THERMAL CONDUCTIVITY OF AEROGEL BLANKET INSULATION UNDER CRYOGENIC-VACUUM CONDITIONS IN DIFFERENT GAS ENVIRONMENTS

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HIGHLIGHTS

• Heat flow in complex, low-density composites

• Uniform thermal performance data for aerogel composite blanket and fiber matrix material

• Effective thermal conductivity ($k_e$) testing:
  • Boundary temperatures of 293 K & 78 K
  • Environments of five different gases

• Apparent thermal conductivity ($\lambda$) testing at ambient conditions in air

• Applications in cryogenic storage, transfer, and handling
AEROGEL COMPOSITE BLANKET & FIBER MATRIX

Silica aerogel with fiber matrix reinforcement (Cryogel® by Aspen Aerogels)

Single fiber: 15 µm dia. (equivalent to ~800 pores of aerogel)
### PROPERTIES OF DIFFERENT GASES

<table>
<thead>
<tr>
<th>Gas</th>
<th>Normal Boiling Point</th>
<th>Density @ STP</th>
<th>Thermal Conductivity (mW/m-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>g/L = kg/m³</td>
<td>100 K</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>77.4</td>
<td>1.25</td>
<td>9.8</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>111.7</td>
<td>0.716</td>
<td>-</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>4.2</td>
<td>0.179</td>
<td>75.5</td>
</tr>
<tr>
<td>Hydrogen (H₂)</td>
<td>20.3</td>
<td>0.090</td>
<td>68.6</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>90.2</td>
<td>1.419</td>
<td>9.3</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>87.3</td>
<td>1.78</td>
<td>6.2</td>
</tr>
<tr>
<td>Krypton (Kr)</td>
<td>119.9</td>
<td>3.749</td>
<td>3.3</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>194.8 (sublimates)</td>
<td>1.96</td>
<td>-</td>
</tr>
<tr>
<td>Xenon (Xe)</td>
<td>165.0</td>
<td>5.76</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*Thermal conductivity of solid CO₂:

- 419 mW/m-K at 210 K
- 500 mW/m-K @ 186 K
- 622 mW/m-K @ 150 K
- 1,168 mW/m-K @ 80 K

Note:  \( T_{\text{mean}} \) for 293 K & 78 K boundary temps is 186 K
CRYOSTAT-100

Cylindrical boiloff calorimeter
(absolute heat flow)

ASTM C1774, Annex A1

- Boundary temps: 293 K & 78 K
- Effective thermal conductivity ($k_e$)
- 1-m tall by 167-mm dia. cold mass
- Guard chambers top & bottom
CRYOSTAT-100 TEST SPECIMEN

For seven test series, A194 – A200
SUMMARY OF CRYOSTAT-100 TEST RESULTS FOR CRYOGEL IN DIFFERENT GAS ENVIRONMENTS

- Variation of $k_e$ with CVP
  - Boundary temperatures: 293 K / 78 K
  - Residual gas: as indicated

- CO2 Testing:
  - N>H = no-vacuum to high-vacuum direction of testing
  - H>N = high-vacuum to no-vacuum direction

- He versus N₂ @ 760 torr:
  - +124% (2.2x) for Cryogel
  - +538% (6.4x) for gas only

Legend (x, n, p) or (20, 2, 130): 20 mm thickness, 2 layers, 130 kg/m³ density
CRYOSTAT-100 RESULTS FOR CRYOGEL IN DIFFERENT GASES: VACUUM TRANSITION REGION FROM 1 TO 100 MILLITORR

- Variation of $k_e$ with CVP
  - Boundary temperatures: 293 K / 78 K
  - Residual gas: as indicated

- $CO_2$ testing:
  - $N>H = \text{no-vacuum to high-vacuum direction of testing}$
  - $H>N = \text{high-vacuum to no-vacuum direction}$

- Observations:
  - $Ar$, $He$, and $CO_2$ are below $N_2$ baseline at moderate vacuum
  - $He$ exceeds baseline at 50 millitorr

Legend (x, n, p) or (20, 2, 130): 20 mm thickness, 2 layers, 130 kg/m$^3$ density
SUMMARY OF CRYOSTAT-500 TEST RESULTS FOR FIBER MATRIX MATERIAL IN COMPARISON WITH CRYOGEL

- Flat plate boiloff calorimeter (absolute)
  - ASTM C1774, Annex A3
  - Test specimens: 204-mm diameter by 18-mm thickness (two layers)

- Variation of $k_e$ with CVP
  - Boundary temperatures: 293 K / 78 K
  - Residual gas: as indicated

- Fiber Matrix compared to Cryogel:
  - 82% higher at 760 torr
  - 29% lower at HV

Legend (x, n, p) or (20, 2, 130): 20 mm thickness, 2 layers, 130 kg/m² density
SUMMARY OF CRYOSTAT TEST RESULTS FOR CRYOGEL AEROGEL BLANKET AND FIBER MATRIX MATERIAL

<table>
<thead>
<tr>
<th>Cryostat Test Specimen*</th>
<th>$k_e$ (mW/m-K) for select CVP (torr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&lt;10^{-4}$</td>
</tr>
<tr>
<td>A112 Cryogel in Nitrogen 2007</td>
<td>1.49</td>
</tr>
<tr>
<td>A194 Cryogel in Nitrogen</td>
<td>1.51</td>
</tr>
<tr>
<td>A196 Cryogel in Argon</td>
<td>1.06</td>
</tr>
<tr>
<td>A197 Cryogel in CO$_2$ (N : H)</td>
<td>---</td>
</tr>
<tr>
<td>A199 Cryogel in CO$_2$ (H : N)</td>
<td>1.31</td>
</tr>
<tr>
<td>A198 Cryogel in Helium</td>
<td>1.23</td>
</tr>
<tr>
<td>A200 Cryogel in Krypton</td>
<td>1.37</td>
</tr>
<tr>
<td>G1-187 Fiber Matrix in Nitrogen</td>
<td>1.13</td>
</tr>
<tr>
<td>G1-188 Fiber Matrix in Helium</td>
<td>1.55</td>
</tr>
</tbody>
</table>

*Boundary temperatures 293 K / 78 K; residual gas as indicated; Cryostat-100 or Cryostat-500 boiloff calorimeter apparatus.

†Liquefaction of argon or solidification of carbon dioxide causes dramatic increase in heat transmission through material.
TEST RESULTS

- Cryogel with nitrogen gas baseline: $k_e$ results
  - 1.5 mW/m-K at high vacuum (near ideal performance of bulk-fill perlite powder)
  - 12.3 mW/m-K at ambient pressure (about that of polyurethane foams)

- Comparison of $k_e$ between Cryogel and fiber matrix shows the dramatic effect of the heat transmission from continuum range to convective:
  - At 760 torr CVP, the fiber matrix is 82% higher than the Cryogel
  - At high vacuum, the fiber matrix is 29% lower (as gas conduction and convection are not factors)

- Gases argon and CO$_2$ are below N$_2$ baseline up to 100 millitorr CVP
  - Helium line trends above N$_2$ line starting at ~50 millitorr

- Ambient testing for apparent thermal conductivity ($\lambda$) in air using a Lasercomp Model 304 Heat Flow Meter at $T_{mean} = 297$ K:
  - Cryogel (density of 164 kg/m$^3$): $\lambda = 19.1$ mW/m-K
  - Fiber Matrix (density of 51 kg/m$^3$): $\lambda = 30.6$ mW/m-K

- While the fiber matrix itself is an effective thermal insulation material, it is 60% to 82% higher thermal conductivity compared to Cryogel (and without the hydrophobic or mechanical properties)
TEST OBSERVATIONS

• Defining and careful execution of the gas-filling approach was critical to the thermal conductivity results obtained:
  • Warm filling or cold filling processes (cold filling reported here)

• Helium observations at 760 torr CVP:
  • Compared to Cryogel in nitrogen, $k_e$ increases by only 124% (2.2x) while the corresponding increase for the gases only would be 538% (6.4x)

• Argon observations show that liquefaction dramatically increases above 200 torr CVP

• CO$_2$ results above about 1 torr CVP show that aerogel blanket material can make a powerful adsorber of solid CO$_2$ within the nanoporous structures:
  • See curve A197 proceeding from the No-Vacuum case
CRYOSTAT-100 TEST RESULTS FOR CRYOGEL IN DIFFERENT GAS ENVIRONMENTS: VARIATION OF INTERLAYER TEMPERATURE T6 WITH CVP

- Interlayer temperature (T6) between layers
- Boundary temperatures: 293 K / 78 K
- Residual gas: as indicated
- Curve A197 attests to the chaotic transitional heat transfer occurring at 50 millitorr
  - transition from free molecular to continuum gas conduction

Legend (x, n, p) means 20 mm thickness, two layers, 130 kg/m³ density.

- Solidification of CO₂
- Liquefaction of Argon
- 50 mtorr

7/12/2017
CRYOTESTLAB @ NASA-KSC
DISCUSSION

• Soft vacuum region (from about 0.1 torr to 10 torr):
  • Complex and difficult to model because all modes of heat transfer – solid conduction, radiation, gas conduction, and convection – are involved
  • Complex composite of nano-porous aerogel within a micro-fibrous matrix

• Thermal conductivity of solid CO₂:
  • 500 mW/m-K at T_{mean} = 186 K
  • Mass fraction of CO₂ and aerogel composite can be estimated

• Mars and Earth environments are comparable, in the heat transmission sense….compared to the vastly different high vacuum environment of the Moon (or space in general)
APPLICATIONS

• Self-pumping (cryo-pumping) vacuum-jacketed (VJ) systems, a valuable technique in many situations for decades:
  • Welded field joint enclosures for VJ cryogenic piping systems
  • Common bulkhead panels for cryogenic tanks on space launch vehicles
  • Vacuum Insulated Panels (VIP) for cold containers
  • Argon filling gas for LH$_2$ systems; CO$_2$ for LO$_2$ systems

• Liquid hydrogen cryofuel systems with helium purged conduits or enclosures

• Mars exploration and surface systems in the CO$_2$ environment:
  • In conjunction with lightweight, jacketed-type constructions
EXAMPLE MARS APPLICATION

Boiloff time on Earth = 2 days
Boiloff time on Mars = 0.5 days
*Boiloff time on Moon = 1,400 days

*With standard 40 layers of foil/paper multilayer insulation (MLI)

KEY POINTS:
✓ Soft vacuum pressure (5 torr) is roughly six orders of magnitude greater than the high vacuum level required for MLI systems
✓ Mars environment similar to Earth's in regard to heat leak into cryogenic systems
✓ Crucial part in estimating the central electrical power requirement for future missions – the cryogenic refrigeration plant
✓ Obvious challenge here is that massive steel vacuum-jacketed equipment is not an option.

Notional 3800-liter liquid oxygen (LO2) tank with a 100-mm thickness of aerogel blanket for insulation
CONCLUSION

Thermal conductivity of aerogel blanket insulation under cryogenic-vacuum conditions in different gas environments

• Uniform thermal performance data for aerogel composite blanket and fiber matrix material

• Effective thermal conductivity ($k_e$) testing:
  • Boundary temperatures of 293 K & 78 K
  • Environments of five different gases (Ar, He, N$_2$, CO$_2$, Kr)

• Complex multi-mode heat transmission in complex, low-density composites is analyzed based on experimental data

• With N$_2$ gas as baseline, $k_e$ of Cryogel ranges from 1.5 mW/m-K at high vacuum (approaching ideal bulk-fill perlite powder) to 12.3 mW/m-K at ambient pressure (about half that of polyurethane foams)

• Applications of include Mars storage systems, self-evacuating (cryo-pumped) systems, vehicle panel structures, and LH$_2$/cryofuel systems

• Thermal performance data provide underpinnings for future physical modeling of complex aerogel composite materials such as the Cryogel and others
THANK YOU

for your attention

Questions?