THE KNUDSEN COMPRESSOR AS AN ENERGY EFFICIENT MICRO-SCALE VACUUM PUMP

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Overview

- Knudsen Compressor Description
- Advantages of Thermal Transpiration Pumps
- Thermal Transpiration Pump History at USC
- Transitional Flow Formulation and Results
- Sample Stage Sizing and Performance
- Special Considerations at the Low Pressure Limit
- Summary
Thermal Effusion and Creep

Rarefied gas phenomena (free-molecular flow driven by gas-surface interactions)

<table>
<thead>
<tr>
<th>Thermal Effusion Through Orifice</th>
<th>Thermal Creep along surfaces</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1 &lt; T_2$</td>
<td>Net effect is a flow from cold to hot side of tube</td>
</tr>
</tbody>
</table>

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

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

• One of the driving mechanisms in Crooke’s radiometer
Knudsen Compressor Stage Operation

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

Rarefied flow in the capillary section

Continuum flow in the connector section

Knudsen Compressor Stage Operation

\[ \text{TMPD} = \frac{\nabla P}{P} \frac{\nabla T}{T} \]

\( \text{FM equations} \)

\[ N_T^F = \left\{ \frac{\sqrt{\pi}}{12} n_v v_o d^3 \right\} \frac{\nabla T}{T} \]

\[ N_p^F = \left\{ -\frac{\sqrt{\pi}}{6} n_v v_o d^3 \right\} \frac{\nabla p}{p} \]

\[ \text{TMPD}_{\text{FM}} = \_ \]

\[ \text{TMPD}_{\text{Cont}} = 0 \]
Why Thermal Transpiration Pumps?

• No moving parts.
• No oil or working fluids.
• Recent availability of small pore membrane materials with very low thermal conductivities.
• Can operate on waste heat from other equipment.
• MEMS fabrication allows for batch fabrication of the many required stages.
• Can operate over a wide range of pressures.
  ∘ Roughing pump from 10 mTorr – 1 atm
  ∘ High pressure gas source from 1 atm to 10 atm
Time-Line for Thermal Transpiration Pumps

- Reynolds -- first explained thermal transpiration
- Knudsen -- experimentally achieved pressure ratio of 10 with first multiple stage pump based on thermal transpiration.
- Pham-Van-Diep – Analysis of MEMS based pump
- Vargo – Demonstrated MEMS based vacuum pump stages
- MEMS Knudsen Pump – Optimize and Construct Multistage MEMS vacuum pump suitable for application

<table>
<thead>
<tr>
<th>Reynolds</th>
<th>Knudsen</th>
<th>Pham-Van-Diep</th>
<th>Vargo</th>
<th>MEMS based Pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>1879</td>
<td>1910</td>
<td>1994</td>
<td>2000</td>
<td>Now</td>
</tr>
</tbody>
</table>
Transitional Flow Formulation

Transitional Flow Equations:

\[ \Delta p = p_{AVG} \frac{\Delta T}{T_{AVG}} \frac{Q_T}{Q_P} \cdot \kappa \]

\[ \text{Kn}_B = \left[ \frac{p_{AVG} F A}{(2(k/m) T_{AVG})^{1/2}} \left( \frac{\Delta T}{T_{AVG}} \right) Q_T (1 - \kappa) \left( \frac{L_r}{L_X} \right) \right] \]

![Graph](image)
Power Consumption Optimization Results

\[ \Delta T = \text{constant} \]
\[ \Delta P = 10, \ L_r = 500 \mu m \]
\[ \alpha_1 = \text{constant} \]

\[ \alpha_1 = \left( \frac{\Delta T \mid_B}{T_{AVG}} \right) \left( \frac{Q_{T,B}}{Q_{P,B}} \right) \]

Kn low: capillary section is not very efficient
Kn high: constant number of stages \( \rightarrow \) energy consumption per unit number flux increases
\( \frac{L_r}{L_t} \) low: little difference between the capillary and connector sections
\( \frac{L_r}{L_t} \) high: constant number of stages \( \rightarrow \) energy consumption per unit number flux constant

Kn low: inefficiency counteracted by increasing \( \Delta T \rightarrow \) no large increase in the number of stages
Kn high: same as \( \Delta T = \text{constant} \)
\( \frac{L_r}{L_t} \) low: same as \( \Delta T = \text{constant} \)
\( \frac{L_r}{L_t} \) high: same as \( \Delta T = \text{constant} \)
Volume Optimization Results

$\Delta T = \text{constant}$

$\alpha_1 = \text{constant}$

Kn low: capillary section is not very efficient

Kn high: constant number of stages $\rightarrow$ volume per unit number flux increases linearly

$L_R/L_t$ low: little difference between the capillary and connector sections

$L_R/L_t$ high: length of the connector is increasing linearly with $(L_R/L_t)_1 \rightarrow$ increase linearly

Kn low: inefficiency counteracted by increasing the temperature difference $\rightarrow$ no large increase in the number of stages

Kn high: same as $\Delta T = \text{constant}$

$L_R/L_t$ low: same as $\Delta T = \text{constant}$

$L_R/L_t$ high: length of the connector is increasing linearly with $(L_R/L_t)_1 \rightarrow$ increase linearly
Previous Experimental Design

- Silicon Aerogel as Transpiration Membrane (0.6mm thick)
- Silicon wafer with DRIE holes and thin film gold heater used to apply temperature gradient
- Pyrex connector sections

- Proof of concept for multiple stages
- Thermally efficient sealing identified as a major problem
- Transitional flow analysis validated
- Operation shown from atmospheric pressure down to several hundred Torr for several different working gases.

Vargo, 2000
Previous Results: Efficiently Sealing Membrane
Previous Results: Validation of transitional flow model

- Model adequate for performance estimation using aerogel
- 10x better flowrate than predicted using nominal pore size and membrane thickness

vs.

\[
\frac{\Delta p}{(\Delta p)_L} = 1.2 \\
\frac{\Delta p}{(\Delta p)_L} = 1 \\
\frac{\Delta p}{(\Delta p)_L} = 0.8 \\
\frac{\Delta p}{(\Delta p)_L} = 0.6 \\
\frac{\Delta p}{(\Delta p)_L} = 0.4 \\
\frac{\Delta p}{(\Delta p)_L} = 0.2 \\
\frac{\Delta p}{(\Delta p)_L} = 0 \\
\]

\( \mu \text{Kn} = 2 \) 

\( V_H = 59.3 \text{ cc}, V_C = 41.2 \text{ cc} \)
Low Pressure Cascade Sizing Using $L_r = 10$nm

$\Delta T = 100K$

$L_r = 10$nm

(2% carbon doped aerogel)

$L_x = .55$ mm

$L_R = 5$mm

$L_X = 20$mm

<table>
<thead>
<tr>
<th>Number of Stages</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Ratio</td>
<td>10 (10-100 mTorr)</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>6E13 (#/s) or 0.186 ml/s</td>
</tr>
<tr>
<td>Volume</td>
<td>33 cm$^3$</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>1.5 W</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>2.5E-14 W/(#/s)</td>
</tr>
<tr>
<td>Volumetric Efficiency</td>
<td>5.5E-19 m$^3$/(#/s)</td>
</tr>
</tbody>
</table>

![Graph showing pressure and stage relationship]

![Graph showing flow rate and $L_r$ relationship]
**Considerations to Optimize Design for Low Pressure Applications**

**Optimize Capillary Pore Diameter**

- $Kn \sim 1$ is optimum in capillary pores, using aerogel pores $\rightarrow Kn = 4.6E5$
- By boring holes in the aerogel transpiration membrane the pore diameter can be optimally sized

**Impose required temperature gradient**

- At low connector $Kn$ the gas is not uniformly hot at the hot side of the pores due to direct reflections from connector walls
- Add thermal adjustment material
**Performance Using Optimized Pore Diameters**

**Modifications:**

1.) Bore Optimized Holes in Aerogel Substrate

2.) Add Thermal Adjustment Material

<table>
<thead>
<tr>
<th>Cascade</th>
<th>$L_r$ (m)</th>
<th>$L_x$ (m)</th>
<th>$L_R$ (m)</th>
<th>$L_X$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-100 mTorr</td>
<td>2.5E-04</td>
<td>5.0E-04</td>
<td>5.0E-03</td>
<td>2.0E-02</td>
</tr>
<tr>
<td>100 mTorr - 1Torr</td>
<td>2.5E-05</td>
<td>5.0E-04</td>
<td>2.8E-03</td>
<td>2.0E-02</td>
</tr>
<tr>
<td>1Torr-10Torr</td>
<td>2.5E-06</td>
<td>5.0E-04</td>
<td>2.7E-03</td>
<td>2.0E-02</td>
</tr>
<tr>
<td>10Torr-760 Torr</td>
<td>1.0E-08</td>
<td>5.0E-04</td>
<td>1.3E-03</td>
<td>5.0E-03</td>
</tr>
</tbody>
</table>
Low Pressure Performance Comparison

**Performance Increases Due to New Design**

<table>
<thead>
<tr>
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<th>24</th>
<th>Number of Stages</th>
<th>33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Ratio</td>
<td>10 (10-100 mTorr)</td>
<td></td>
<td>Pressure Ratio</td>
<td>10 (10-100 mTorr)</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>6E13 (#/s)</td>
<td></td>
<td>Flow Rate</td>
<td>3E16 (#/s)</td>
</tr>
<tr>
<td>Volume</td>
<td>33 cm³</td>
<td></td>
<td>Volume</td>
<td>45 cm³</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>1.5 W</td>
<td></td>
<td>Power Consumption</td>
<td>1.1 W</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>2.5E-14 W/(#/s)</td>
<td></td>
<td>Energy Efficiency</td>
<td>7.5E-17 W/(#/s)</td>
</tr>
<tr>
<td>Volumetric Efficiency</td>
<td>5.5E-19 m³/(#/s)</td>
<td></td>
<td>Volumetric Efficiency</td>
<td>1.5E-21 m³/(#/s)</td>
</tr>
</tbody>
</table>

- increased pore diameter $\Rightarrow$ increased conductance
- increased conductance $\Rightarrow$ increased mass flow
- decreased $\lambda$, $Kn$ $\Rightarrow$ decreased TMPD
- decreased pressure ratio $\Rightarrow$ increased number of stages
- Net Results: more stages and volume, less power and volume/ upflow
## Performance of New Design

<table>
<thead>
<tr>
<th>Cascade</th>
<th>Volume (cm³)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-100 mTorr</td>
<td>45.1</td>
<td>1.07</td>
</tr>
<tr>
<td>100mTorr-1Torr</td>
<td>13.0</td>
<td>0.297</td>
</tr>
<tr>
<td>1Torr-10Torr</td>
<td>11.8</td>
<td>0.268</td>
</tr>
<tr>
<td>10Torr-760Torr</td>
<td>5.26</td>
<td>0.92</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>75.2</strong></td>
<td><strong>2.56</strong></td>
</tr>
</tbody>
</table>

### Graph

- **Power Efficiency**: 8.5E-17 W/(#/s)
- **Volumetric Efficiency**: 2.5E-21 m³/(#/s)

### Diagram

- **Stage**: 1 to 121
- **Pressure (Pa)**: 1 to 100000
- **33 stages, 28 stages, 28 stages, 38 stages**
Status of Experimental Work

• One stage device constructed and testing is ready to begin

Device Setup

Si Thermal Guard Holes

10 mg/cc Si aerogel
Conclusions

• Optimum operation (based on thermal and volumetric efficiency) occurs at Capillary Kn ~ 1.

• Pore sizes must be optimized for low pressure application.

• Thermal adjustment material must be added at low pressures

• 10 mTorr identified as the lowest practical pressure attainable with a MEMS Knudsen Compressor.

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