Status of the Knudsen Compressor for Use in Distributed and Autonomous Sampling Systems

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Overview

- Requirement for Micro-scale Gas Roughing Pumps
- Introduction to Thermal Transpiration
- The Knudsen Compressor
- Knudsen Compressor Performance Models
- Radiantly Driven Knudsen Compressors
- Knudsen Compressor Cascade Experiments
- Perforated Aerogel Transpiration Membrane Experiments
- Optimization Results
- Sample Compressor Sizing
- Summary

Micro/Meso-Scale Gas Roughing Pumps

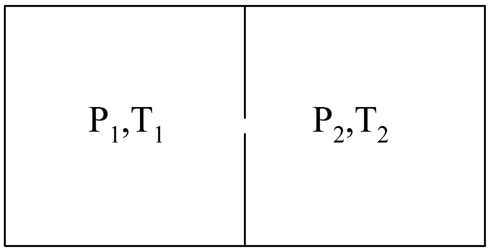
- Micro/meso-scale gas sensors are being developed that require gas pumping.
- Both roughing pumps and high vacuum pumps are required.
- Two possible development strategies: shrink down existing technology or develop new technology.
- Problems with shrinking down existing technology:
  - Moving parts, required manufacturing tolerances, oil.
- Worth considering new pump technology for micro/meso-scales.
- A pump based on thermal transpiration is one promising technology for micro/meso-scale gas roughing pumps:
  - No moving parts, no oil or supplementary fluids, scalable, similar technology applicable to high-pressure gas compressors, variety of powering options including: radiative, solar, resistive, waste heat, combustion.

Thermal Transpiration (Thermal Effusion and Creep)

- Rarefied gas phenomena (free-molecular or transitional flow driven by surface temperature gradient)

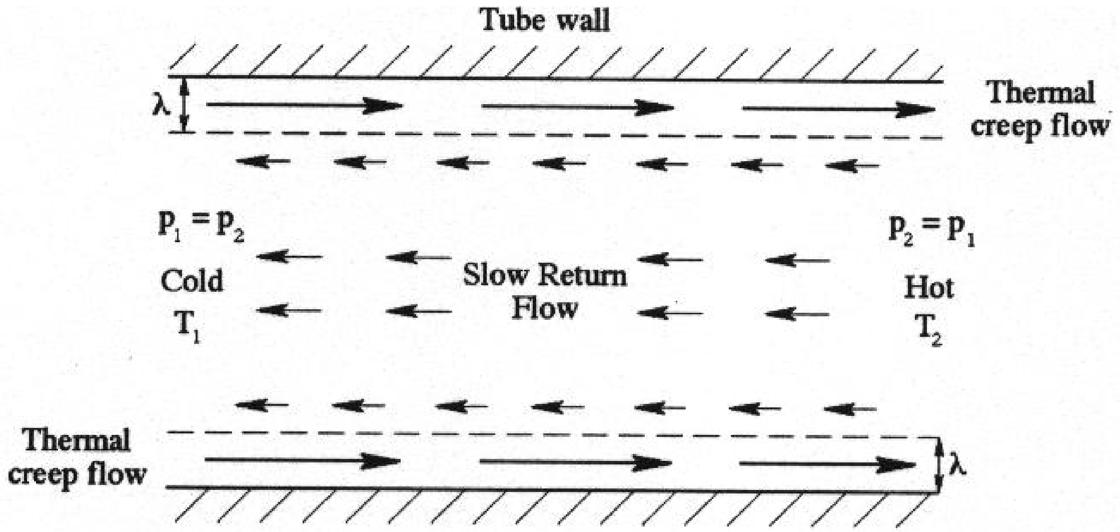
Thermal Effusion Through Orifice

$T_1 < T_2$



$$\frac{p_1}{p_2} = \sqrt{\frac{T_1}{T_2}}$$

Thermal Creep along surfaces



•Longitudinal Wall temperature gradient drives creep flow, counterbalanced by pressure driven return flow (Poiseuille flow)

•One of the driving mechanisms in Crooke's radiometer

•Net effect is; for $P_2 = P_1$ a Maximum flow from cold to hot, for P2 > P1 Reduced Flow Reaching Zero for Maximum P_2/P_1

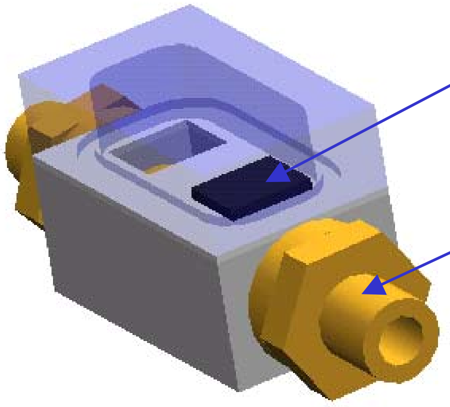
Using Thermal Transpiration

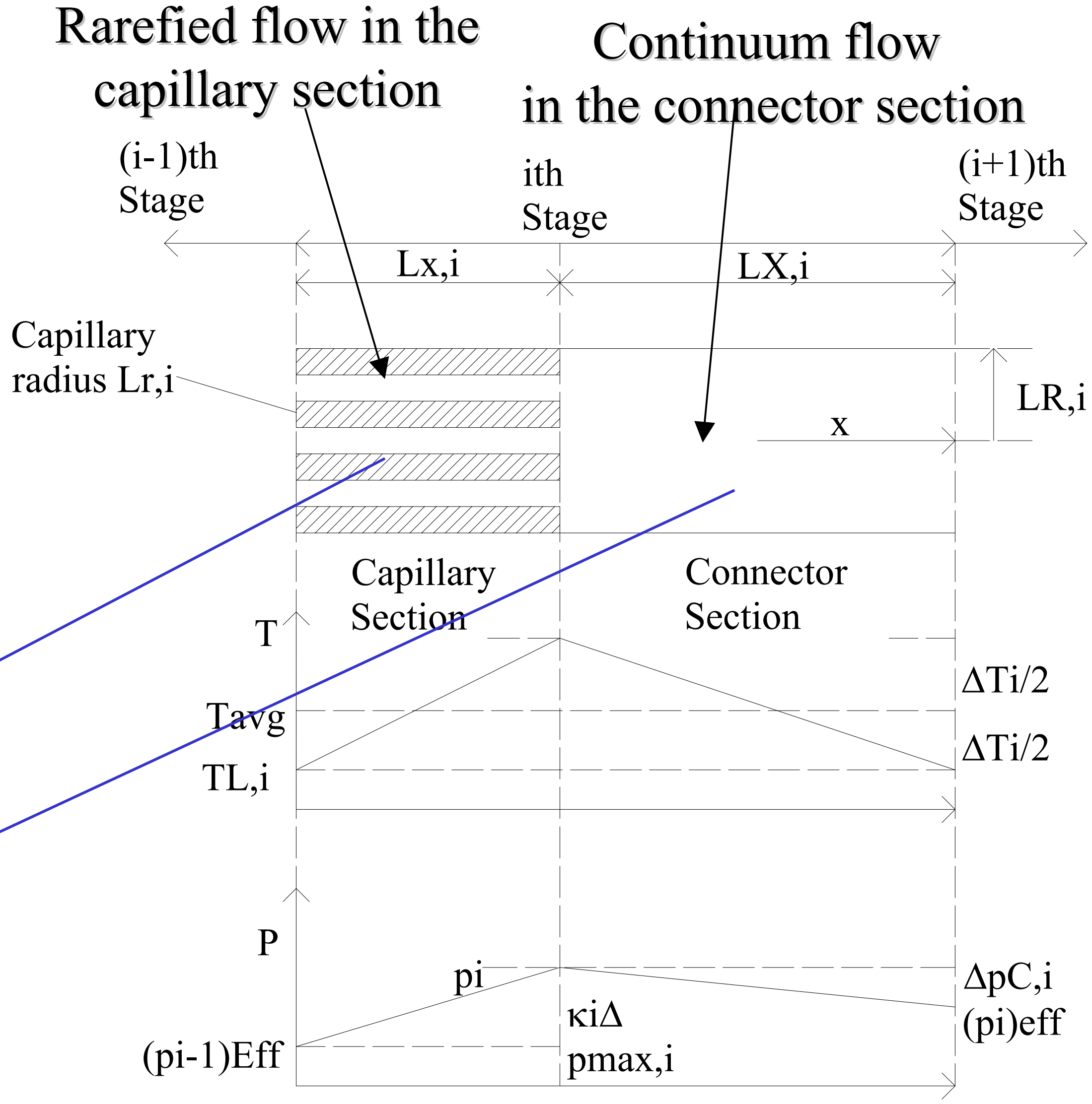
Flow in a Knudsen Compressor is the difference between thermal creep and pressure driven return flows

$$TMPD = \frac{\nabla P / P}{\nabla T / T}$$

$$\mathrm{TMPD}_{\mathrm{FM}} = \tfrac{1}{2}$$

$$\mathrm{TMPD}_{\mathrm{Cont}} = 0$$



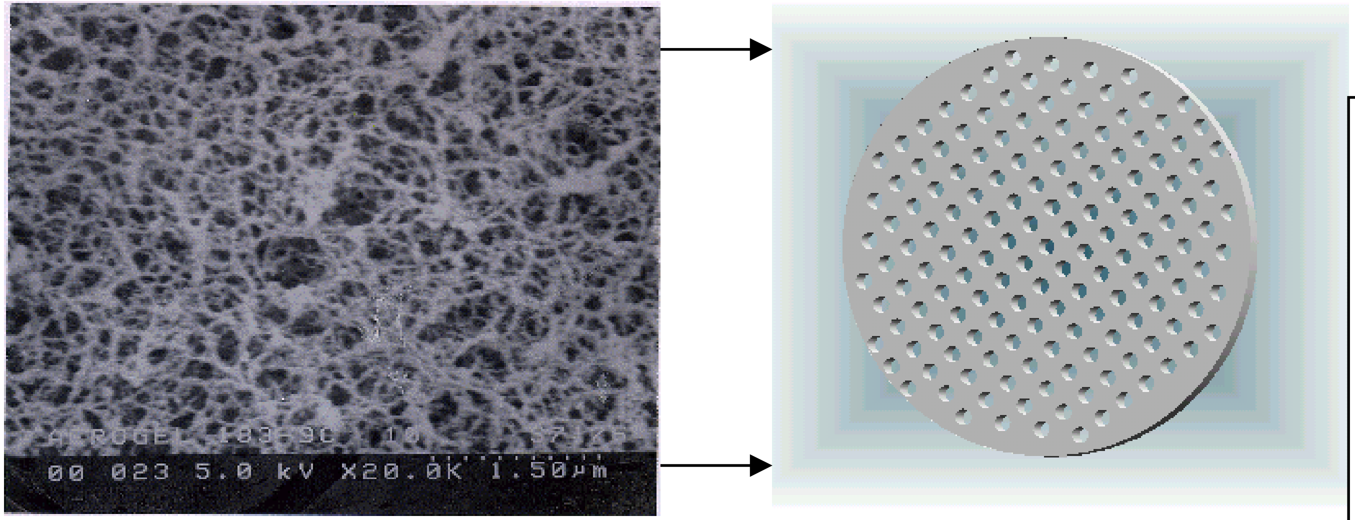


Rarefied flow in the capillary section

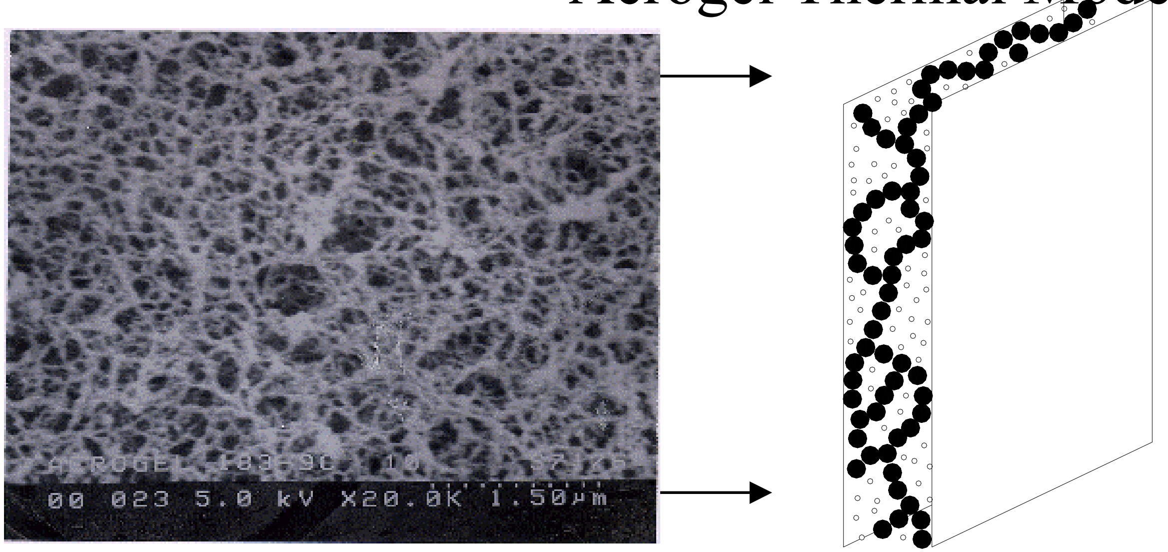
Continuum flow in the connector section

Knudsen Compressor Membrane (Aerogel) Models

- Aerogel Gas Flow and Thermal Transpiration Model



- Aerogel Thermal Model



Important Parameters

$$\frac{\rho_a}{\rho_t} = \frac{\pi}{6}\,\frac{3\,{}^{L_r}\!/_{d_a} + 1}{\left({}^{L_r}\!/_{d_a} + 1\right)^3}$$

$$A_{pores} = \Pi \cdot A$$

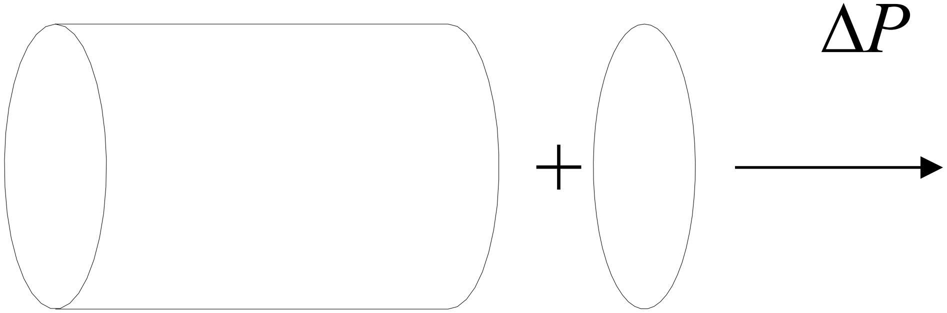
$$\Pi = 1 - \frac{\rho_{por}}{\rho_t}$$

S_s (m^2/g)

Knudsen Compressor Flow Model

- Flow properties are dominated by transpiration membrane properties

Gas Conductance $C = \dot{V}\frac{P_{avg}}{\Delta P}$ (Including short tube effects)



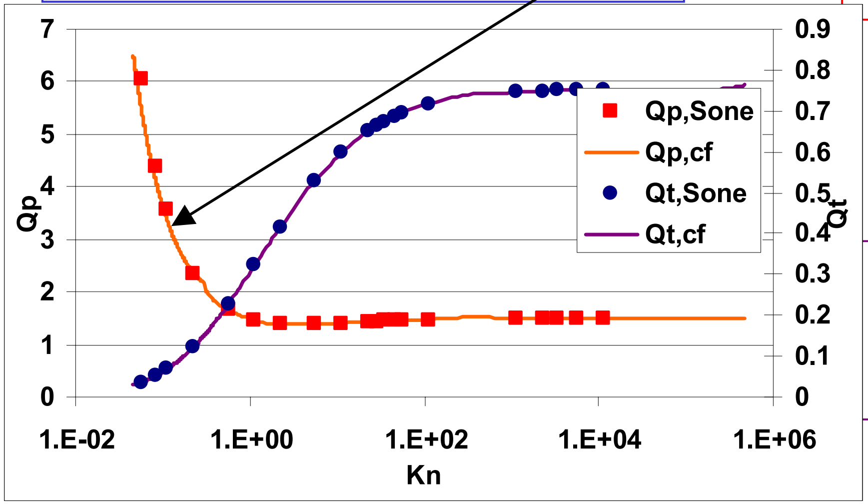
$$C_{ST} = \left\{\frac{1}{C_{LT}} + \frac{1}{C_a}\right\}^{-1}$$

$$C_{LT} = A\sqrt{\frac{k_b T_{avg}}{8m}}\,\frac{2L_r}{L_x}\,Q_p$$

$$C_a = C_{ma} + \left(C_i - C_{ma}\right)\left\{1 - 1.05^{-\frac{1}{2\cdot Kn_r}}\right\}$$

$$C_{ma} = A\sqrt{\frac{k_b T_{avg}}{2\pi m}}$$

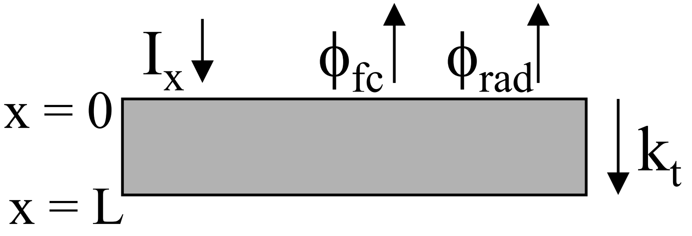
$$C_i = A\sqrt{\frac{k_b T_{avg}}{m}}\,\frac{p_+}{\Delta p}\,X_p^{-\frac{1}{\gamma}}\left[\frac{2\gamma}{\gamma-1}\left(1 - X_p^{\frac{(1-\gamma)}{\gamma}}\right)\right]^{1/2}$$



Knudsen Compressor Membrane Thermal Model

- Radiantly heated transpiration membrane.
- Optical energy is absorbed throughout the body.

$$I_x = I_o e^{-(k_v+\sigma_v)\rho x} = I_o e^{-\lambda x}$$



$$T(x) = \frac{I_o L}{k}\left[x - L + \left(\frac{1}{\lambda L}\right)\left\{e^{-\lambda x} - e^{-\lambda L}\right\}\right] + T_c$$

- Energy is lost through conduction through the material, radiation outward and free convection outward.

$$\phi_{fc} = \frac{k_{amb}}{L} C_{fc} Ra^n \left(T_h - T_{ambient}\right)$$

$$\phi_{rad} = \varepsilon\sigma\left(T_h^4 - T_c^4\right)$$

- Thermal energy conducted through the porous material is the sum of the radiation, solid conduction, and gas conduction.

$$k_t = k_s + k_g + k_r$$

$$k_{s,si} = c_{si}\,\rho_{por}^{\alpha_a}$$

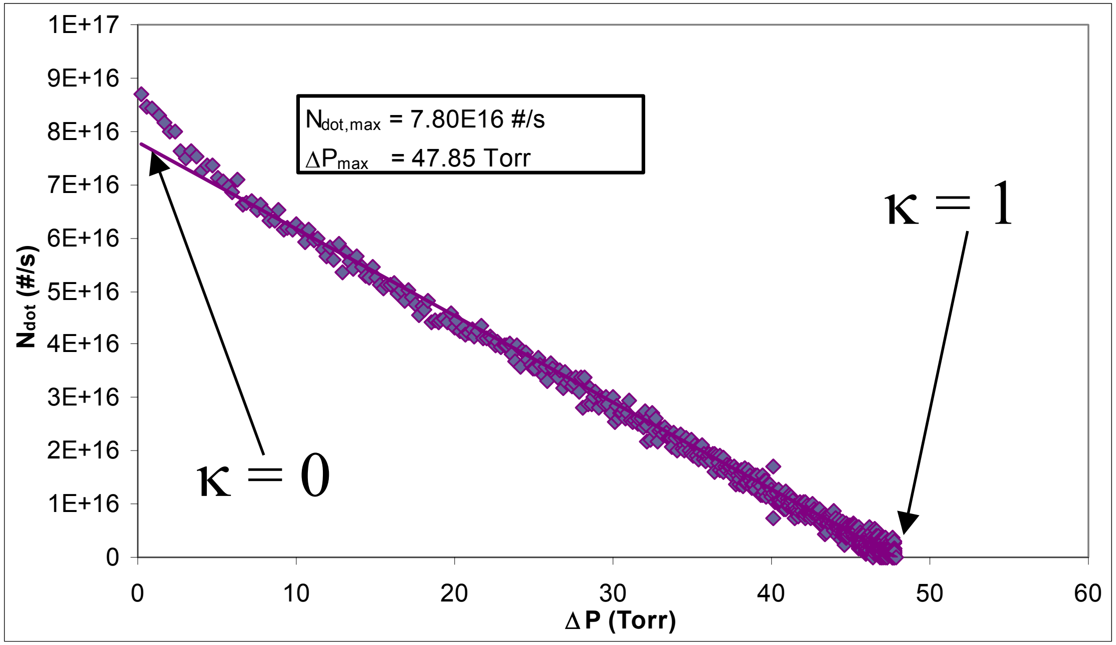
$$k_g = \frac{k_{g,c}}{1 + 4\beta Kn_r}$$

$$k_r = \frac{16\sigma T_{rad}^3}{3\lambda}$$

Knudsen Compressor Membrane Transpiration Model

- Calculate Pressure Difference and Throughput for Membrane

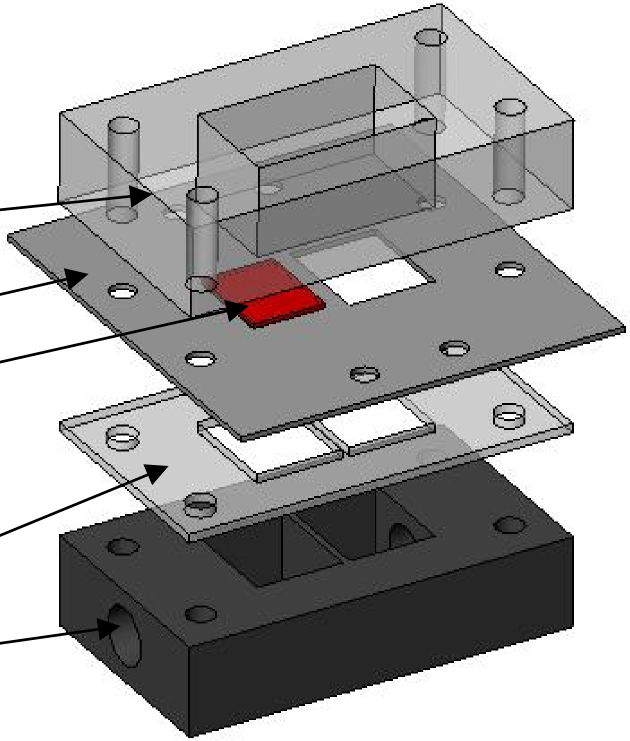
$$\Delta p = p_{avg}\frac{\Delta T}{T_{avg}}\frac{Q_T}{Q_P}\kappa \qquad \dot{M} = \frac{m}{kT_{avg}}C_{tm}\left\{P_{avg}\frac{\Delta T}{T_{avg}}\frac{Q_T}{Q_P}\right\}\left(1-\kappa\right)$$



- Same Analysis Works for the Connector Section, but is Neglected in the Current Work

Single Stage Knudsen Compressor (MEMS)

- Radiant Heating Used to Simplify Manufacturing
- Transpiration Membranes Aligned to Simplify Heating



Pyrex Cover

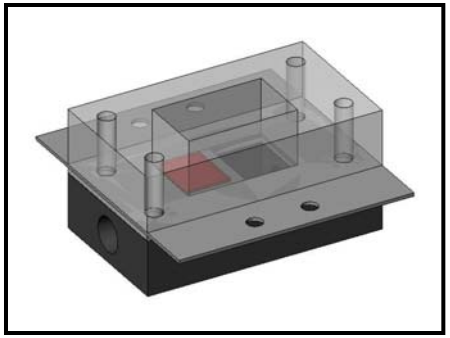
Silicon Thermal Guard

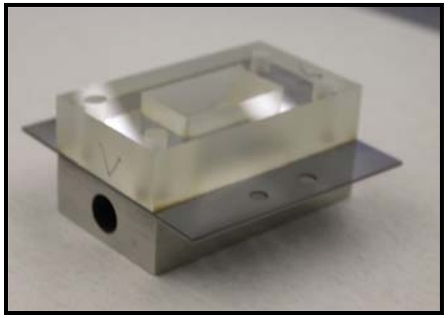
Aerogel (in red)

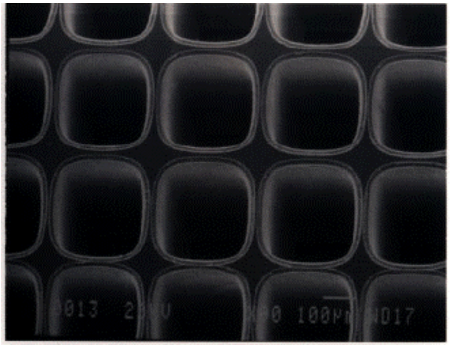
(8mm x 10mm x 1mm)

Pyrex Bonding Window

Kovar Inlet/Outlet





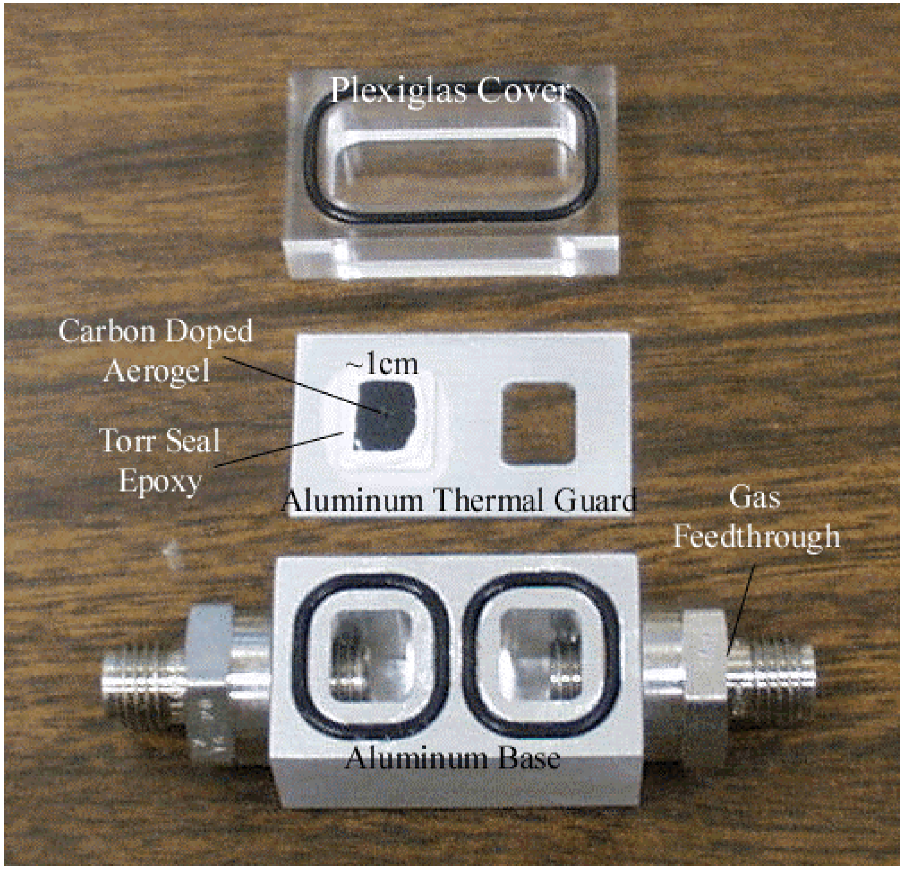


- Parts Anodically Bonded
- Design Optimizations Can Be Tested With Conventionally Machined Version

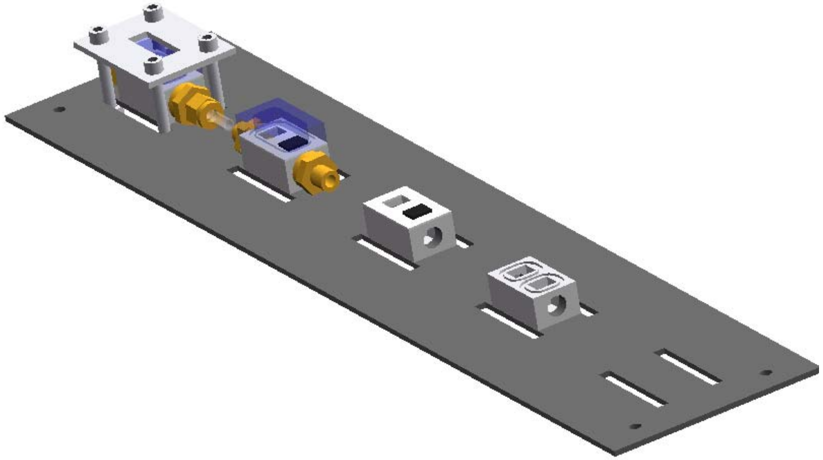
Conventionally Machined Knudsen Compressors

- Much Cheaper to Fabricate Than MEMS Version
- Very Similar Geometry
- O-Ring Seals Allow Multiple Transpiration Membranes to be Tested in Same Device

Single Stage

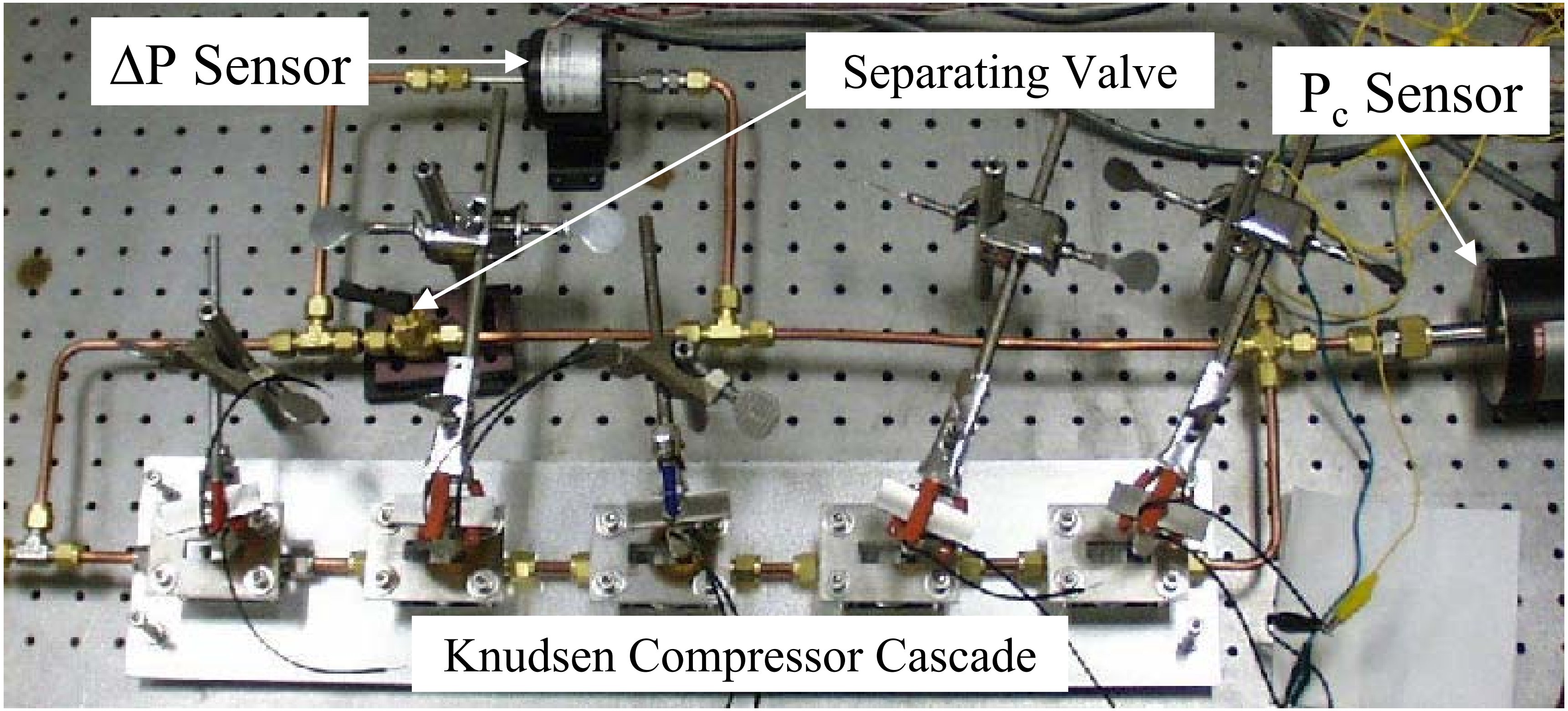


Cascade of 5 Single Stages

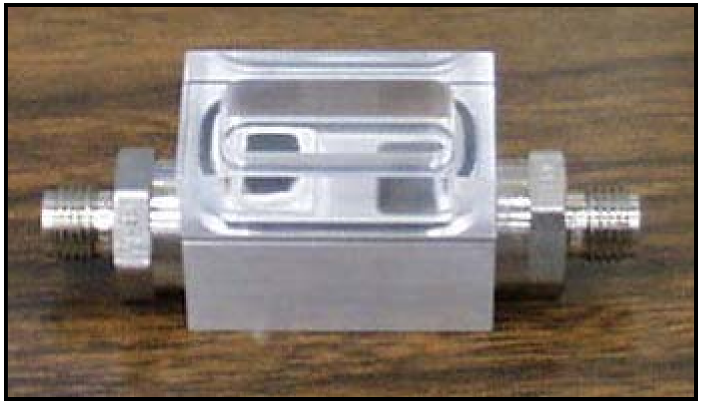


15 Stage Cascade

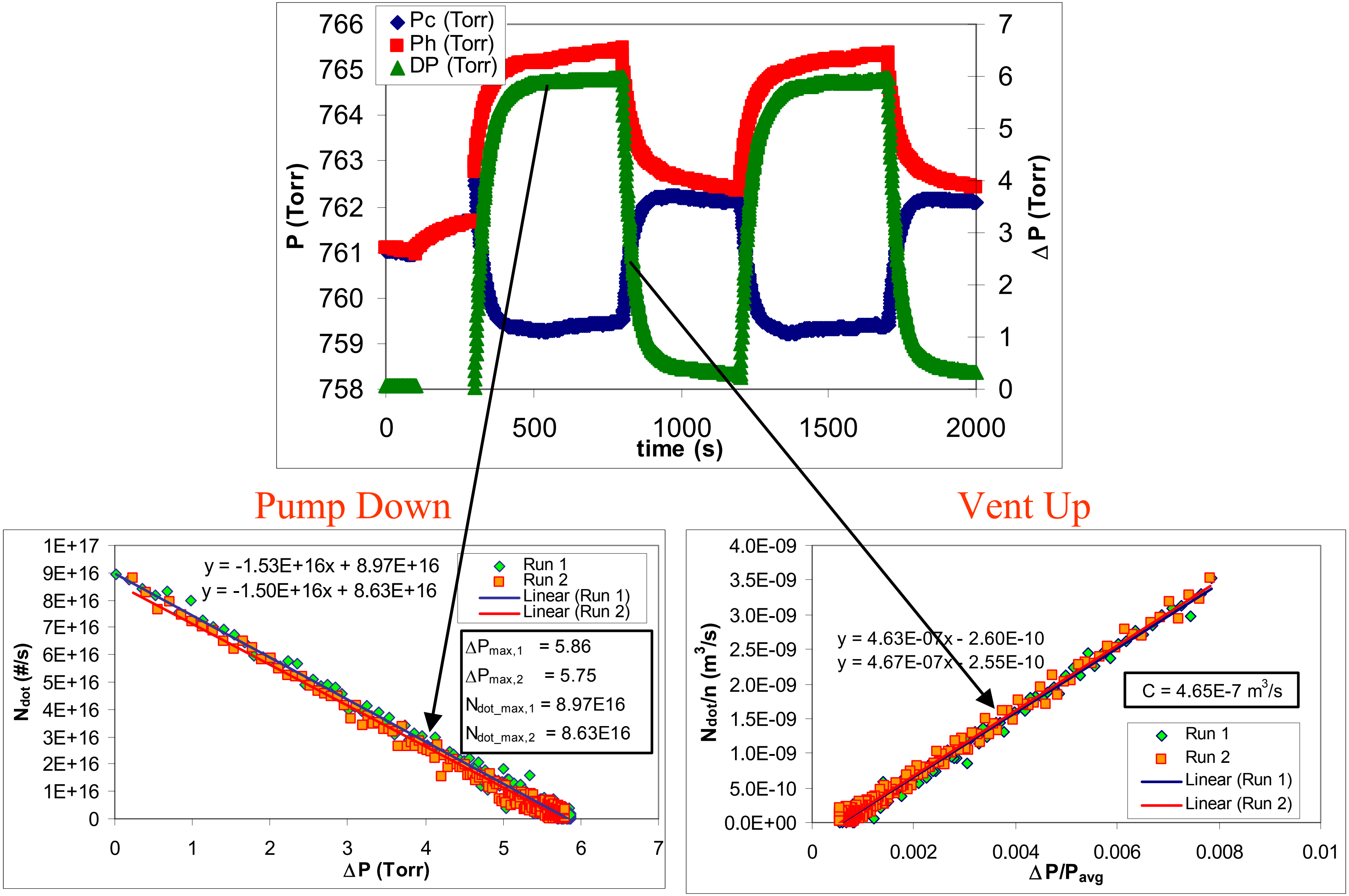
Experimental Cascade Setup



- Pump filled with pure gas
- Light Source turned on
- Separating valve closed
- Pressure rise vs. time measured



Experimental Process and Analysis



Pump Down

Vent Up

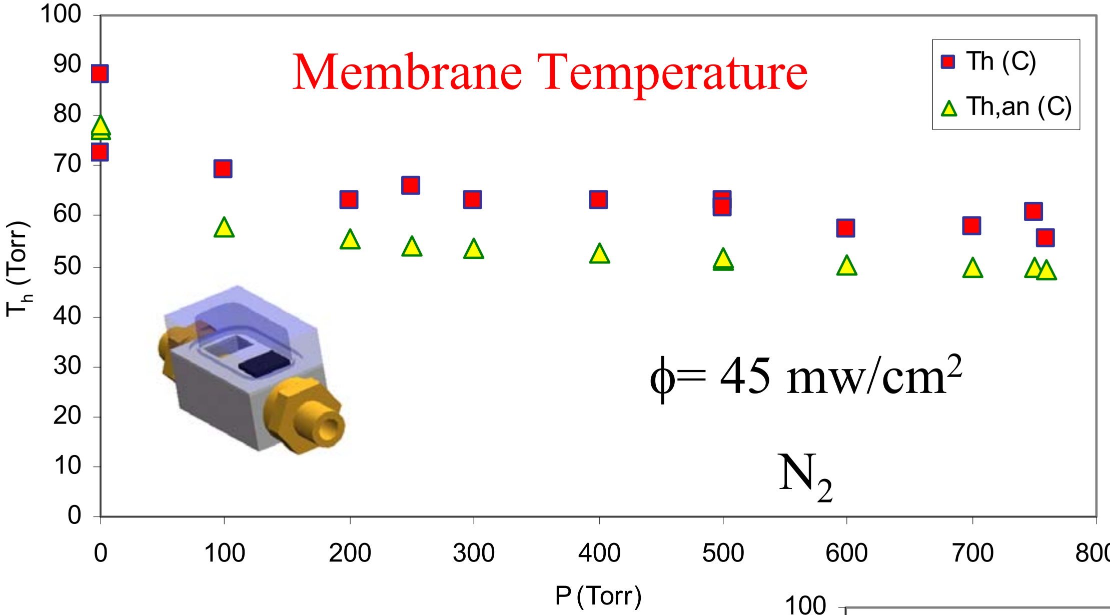
y = -1.53E+16x + 8.97E+16
y = -1.50E+16x + 8.63E+16

$\Delta P_{max,1}$ = 5.86
$\Delta P_{max,2}$ = 5.75
$N_{dot\_max,1}$ = 8.97E16
$N_{dot\_max,2}$ = 8.63E16

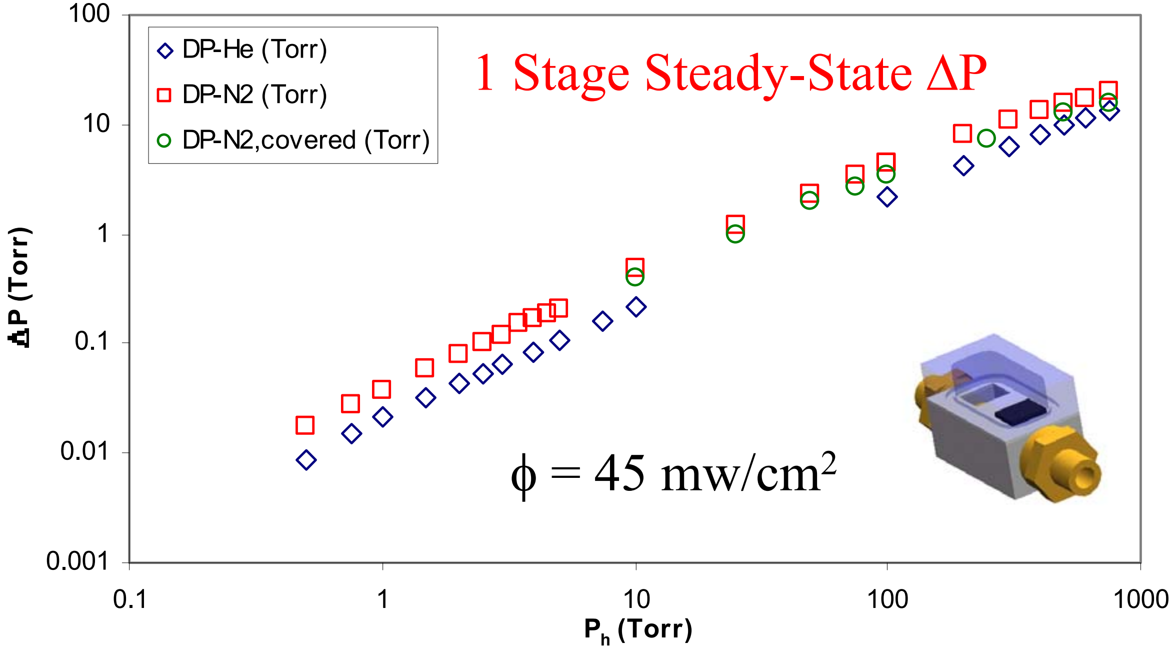
y = 4.63E-07x - 2.60E-10
y = 4.67E-07x - 2.55E-10

C = 4.65E-7 m^3/s

Experimental Results – Single Stage

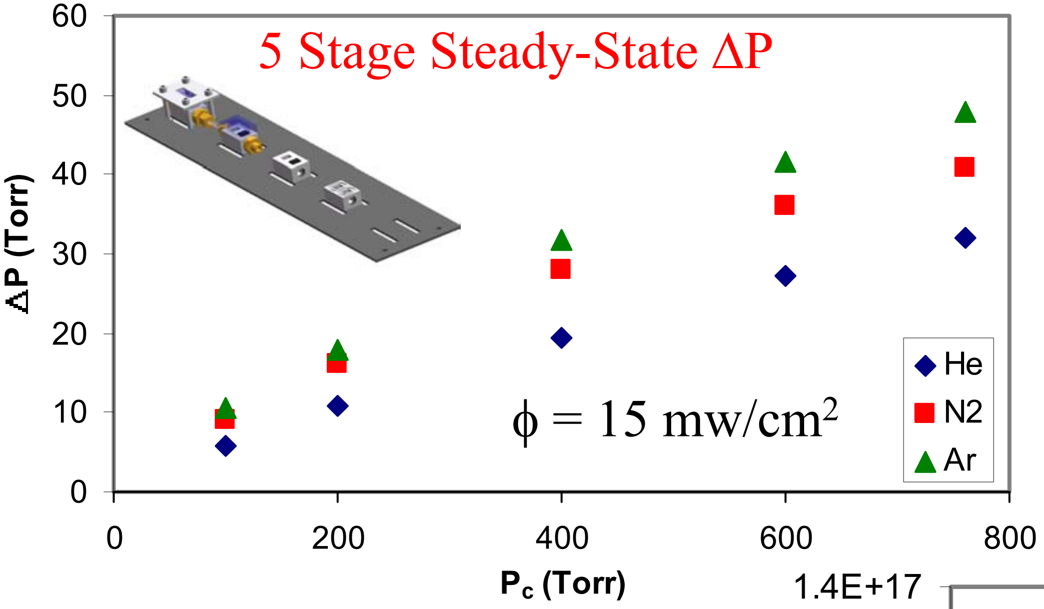


Consistent underprediction of T_h due to overprediction of ϕ_r



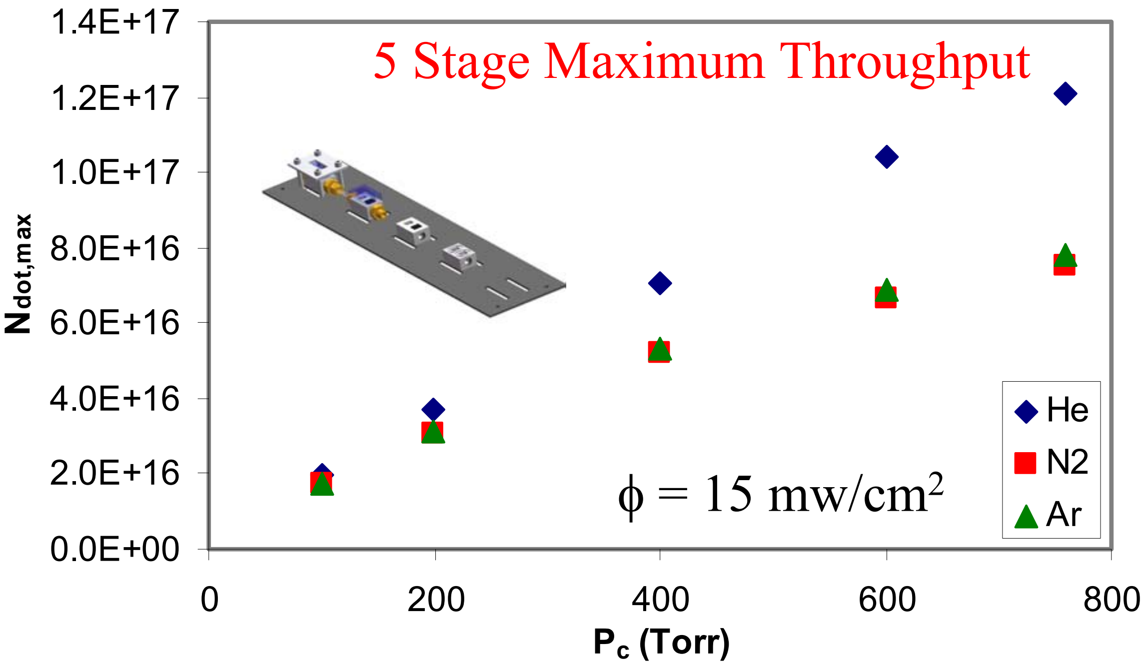
He produces a smaller ΔP due to a smaller ΔT from increased k_g and ϕ_{fc}

Experimental Results – 5 Stage Cascade

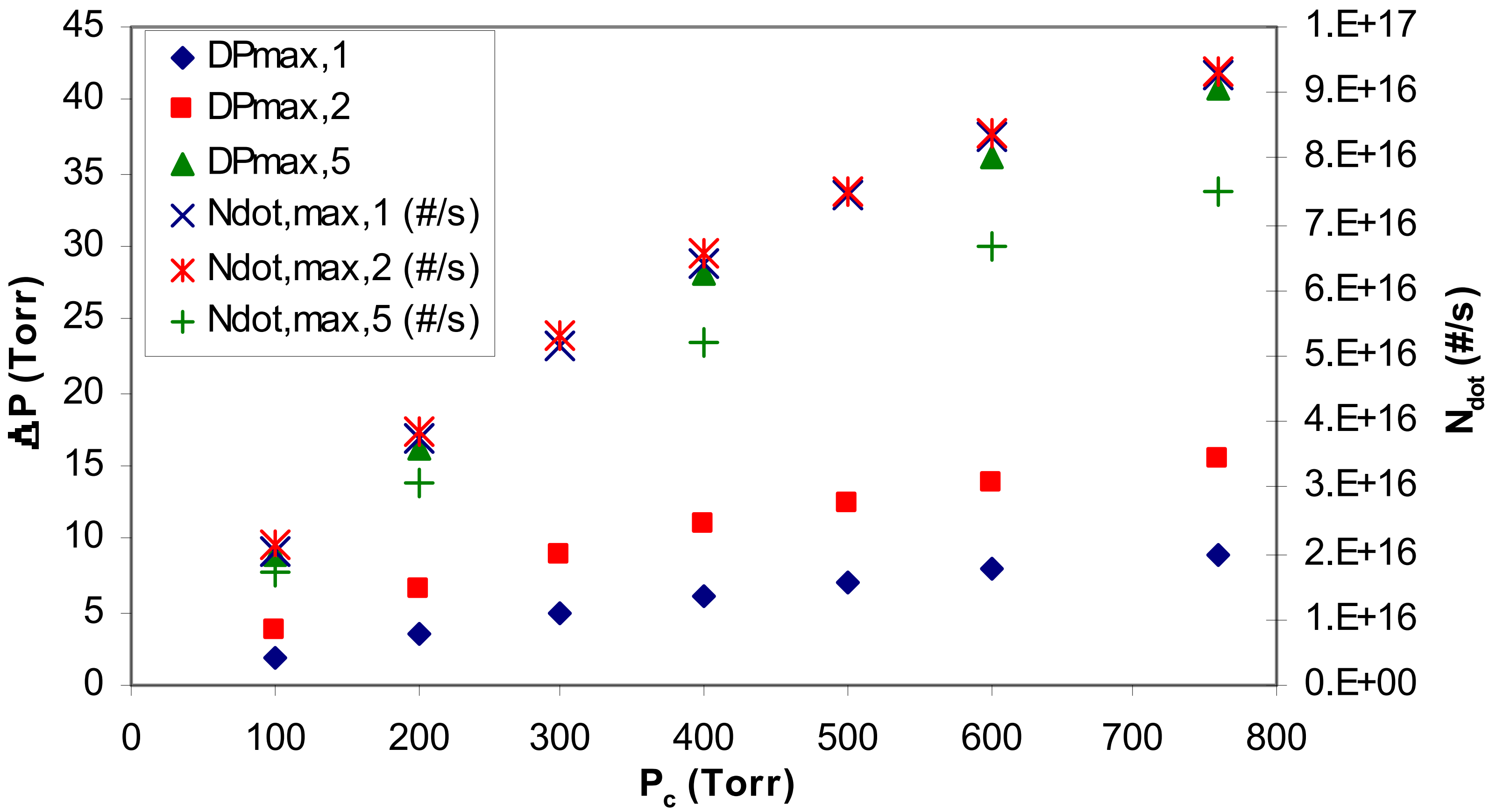


Difference in ΔP due primarily to differences in cooling and ΔT

Difference in throughput also depends on gas conduction → He has the highest throughput, but lowest ΔP



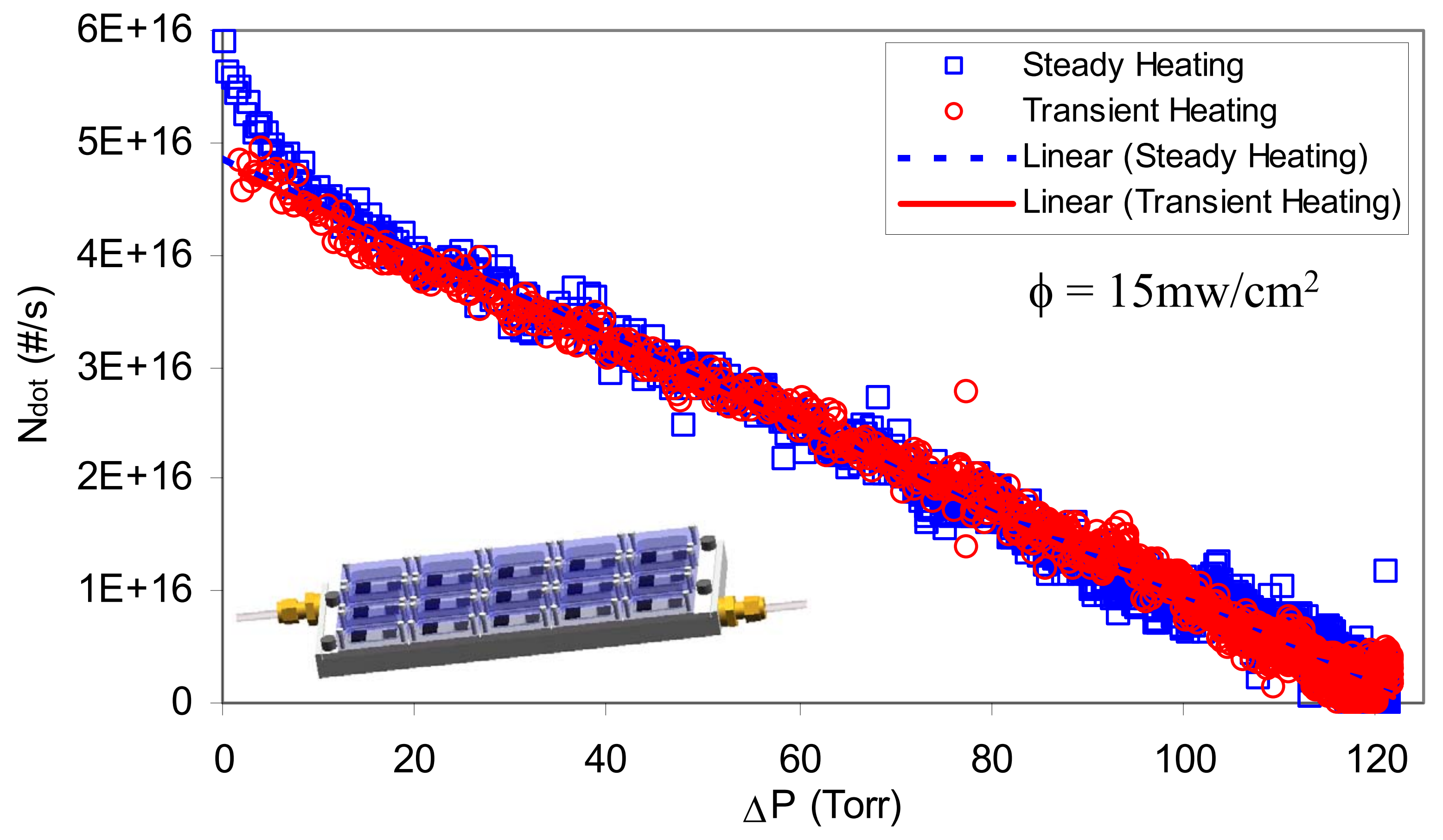
Experimental Results Summary – 1,2,5 Stages



- For these conditions throughput is relatively constant for various numbers of stages (dependence is due to manufacturing differences between the different stages)

- For these conditions the pressure difference scales with the number of stages

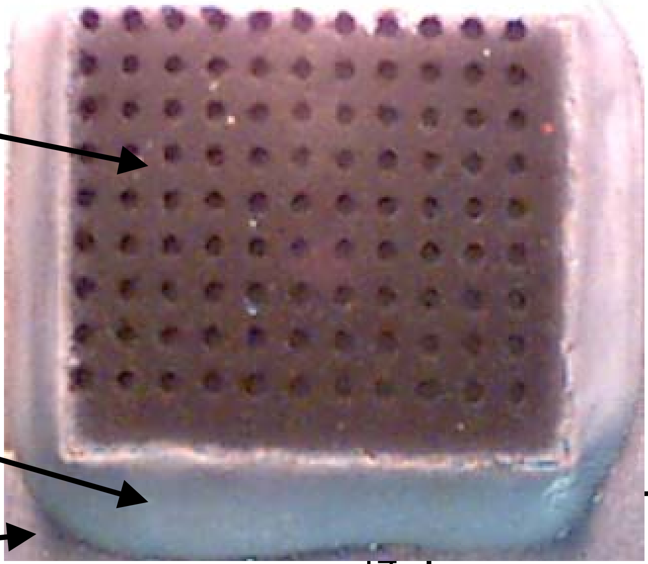
Experimental Results – 15 Stage Cascade



- Approximately the same throughput as for 1,2,5 stages
- ΔP of 8 Torr per stage – same as for 1,2,5 stages

Perforated Aerogel – Low Pressures

- Optimal operation requires Kn ~ 1
- Array (9x11) of 380 µm holes drilled through aerogel transpiration membrane.

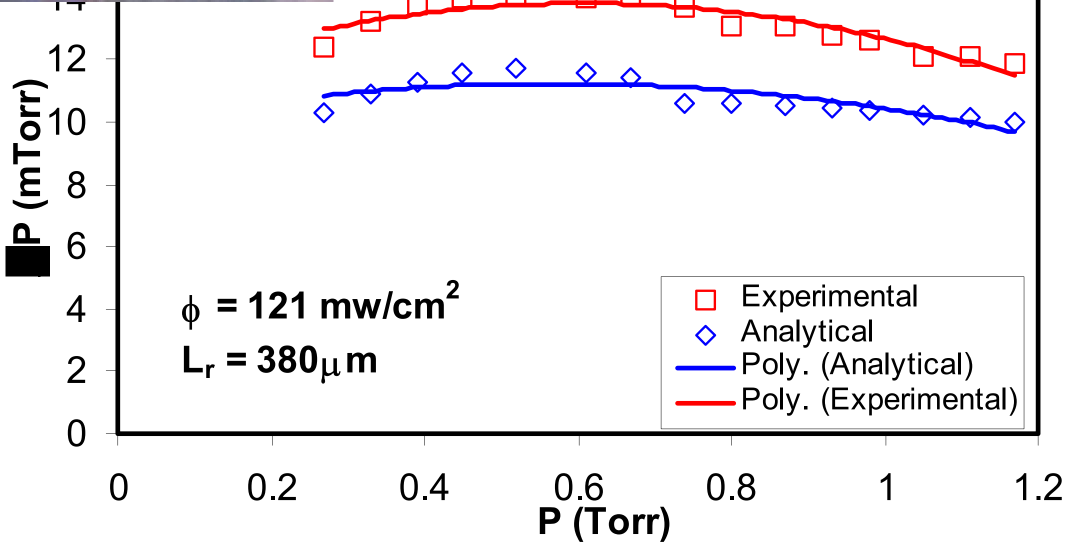


Silica Aerogel Transpiration Membrane (80mg/cc, 8% carbon)

Torr Seal Epoxy

Aluminum Thermal Guard

- Testing Conventionally Drilled Holes to L_r = 250µm.
- Testing Laser Drilled Holes for L_r = 250 µm to 25 µm.

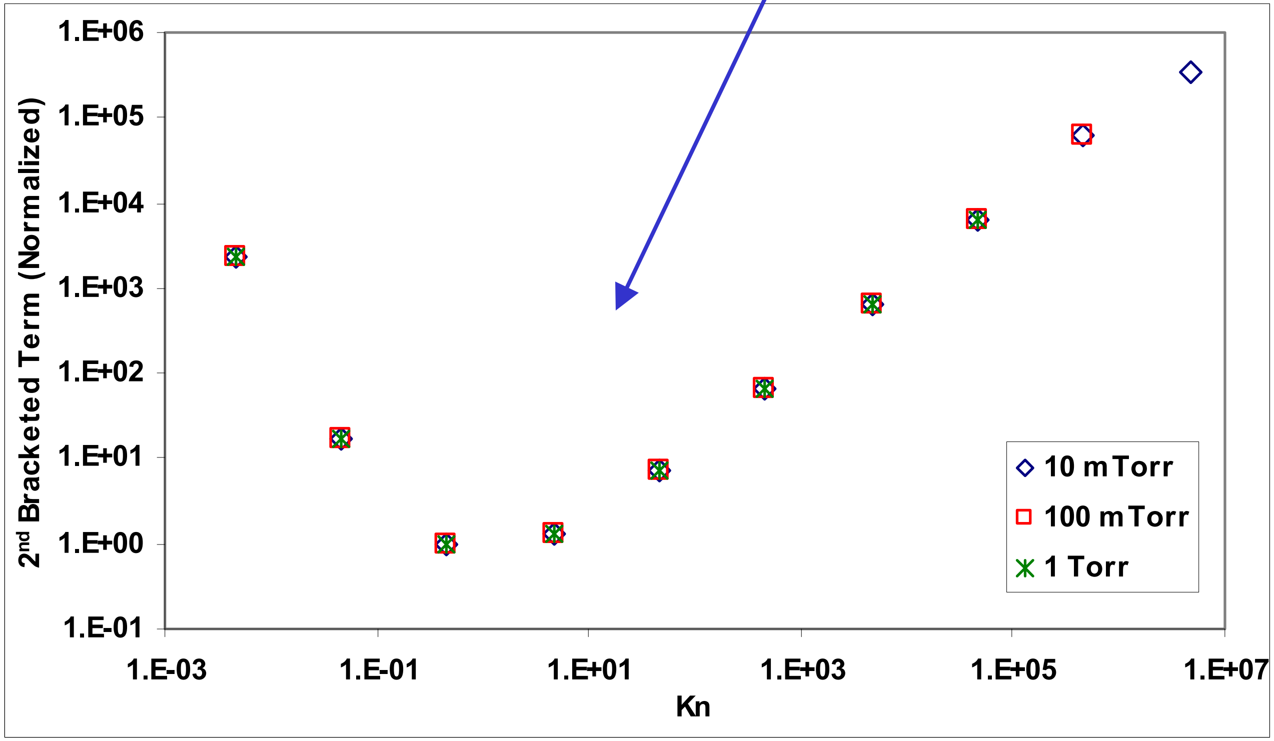


- ΔP_{max} Still Underpredicted by ~ 15-20%.
- Proof of Concept Shown.

Future Optimization – Cascade Operation

- Minimize energy consumption per unit throughput and pressure ratio

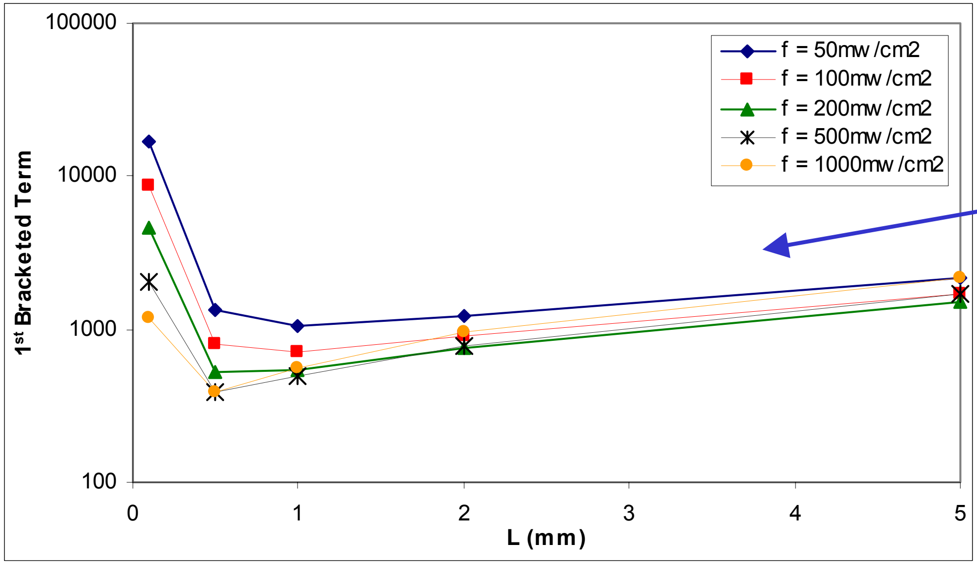
$$\aleph = \frac{\dot{Q}}{\dot{N}\cdot\dfrac{\Delta P}{P_{avg}}} \quad \longrightarrow \quad \aleph = \left\{\frac{\phi L_x}{\dfrac{\Delta T^2}{T_{avg}^{2.5}}}\right\}\cdot\left\{\frac{1}{2L_r}\frac{Q_p}{Q_t^2}\right\}\cdot\left\{\frac{\sqrt{8km}}{P_{avg}}\right\}\cdot\left\{\frac{1}{\left(\kappa-\kappa^2\right)}\right\}$$



Conclusion: Operate with Kn ~ 1 to minimize energy consumption

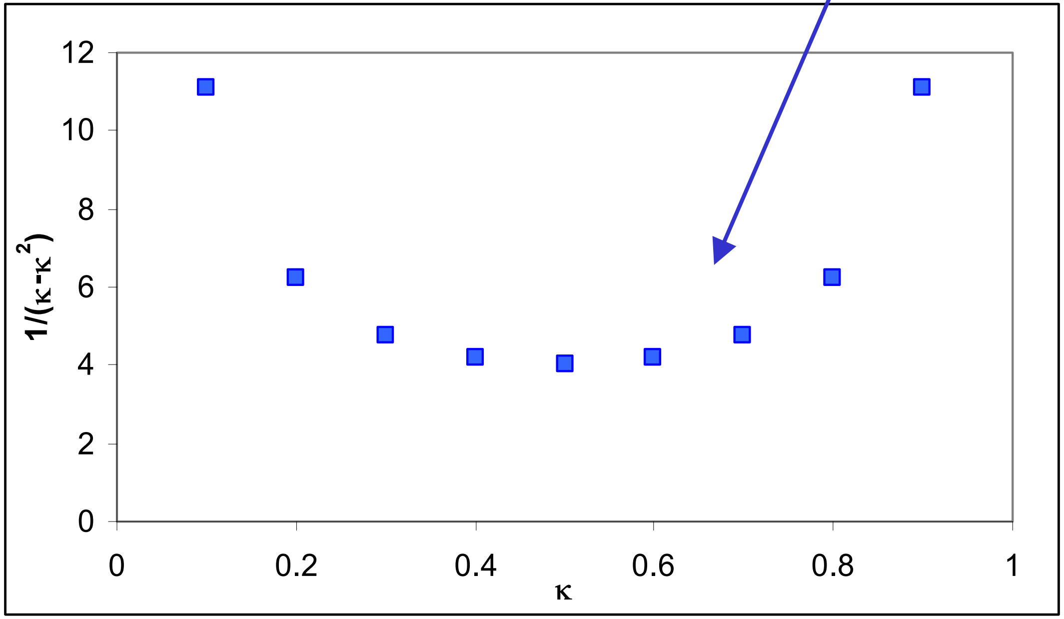
Optimization – Cascade Operation II

$$\aleph = \left\{ \frac{\phi L_x}{\frac{\Delta T^2}{T_{avg}^{2.5}}} \right\} \cdot \left\{ \frac{1}{2L_r} \frac{Q_p}{Q_t^2} \right\} \cdot \left\{ \frac{\sqrt{8km}}{P_{avg}} \right\} \cdot \left\{ \frac{1}{\left(\kappa - \kappa^2\right)} \right\}$$



Conclusion: Operate at $L_x \sim 0.5$mm, $\phi = 1000$ mw/cm^2

Conclusion: Operate with k = 1/2 to minimize energy consumption



System Sizing – Matched to Creare's Turbopump

- Design Meso-Scale Gas Pumping System Operating on Air from 1E-5 Torr to 1 atm.

High Vacuum

Size	$\phi = 5$cm
Power	1 W
Flow Rate	5 l/s @ 1E-5 Torr
Backing Pressure	200 mTorr
Lifetime	1 Year Continuous Operation

Roughing Pump

- Based on Radiantly Driven Knudsen Compressor
- Design Based on Optimization Analysis
- Calculation Made Using Experimentally Validated Knudsen Compressor Performance Model
- $P = 200$mTorr to 1 atm.
- $\dot{N} = 1.7\mathrm{E}15$ mol/sec (5 l/s @ 1E-5 Torr)
- $\phi = 1000$mw/cm^2, $L_x = 0.5$mm, $\rho = 80$mg/cc, 8% carbon doped

Cascade Characteristics

STAGES = 258
POWER = 300 mw
VOLUME = few cm^3

- Stated power does not include conversion and distribution inefficiencies.

Current Status

- Experimentally Demonstrated:
  - Cascades of up to 15 stages.
  - Cascades operating on N_2, He, Ar, Air from P = 250 mTorr to 1 atm.
  - Radiant Driving at $\phi = 15 mw/cm^2$ to $125 mw/cm^2$ (including direct solar illumination).
- Knudsen Compressor Performance Code Validated Over Experimental Conditions.
- Required MEMS meso-scale manufacturing processes shown.

Required Future Work

Proof of Concept Demonstration

- Continue demonstration of perforated aerogel transpiration membranes.
- Demonstrate high flux (1000 mw/cm^2) operation.

Manufacturing Processes

- Stage miniaturization (1cm^2 → < 1mm^2)
- Aerogel bonding process
- Aerogel sealing process
- Packaging and feedthroughs
- Make practical comparisons of different candidate heating techniques

Summary

- Micro/meso-scale Gas Roughing Pumps Based on Thermal Transpiration Can Efficiently Operate to a Pressure of 10 mTorr.
- Knudsen Compressor Performance Model Has Been Built and Experimentally Validated and Used in Optimizing Knudsen Compressor Designs.
- Cascades of Up to 15 Conventionally Machined Stages Have Been Designed, Built, and Tested.
- Experimental Results for the Gas Throughput, Pressure Difference, and Temperature Difference Agree with Model Results to Within 15%.
- Optimized Knudsen Compressor Designs for a Gas Roughing Pump Appear Viable.
- Initial Experimental Results with Etched Aerogel Transpiration Membrane Agree with Expectations.