Latent Heat Fluxes Through Nano-engineered Porous Materials

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Research Objectives

1. Big Picture: self cooling protective garments

2. Study heat and mass transport enabled by membranes with micro-scale pores

3. Demonstrate multi-functionality of nano-enabled components

4. Create engineering correlations to inform design of future systems
Inspirational System – The Camel

Evaporation At Skin Surface

Evaporation At Fur Surface

Adapted from original in Schmidt-Nielsen (1979)
Armor: Steady Temperature Profile

Temperature, °C

No Evap
Evap at Armor Surface
Evap at Skin Surface

Benefit of Integrated Thermal Management

\[ Q_{\text{met}} \]
\[ R_{\text{armor}} \]
\[ R_{\text{conv}} \]
\[ m \cdot H_{\text{vap}} \]
\[ Q_{\text{conv}} \]
\[ Q_{\text{sun}} \]
Identifying Micro-truss Simulant

2-D Micro-truss Fabricated via Interference Lithography at MIT

Nucrel Porous Membrane Fabricated by DuPont
Study of Pore Size

Hytrel® is a polyester elastomer, formed by condensation of polybutylene terephthalate (PBT) and terathane (polyether). The PBT blocks form the hard segment and the polyether blocks form the soft segment.

Nominally 13μm hydraulic diameter pores

Nucrel® is a random copolymer of ethylene and methacrylic acid. The membranes used contain 12% methacrylic acid by weight.

Nominally 1μm hydraulic diameter pores

Kapur, DuPont, 2005
Nucrel Membrane – Straight Through Pores Normal to the Membrane Face

Sample was prepared by microtome slicing, and was imaged under SEM.
## Porous Membrane Characterization

### Properties Important to Heat and Mass Transfer

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Nucrel A</td>
<td>112 ± 3</td>
<td>7.6 ± 2.5</td>
<td>0.8 ± 0.3</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>Nucrel B</td>
<td>119 ± 4</td>
<td>7.5 ± 3.3</td>
<td>1.6 ± 0.5</td>
<td>1.4 ± 0.2</td>
</tr>
<tr>
<td>Hytrel A</td>
<td>113 ± 3</td>
<td>11.2 ± 3.1</td>
<td>161 ± 36</td>
<td>14.2 ± 1.6</td>
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<tr>
<td>Hytrel B</td>
<td>123 ± 3</td>
<td>8.6 ± 2.7</td>
<td>126 ± 31</td>
<td>12.6 ± 1.5</td>
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<tr>
<td>Latex</td>
<td>141 ± 3</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
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</tbody>
</table>
Evaporation Chamber Schematic

- **N₂ gas**
  - V = 2.8 m/s
  - RH ≈ 0%

- **Ambient Temp**, $T_{amb}$
- **Upstream Temp**, $T_2$
- **Downstream Temp**, $T_3$
- **Heat Flux**, $Q_{in}$
- **Interface Temp**, $T_1$
  - (analog to soldier skin)

- **Air Head Space**
- **Copper Chamber**
- **Water**
- **Heating Element**

- **Insulation**
Evaporation Chamber

Dimensions:
- 121 mm diameter
- 33 mm diameter
Mass Transfer Resistances

- Liquid Water
- Head Space
- Circulation Cells
- Turbulent Boundary Layer
- Viscous Sub-layer
Mass Transfer Resistances

\[ m = \frac{A_{\text{membrane}} \left( \rho_{\text{downstream}} - \rho_{\text{upstream}} \right)}{R_{BL,\text{upstream}} + R_{\text{membrane}} + R_{BL,\text{downstream}}} \]
Micro-porous Membranes Facilitate Significant Cooling

Open Chamber

Closed Chamber

Hytrel Membrane $d_e=13.5\mu m$

Nucrel Membrane $d_e=1.2\mu m$

$35.2 \pm 1.3^\circ C$

$13.4 \pm 2.4^\circ C$

$14.0 \pm 2.0^\circ C$

Micro-porous Membranes Facilitate Significant Cooling


Membrane volume flux rates are consistent with human sweat rates: 2.1 L/(m²-hr) vs. 0.5 – 1.5 L/(m²-hr)

Cumulative Mass Lost [grams]

Time [minutes]

Intrinsic (Apparatus-independent) Diffusion Coefficients

Disaggregated boundary layer impacts on mass transfer to isolate effective membrane diffusion coefficient for comparison to theory

\[
\bar{m}_{\text{ave}} = \int_{r_o}^{r=0} \frac{2\pi \cdot r}{R_{BL,\text{downstream}} + R_{\text{membrane}}} \left\{ \int_{r_o}^{r=0} \frac{1}{\delta(r)v(r)} \left[ \frac{\rho_{\text{chamber}} - \rho(r)}{R_{BL,\text{upstream}}} - \frac{\rho(r)}{R_{\text{membrane}} + R_{BL,\text{downstream}}} \right] dr - \rho_{\text{ambient}} \right\} dr
\]

<table>
<thead>
<tr>
<th>Run Name</th>
<th>Continuum Theory $D_{H2O,\text{air}}$</th>
<th>Rarified Theory $D_{H2O,\text{air}}$</th>
<th>Apparatus-ind. Experimental $D_{H2O,\text{air}}$</th>
<th>% Difference Rarified vs. Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucrel, Sample A</td>
<td>2.37E-05 [m$^2$/s]</td>
<td>2.12E-05 [m$^2$/s]</td>
<td>1.95E-05 [m$^2$/s]</td>
<td>-9</td>
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<tr>
<td>Nucrel, Sample B</td>
<td>2.36E-05 [m$^2$/s]</td>
<td>2.18E-05 [m$^2$/s]</td>
<td>2.68E-05 [m$^2$/s]</td>
<td>19</td>
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<tr>
<td>Hytrel, Sample A</td>
<td>2.35E-05 [m$^2$/s]</td>
<td>2.33E-05 [m$^2$/s]</td>
<td>1.68E-05 [m$^2$/s]</td>
<td>-38</td>
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<tr>
<td>Hytrel, Sample B</td>
<td>2.39E-05 [m$^2$/s]</td>
<td>2.36E-05 [m$^2$/s]</td>
<td>1.68E-05 [m$^2$/s]</td>
<td>-40</td>
</tr>
</tbody>
</table>
Does Nanometer Length Scale Matter?

Rarified flow reduces diffusion mass flux by 10% between 13.5 μm and 1.2 μm diameter pores; undetectable using current apparatus.

\[ Kn = \frac{\lambda}{d} \]

Nucrel, \( d_e = 1.2 \mu m \)

Hytrel, \( d_e = 13.5 \mu m \)

Mills Model
Conclusions

1. Measured water vapor mass flux rates through porous membranes are consistent with human perspiration rates.

2. Surface cooling ~ 40% theoretical maximum was achieved despite low membrane porosity.

3. Despite a 10-fold difference in pore size, no impact on cooling or mass transport rate was detected – this result is consistent with rarified diffusion theory.

4. Integrated components can be designed to achieve multi-functionality (evaporative cooling, mechanical energy absorption, light-weight).
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Backup Slides Follow

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References

- Kapur, V., DuPont, personal e-mail communication (10/4/2005).