Two-Phase Thermal Switch for Spacecraft Passive Thermal Management

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• Thermal management systems with high turndown capabilities are required for future human spacecraft
• Thermal switches are capable of dissipating a wide range of heat loads in widely varying thermal environments with low SWAP
• Lower mass and higher On/Off conductance ratios are desired

• Available Thermal Switch Technologies:
  – Mechanical Thermal Switches
    • Paraffin actuated heat switch, CTE-CTSW, SMA-CTSW
  – Gas-gap Thermal Switch
    • Disadvantages: Complex, expensive, slow response, difficult to manufacture
  – Diode Heat Pipe
    • Disadvantages: High “Off” conductance, 0g concerns, slow response

• Less complex, lower cost alternatives are desired
Two-phase thermal switch concept

- Two-phase thermal switch consists of a metallic bellows encapsulated in a hermetic enclosure
- Uses condensing vapor to both transfer heat and provide pressure for expansion and contact
- Lower complexity, mass, and cost with improved performance

- Works like a vapor chamber or heat pipe with flexible walls
- Vapor pressure is driving force for bellows expansion and contact
- Thermal switch “set point” is the lowest temperature for which the vapor pressure brings the heat transfer surface in contact with the heat sink
Two-phase thermal switch operation

- One end of bellows is fixed to enclosure, which is in contact with heat source
- Other end of bellows is free
- Capillary wick structure connecting two ends inside bellows
- Heat applied causes working fluid in bellows to vaporize
- Vapor generated causes bellows to expand until contact with heat sink
- When in contact with sink, vapor condenses and is returned to heat source through capillary action in wick
- As some heat is transferred, vapor temperature/pressure in bellows drops – bellows disconnects from sink
- Continued heat application raises temperature and causes bellows to expand again
- Some heat is transferred, bellows disconnects…
In normal two-phase thermal switch operation, bellows oscillates in and out of contact with heat sink.

In this way, the vapor temperature inside bellows, and thus the heat source temperature, are approximately held at a “set-point”.

This set-point is determined by vapor pressure required to expand bellows enough to come in contact with sink.

Set point temperature can be manipulated by changing pressure of the gas in the enclosure acting against the bellows.

For high enough powers, the bellows will not disconnect from the sink, and essentially acts as a heat pipe.
First order performance model

• Static thermo-structural model for predicting thermal switch set point based on force balance

\[
\Delta y_o = \frac{A_c}{k} \left( P_g - P_v(T_o) \right)
\]

\[
\Delta y_{\text{ext}} = \Delta y_o - \Delta y_T = \Delta y_o - \frac{A_c}{k} \left( P_g - P_v(T) \right)
\]

• Static model does not capture full dynamic operation of thermal switch

• Provides basis for full dynamic mode to be developed in the future
First prototype design

- First prototype designed as a thermosyphon (no wick) for proof-of-concept demonstration
- Beryllium copper bellows ($k = 19 \text{ lb/in}$)
- Stainless steel enclosure
- Copper end caps housing heat source and heat sink
First prototype experimental results

- Testing of first prototype demonstrated ability to maintain heat source set point temperature as heat sink temperature decreases
- Determined heat source set point for several enclosure gas counter pressures, demonstrating ability to manipulate set point by varying the enclosure gas pressure
- Tests also showed that heat leaks through the enclosure are important
Second prototype design

- Same beryllium copper bellows
- Delrin enclosure to minimize heat leaks
- Copper end caps with incorporated heat source and heat sink
- Copper wick structure in bellows for liquid return
Second prototype design

- Since the two-phase thermal switch is essentially an expandable heat pipe, heat pipe limit calculations were performed
- Capillary limit and predicted maximum power calculated
- Additional performance limits calculated at operating power of 100 W
- Predicts two-phase thermal switch to be operating well below all limits

Capillary limit

Maximum power
Second prototype experimental results

- Initial tests done heat pipe (against gravity) orientation to demonstrate wicking and orientation independence
- Tests done at multiple counter pressures to determine set point temperature
- Some decay in set point temperature (~3°C) as sink temperature drops due to heat leaks through enclosure

7 psia counter pressure

10 psia counter pressure
Second prototype experimental results

- Additional tests performed in thermosyphon orientation (gravity assisted liquid return)
- Set points similar in both orientations — orientation independent operation
Second prototype experimental results

- Thermal conductance testing of second prototype
  - Maximum power applied to determine maximum “On” conductance
  - Power reduced until bellows breaks contact to determine heat leaks – “Off” conductance
  - Heat leaks to ambient characterized
  - On/Off conductance ratios then calculated
  - Evident that “On” conductance and conductance ratio varies with sink temperature due to variable conductance aspect

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum Conductance (W/K)</th>
<th>Minimum Conductance (W/K)</th>
<th>Conductance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.7 psia, 0° Sink</td>
<td>0.70</td>
<td>0.04</td>
<td>16.1</td>
</tr>
<tr>
<td>14.7 psia, -40° Sink</td>
<td>0.56</td>
<td>0.04</td>
<td>14.8</td>
</tr>
<tr>
<td>5 psia, 0° Sink</td>
<td>0.69</td>
<td>0.04</td>
<td>17.2</td>
</tr>
<tr>
<td>5 psia, -40° Sink</td>
<td>0.64</td>
<td>0.03</td>
<td>20.1</td>
</tr>
<tr>
<td>5 psia, 15°C sink</td>
<td>0.74</td>
<td>0.04</td>
<td>19.9</td>
</tr>
</tbody>
</table>

- Thermal conductance of 0.7 W/K and conductance ratio of 20:1 demonstrated
Second prototype experimental results

- Examples of thermal conductance measurement for second thermal switch prototype

14.7 psia counter pressure; 0°C sink

5 psia counter pressure; 15°C sink
Conceptual next generation design

- Prototype two-phase thermal switches were not optimized for mass, but to demonstrate the concept.
- A preliminary design was developed for an estimate of the mass of an actual device:
  - Ammonia working fluid
  - Stainless steel bellows
  - Ceramic enclosure to reduce heat leaks
  - Copper end caps

- Total mass of ~61 g much lower than conventional thermal switch technologies.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enclosure Material</td>
<td>Ceramic</td>
</tr>
<tr>
<td>Bellows Material</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>End Cap Material</td>
<td>Copper</td>
</tr>
<tr>
<td>Hot Contact Surface Material</td>
<td>Copper</td>
</tr>
<tr>
<td>Ammonia Charge</td>
<td>12mL</td>
</tr>
<tr>
<td>Dimensions</td>
<td>2.2in long x 1.0in diameter</td>
</tr>
<tr>
<td>Total Mass</td>
<td>0.061 kg</td>
</tr>
</tbody>
</table>
Future work

• Dynamic performance model development
  – Transient heat transfer in all components
  – Detailed modeling of fluid and vapor flow in bellows
  – Couple heat transfer model to dynamic spring model of the bellows
  – Changes in enclosure gas pressure due to compression and temperature change
  – Goal of predicting set point temperatures, thermal conductance, and bellows oscillation frequency

• Dynamic performance of two-phase thermal switch is complicated and somewhat unintuitive

• A high-fidelity model will be required for use as a design and optimization tool

• Model also used to predict fatigue life of bellows
  – Two modes of fatigue
    • Large amplitude, low frequency cycles (On/Off)
    • Small amplitude, high frequency cycles (Oscillation during operation)
Future work

• Performance improvements
  – Decrease “Off” conductance
    • Enclosure design and materials – reduce heat leaks
  – Increase “On” conductance
    • Reduce contact conductance with TIM and mated surfaces
  – Optimize wick structure
  – Use dynamic model to optimize overall design

• Perform thermal switch life tests
  – Evaluate change in performance due to material wear or bellows fatigue
Conclusions

- Developed a design for a two-phase thermal switch
  - Operates in On/Off mode when heat load is removed
  - Variable conductance device to maintain set point temperature as sink temperature changes
- Initial static model to describe operation
- Prototype demonstration
  - Maintenance of set point temperature
  - Change in set point temperature through change of enclosure gas pressure
- Clear path for improving On/Off conductance ratio
- Mass benefit over existing thermal switch technologies

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</thead>
<tbody>
<tr>
<td>Mass (g)</td>
<td>110</td>
<td>320</td>
<td>~61</td>
<td>&lt; 75</td>
</tr>
<tr>
<td>&quot;On&quot; Conductance (W/K)</td>
<td>1.2</td>
<td>1.6</td>
<td>0.7</td>
<td>1.5</td>
</tr>
<tr>
<td>&quot;Off&quot; Conductance (W/K)</td>
<td>0.018</td>
<td>0.012</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>On/Off Conductance Ratio</td>
<td>67</td>
<td>127</td>
<td>20</td>
<td>150</td>
</tr>
</tbody>
</table>

**Conceptual design**

**Measured**

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References:
