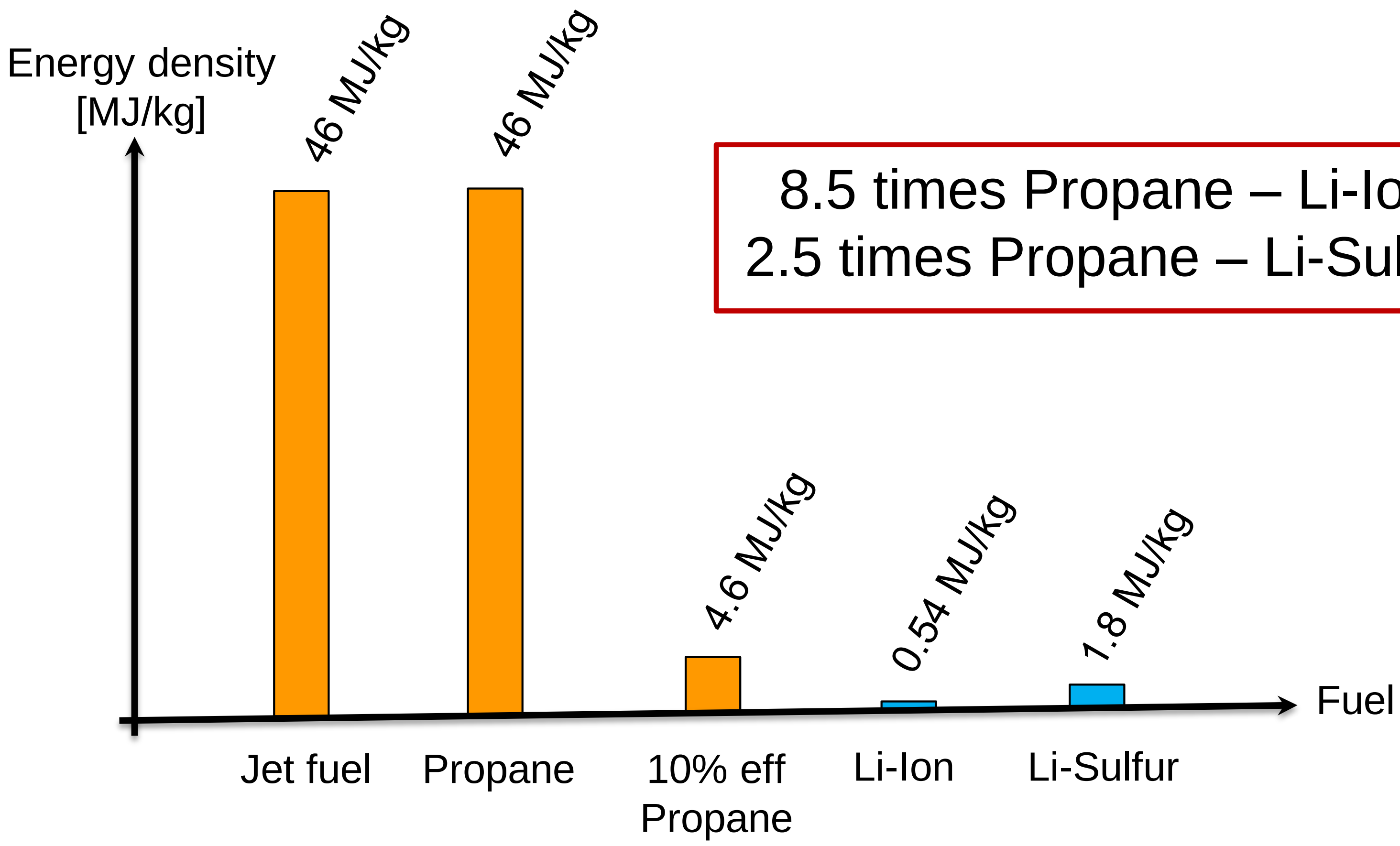
Los Angeles California USA

USC Viterbi

School of Engineering

Motivation

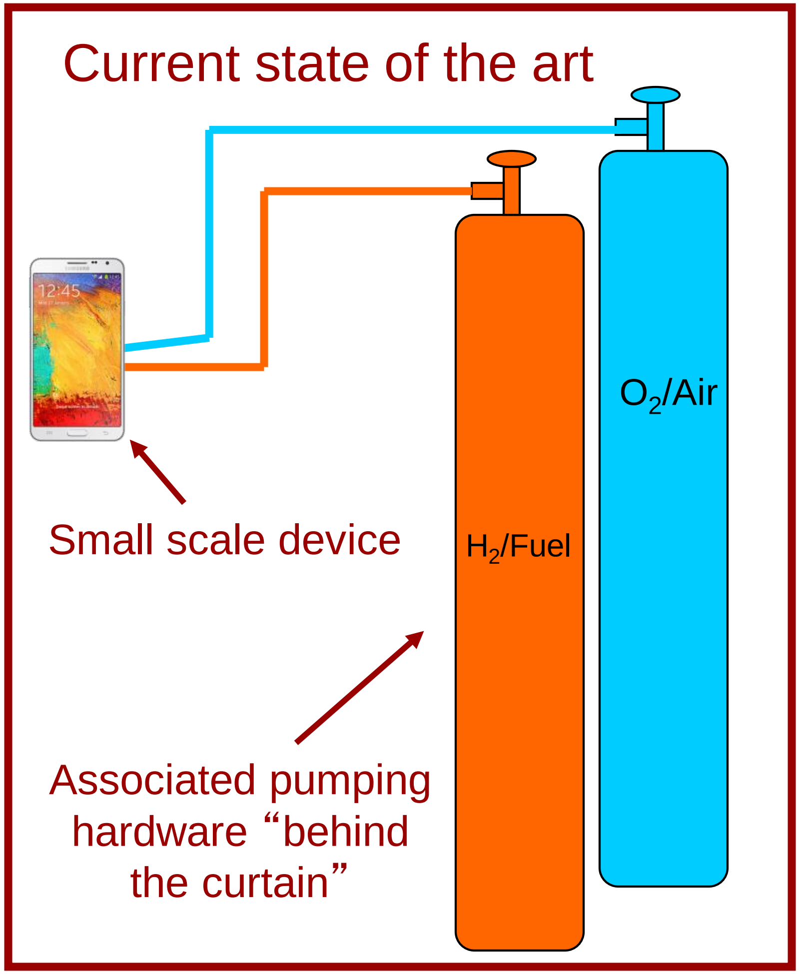
Energy density



8.5 times Propane – Li-Ion
2.5 times Propane – Li-Sulfur

Motivation

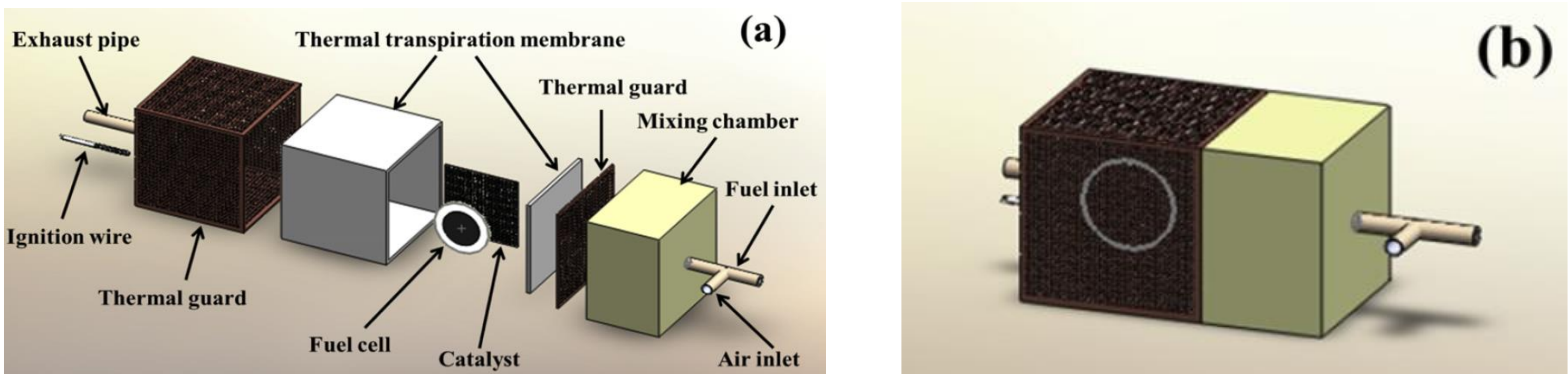
- Hydrocarbons offer superior energy storage density compared to batteries
- Any device processing fuel/air mixtures requires means to pump air
- **Pumping option 1**
  - Scaled down a macroscale device (e.g piston/cylinder, gear pump, compressor)
- Problem with option 1 at small scales
  - Moving parts
  - Friction, sealing, manufacturing, …
  - Parasitic electrical power requirement



Motivation

- **Pumping option 2** (no moving parts)
  - Buoyancy (e.g BBQ grill, candle, camp stove)
- Problem with pumping option 2 at small scale
  - Buoyancy ineffective at small scales (small Rayleigh #)
  - Orientation sensitive
- **OUR SOLUTION: THERMAL TRANSPIRATION**
  - No moving parts
  - Pumping cost is thermal energy (not electrical energy)
  - Orientation independent
  - Integrating with catalytic combustion and single-chamber solid oxide fuel cells (SCFCs)

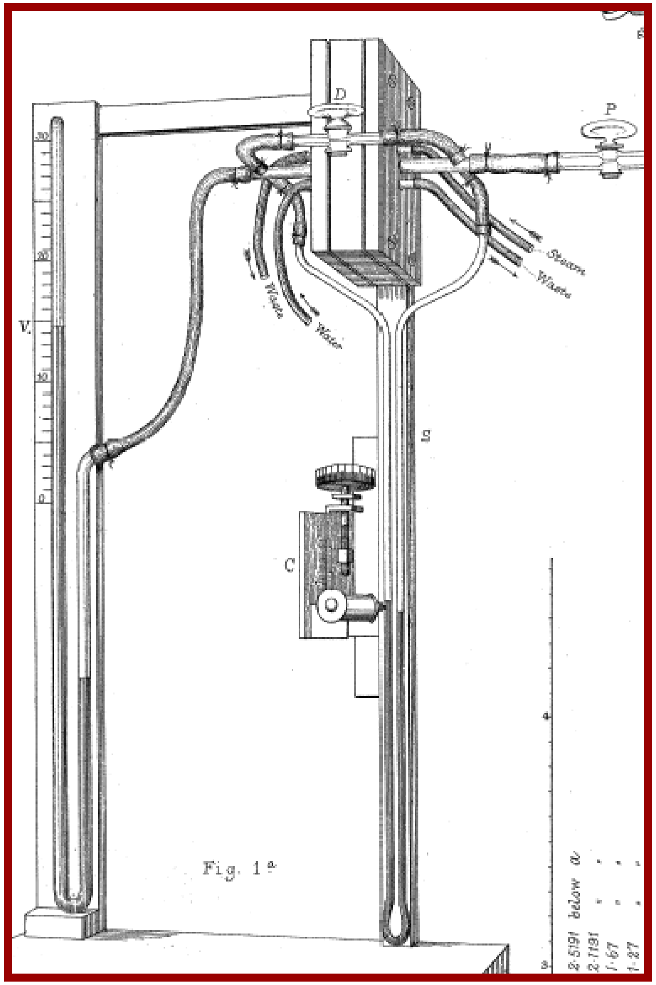
Cubic Chamber



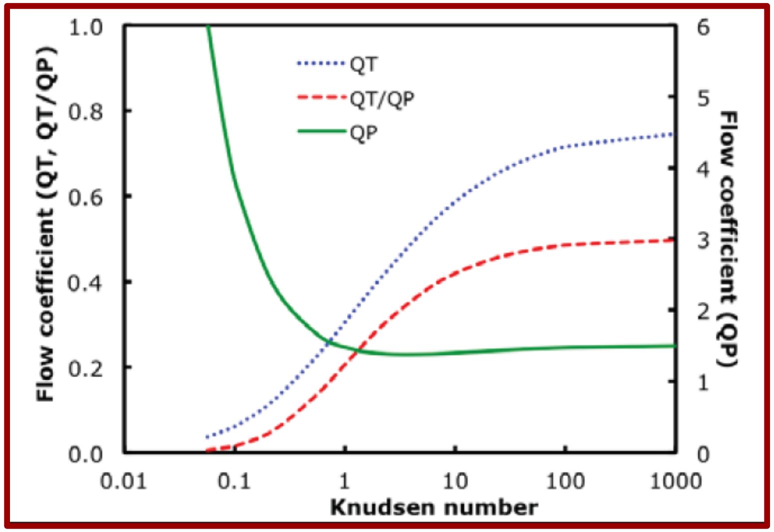
- Wang et.al. (2012)
- Power generation
  - Single-chamber solid oxide fuel cells
  - Catalytic combustion
  - Thermal transpiration pump
- The first example of a self-sustaining with no moving parts that uses no other energy feedstock besides hydrocarbon fuel power generator
- Efficiency ≈ 0.092%

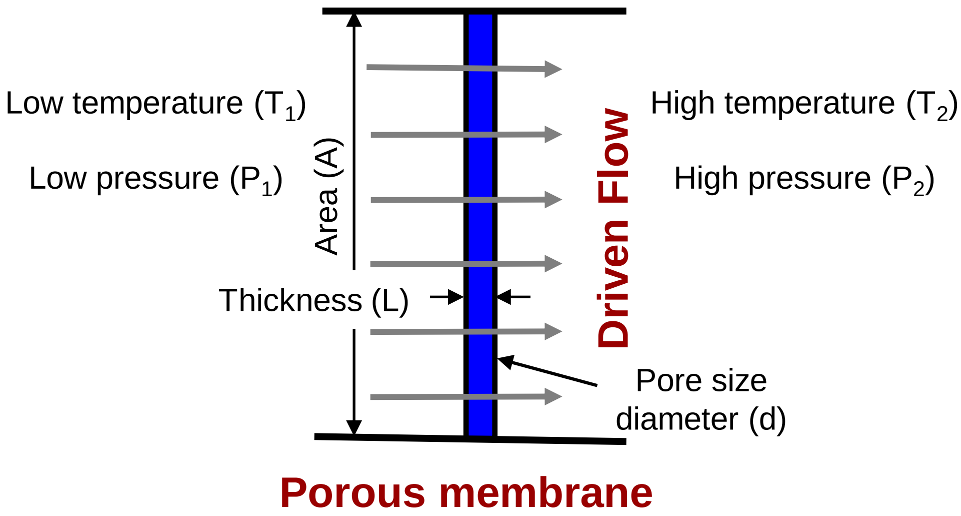
Thermal Transpiration Process

- First observed and term coined by Osborne Reynolds in 1878
- Occurs in porous media or capillary tubes with an applied temperature gradient
- Net flow of gas from cold to hot side
- Cost is thermal energy required to maintain ΔT
- Reynolds used stucco porous plates; high conductivity thus high thermal power costs



Knudsen Pump





- Muntz et.al. (2002)
- Kn = λ/d; λ is gas mean free path, d is pore size
- Volume flow rate: $\dot{V} = \frac{P_{avg}}{\rho_{avg}} \sqrt{\frac{m}{2kT_{avg}}} A \frac{d}{2L} \left[\frac{T_2 - T_1}{T_{avg}} Q_T - \frac{P_2 - P_1}{P_{avg}} Q_P \right]$
- Low Kn and low ΔP, volume flow rate: $\dot{V} = \frac{c_1 A}{\sqrt{\gamma}} \frac{d}{L} \sqrt{\frac{T_1 (T_2 - T_1)^2}{(T_2 + T_1)^3}} Q_T$

Porous Membrane

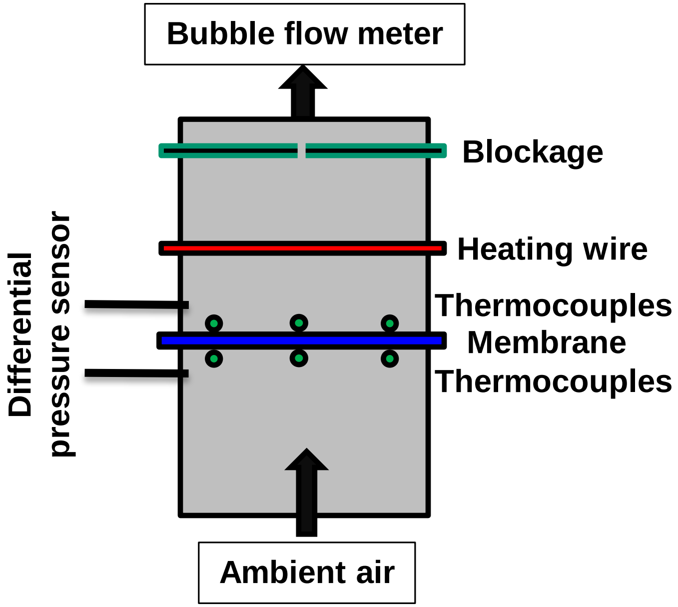
Whatman™ 1825-090 glass microfiber filter

Effective pore diameter ~ 0.7 μm

Diameter 90 mm

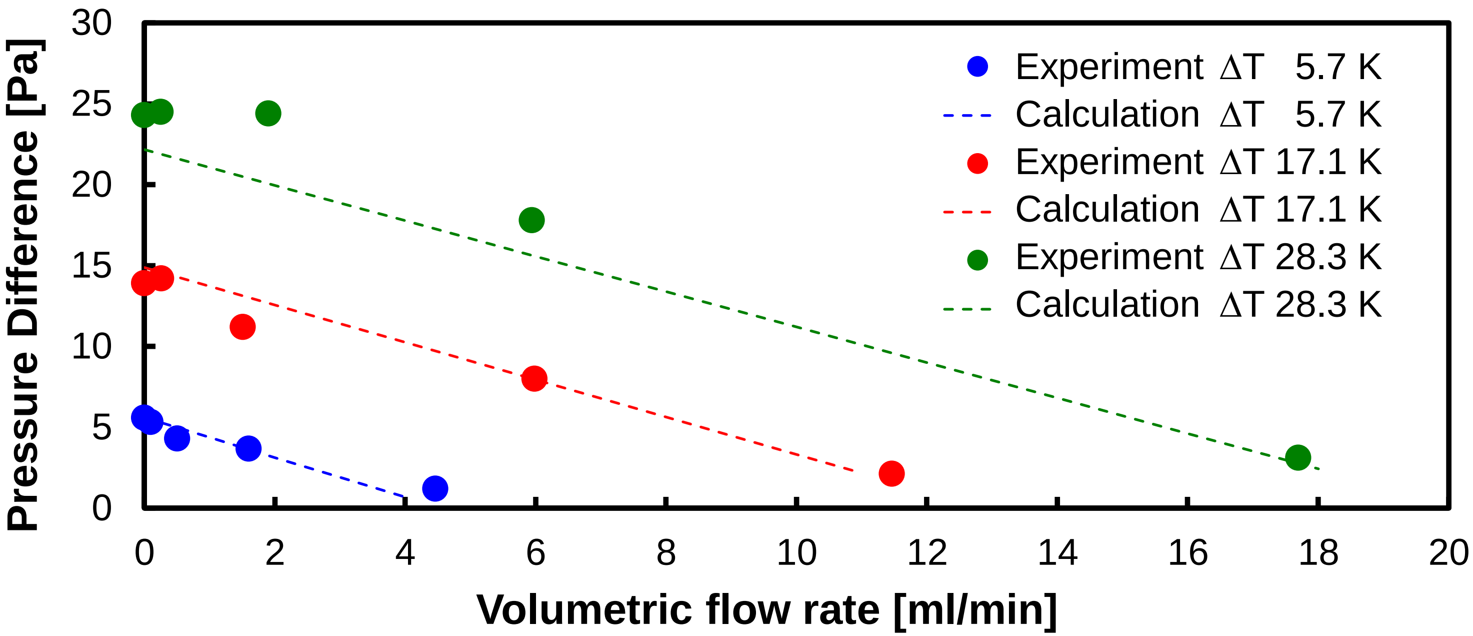
Thickness 470 μm

1D Flow Thermal Transpiration Membrane



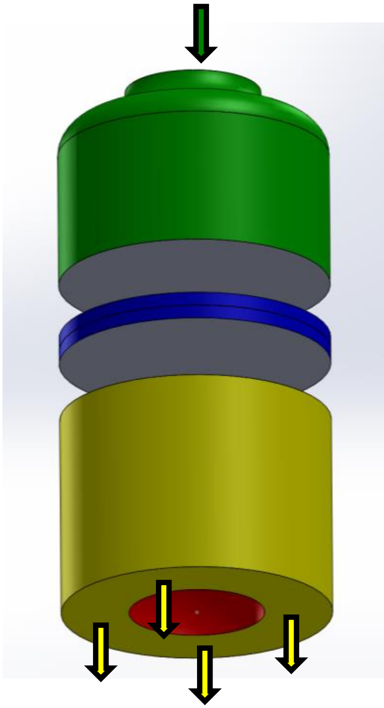
- Electrical wire was used to supply heat to the membrane
- Zero flow conditions and zero pressure difference conditions were tested to verify effective pore radius and effective capillary's cross-sectional area

1D Flow Thermal Transpiration Membrane

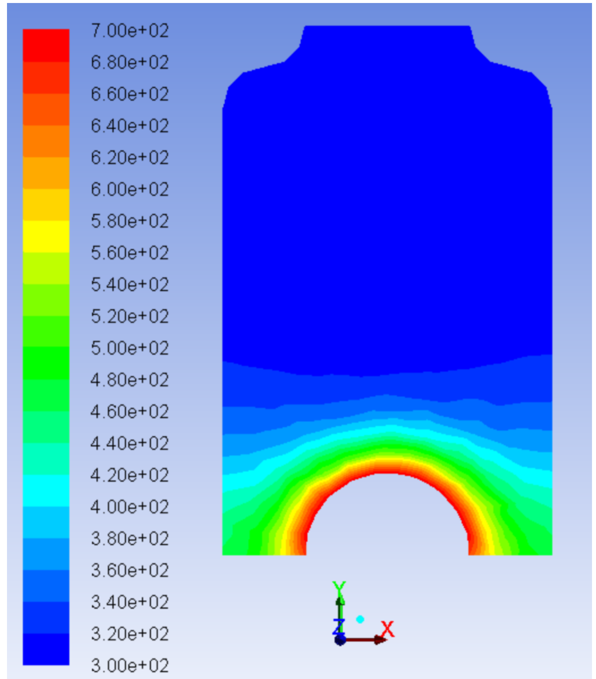


- Results from the experiment and calculation fitted by 2.12 μm effective pore radius and 32.6% effective capillary's cross-sectional area.
- Higher temperature difference generates higher air flow rate.

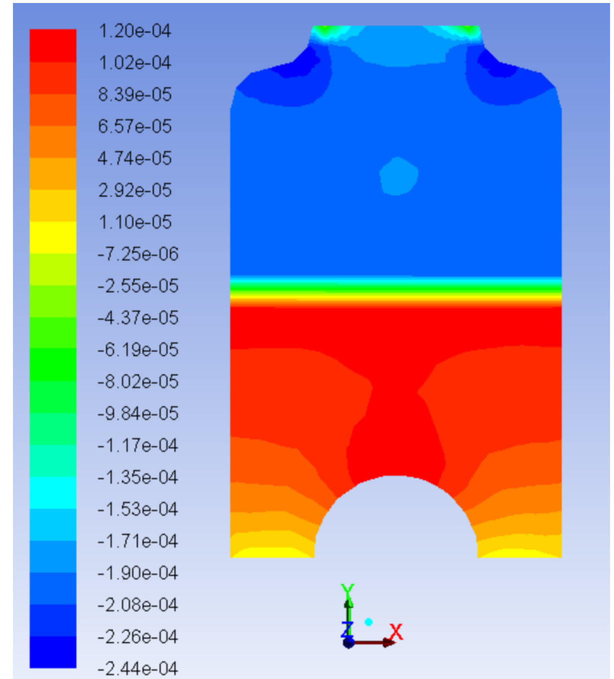
Thermal Transpiration Membrane Simulation



Exploded view



Temperature gradient

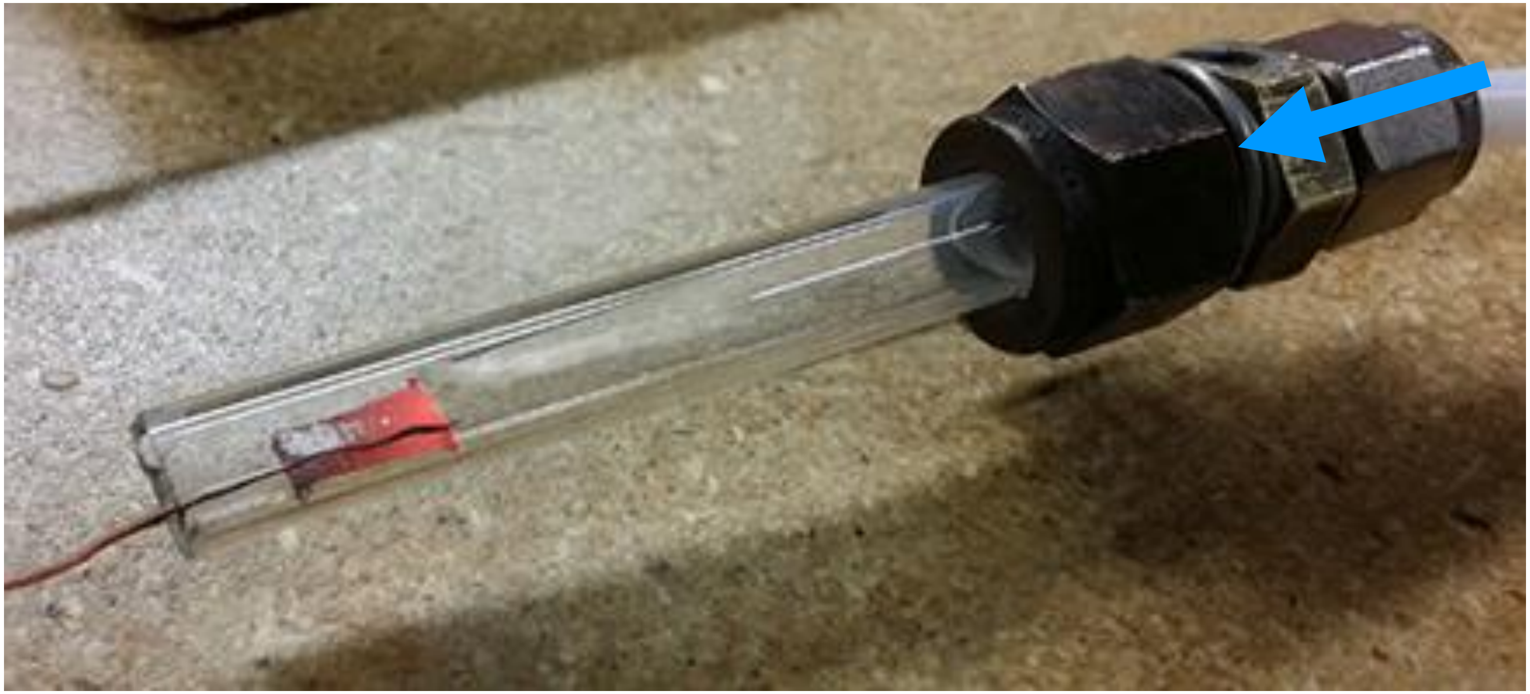


Pressure gradient

- ANSYS Fleunt was used to simulate temperature and pressure distribution from thermal transpiration membrane.

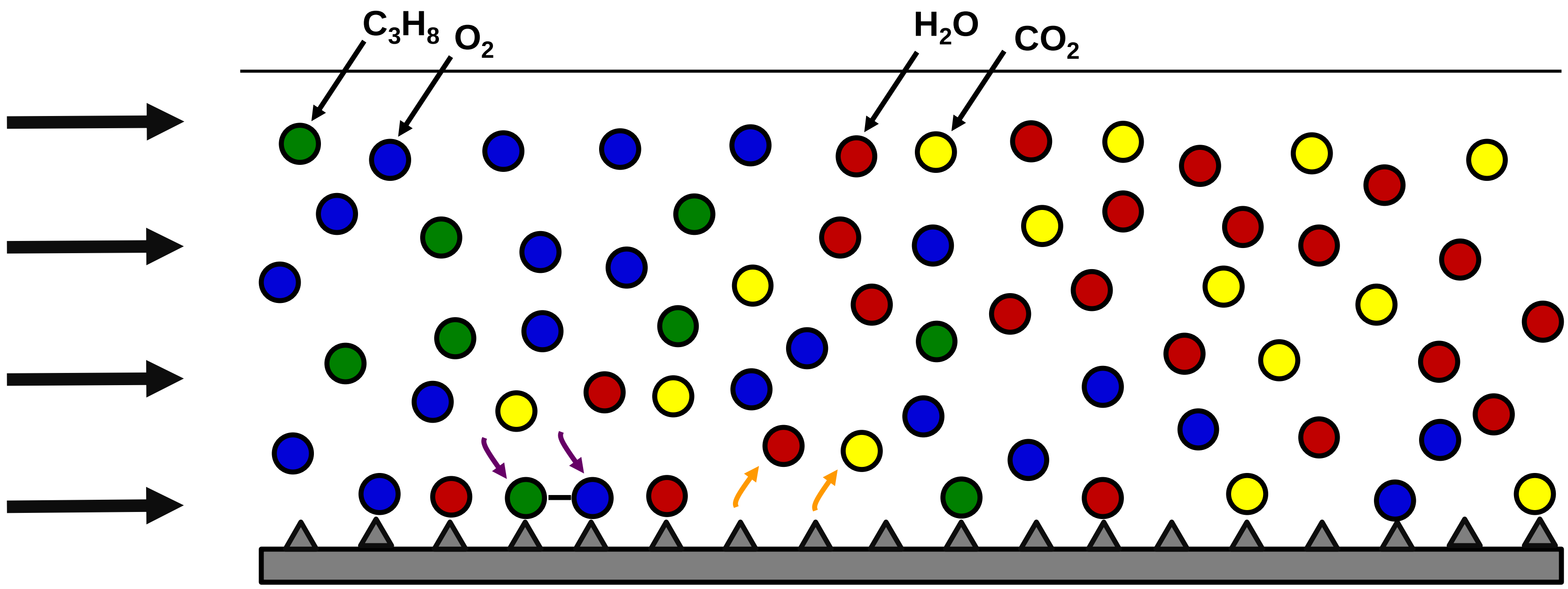
Ref. Muntz, E. P., Sone, Y., Aoki, K., Vargo, S., Young, M., "Performance Analysis and Optimiztion Considerations for a Knudsen Compressor in Transitional Flow, "J. Vac. Sci. Technol. A, Vol. 20(1), 214-224, Jan/Feb (2002).

Catalytic Combustion Over Platinum Catalyst

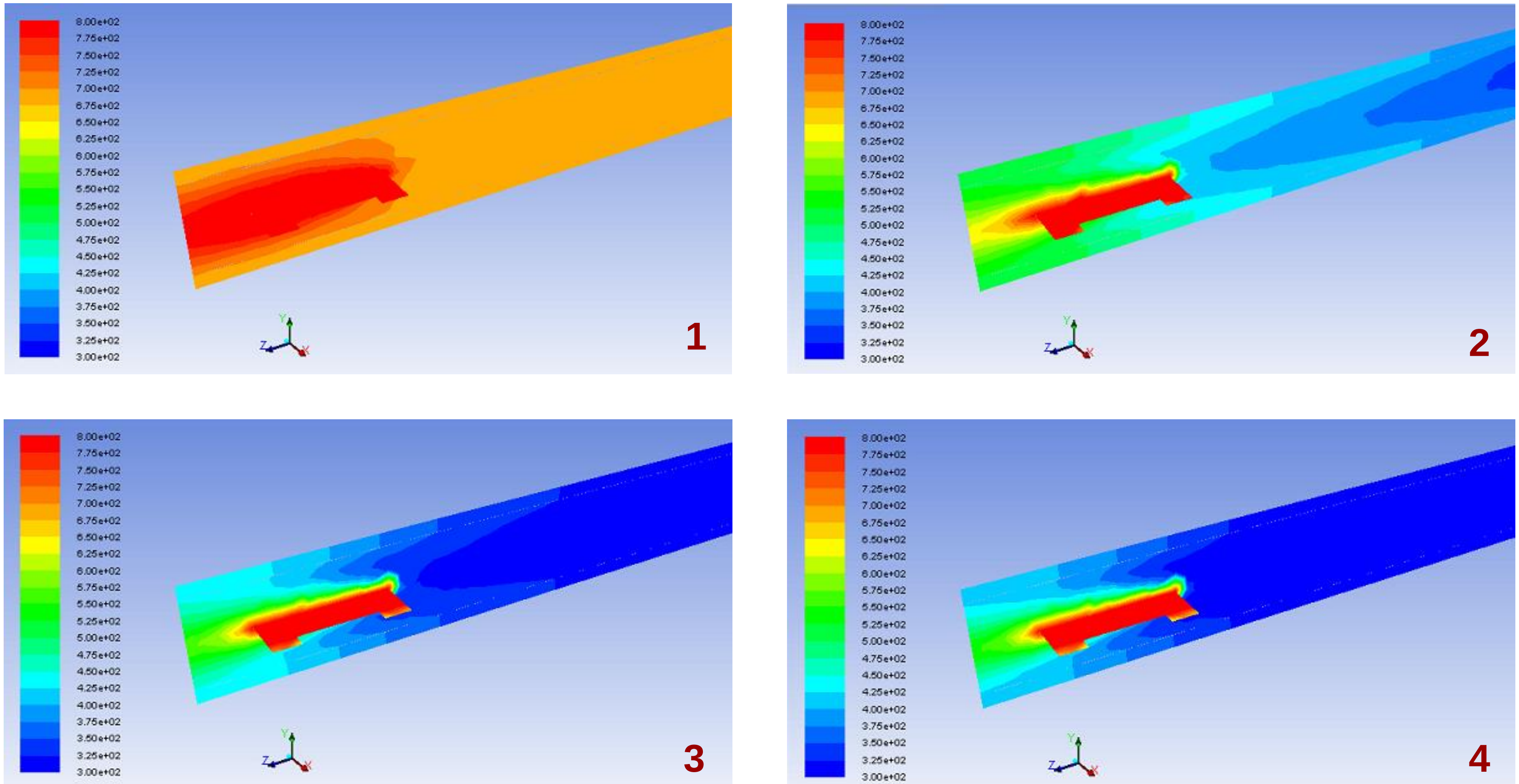


- Propane-air premixed combustion
- 9.0 equivalent ratio and 0.2 premixed gas velocity

Catalytic Combustion Over Platinum Catalyst



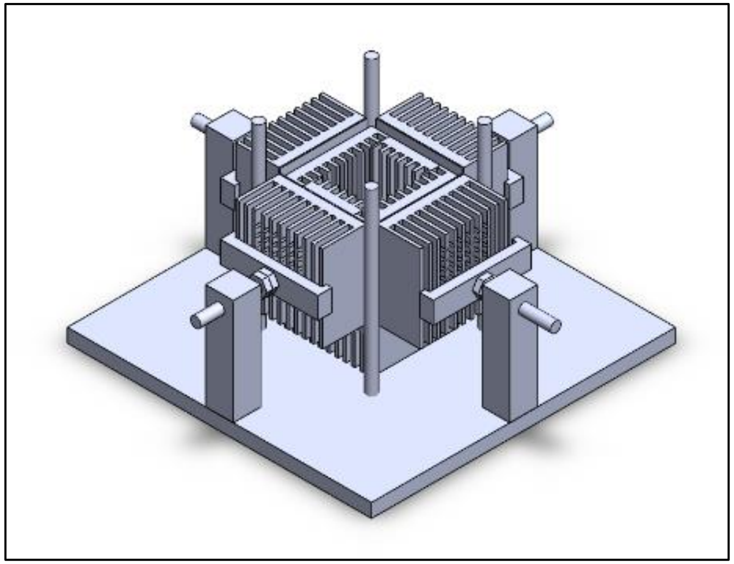
Catalytic Combustion Simulation



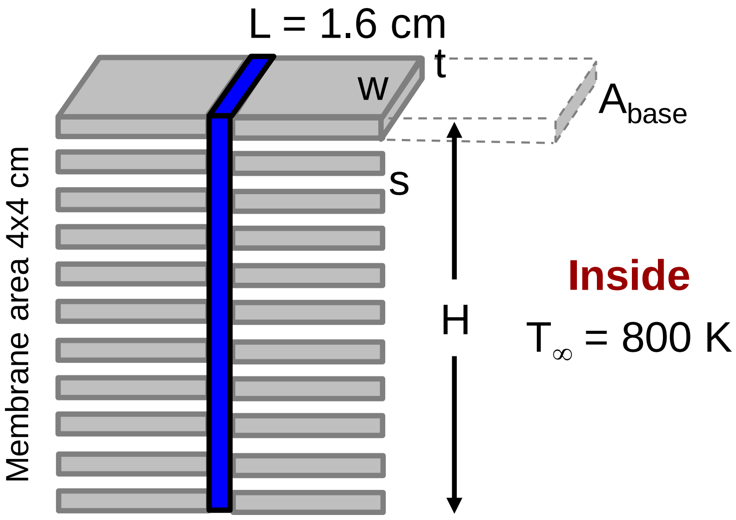
Temperature gradient using transient simulation

Ref. S.R. Deshmukh, D.G. Vlachos, "A reduced mechanism for methane and one-step rate expressions for fuel-lean catalytic combustion of small alkanes on noble metals," Combustion and Flame, Vol. 149(4), 366-383, Jun (2007).

Chamber Design



Combustion chamber with fins on each face

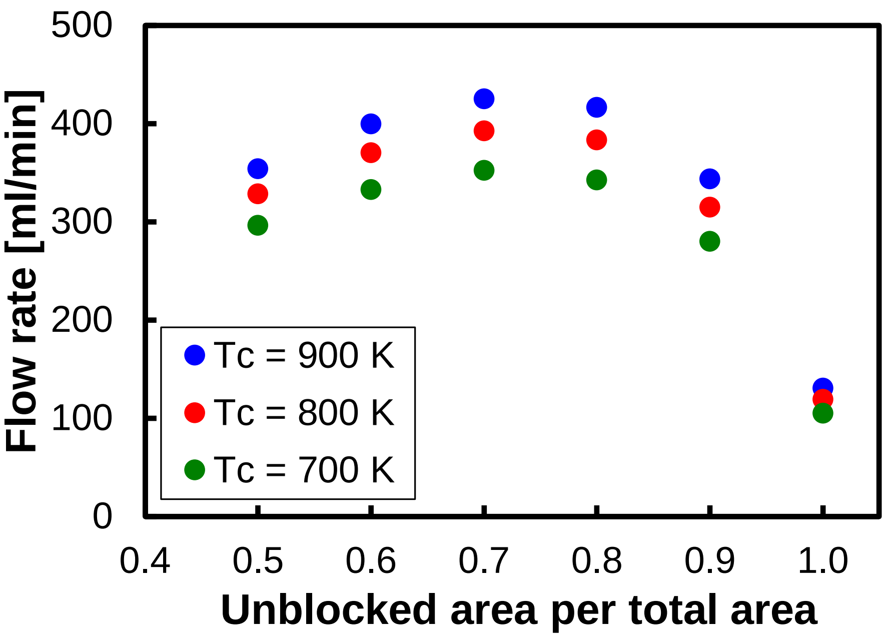


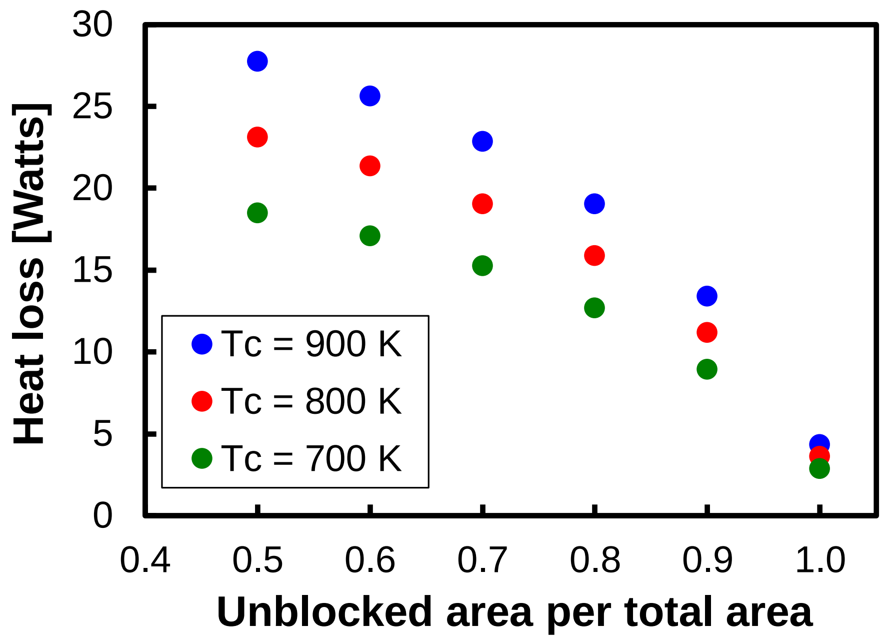
fin cross section

Fin design

- Fins increase heat transfer coefficient
- Temperature gradient also increases

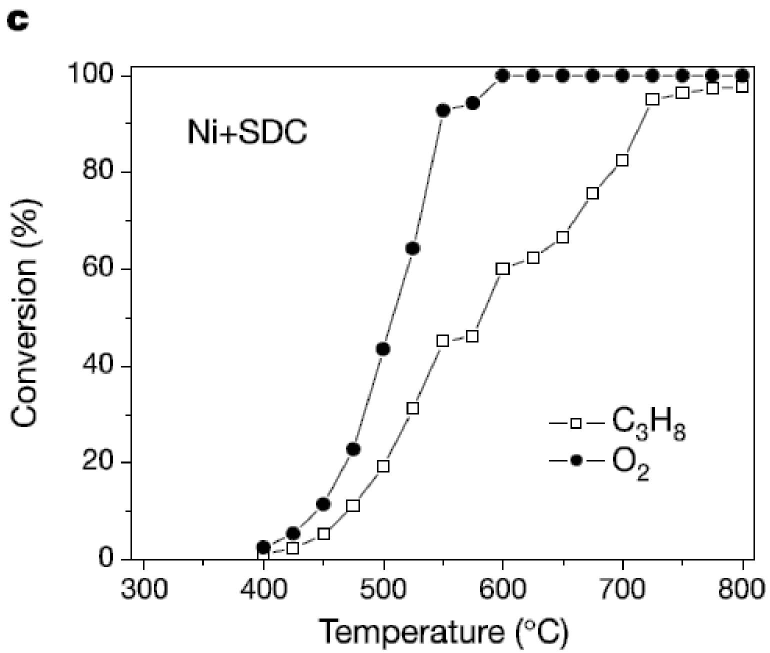
Chamber Design

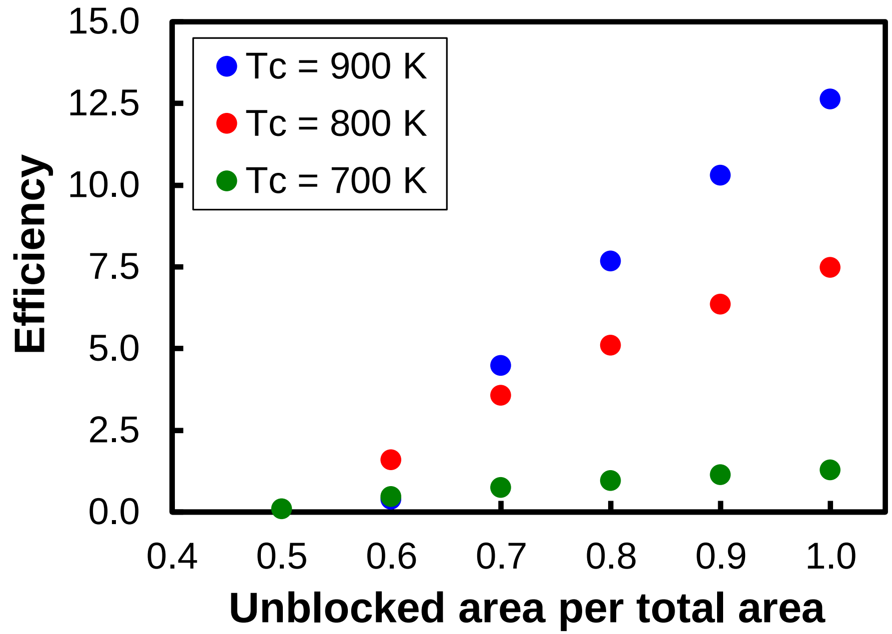




- Maximum flow occurs when the unblocked area per total area is 0.7 at the highest chamber temperature
- However fins are generating heat loss

Power Generation Efficiency

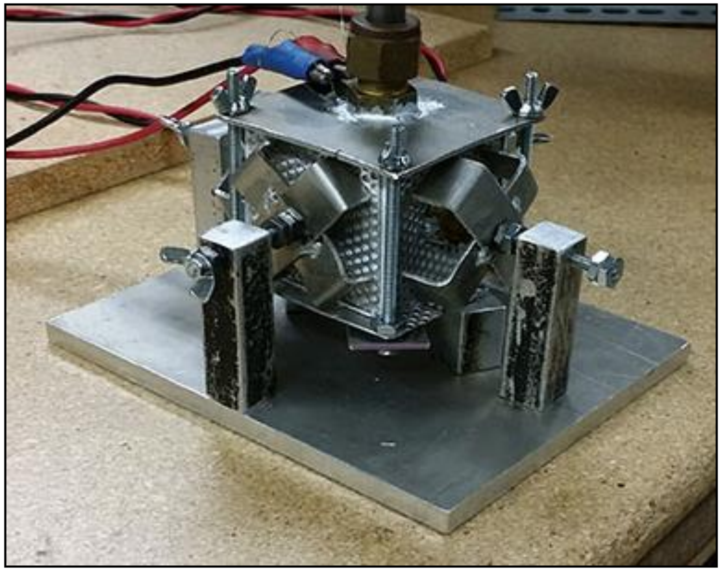




- The estimation is based on 40% efficiency of SOFC power generation at 100% propane conversion.
- Higher chamber temperature will provide higher efficiency

Ref: Z.Shao, S.M.Haile, J.Ahn, P.D.Ronney, Z.Zhan & S.A.Barnett, "A thermally self-sustained micro solid-oxide fuel-cell stack with high power density," Nature., Vol. 435, 795-798, Jun (2005).

Future Work

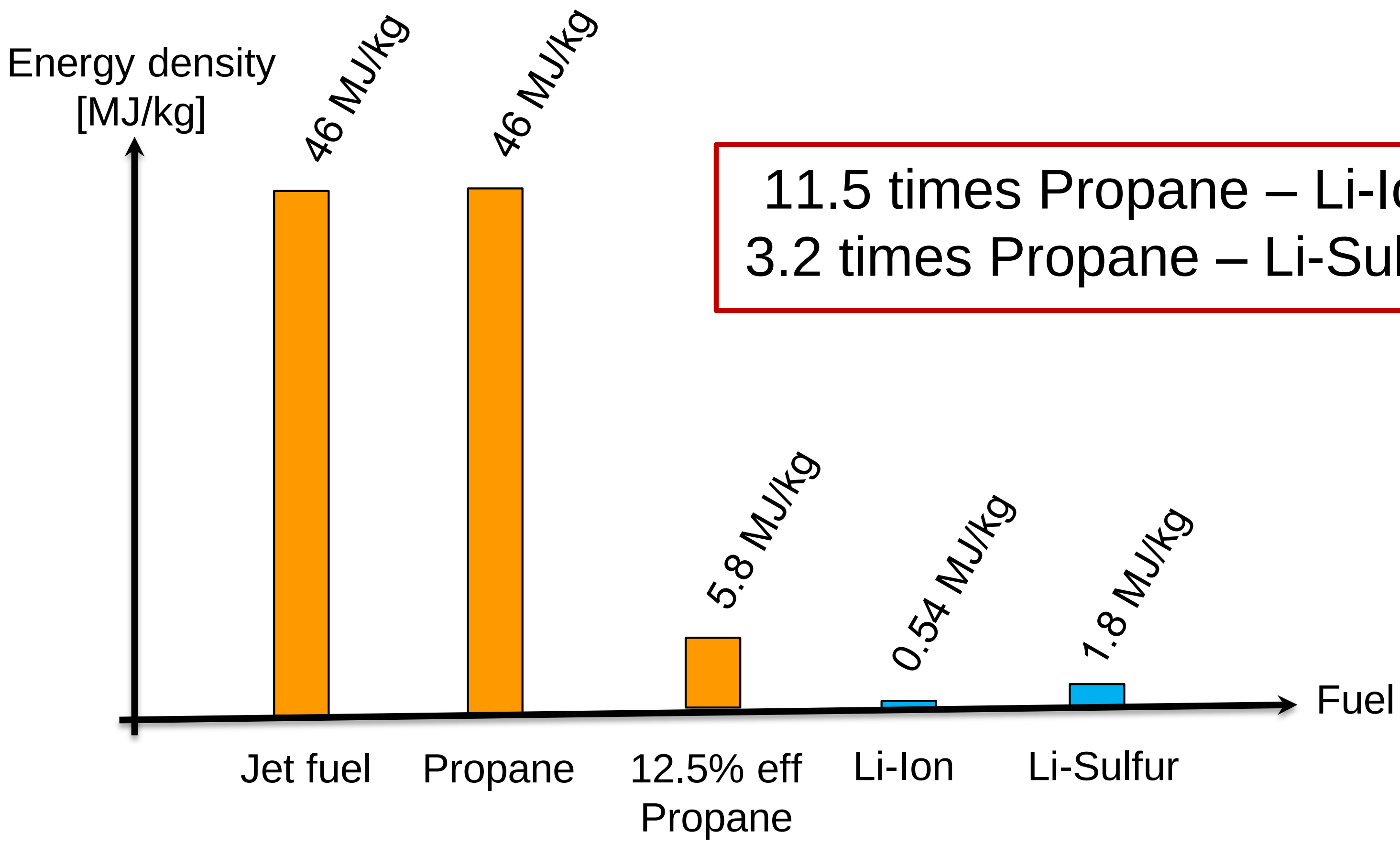


Design Concept

- Maximize efficiency by optimizing catalyst surface area, SOFC operating condition, thermal transpiration membrane properties and operating temperature.
- Manufacturing process is feasible.

Motivation

Energy density



11.5 times Propane – Li-Ion
3.2 times Propane – Li-Sulfur

Thermal Transpiration Pump for Self-Sustaining Power Generation Devices

Q & A