Thermal Systems Modeling of a Variable Emittance Coating for Human Spacecraft Applications

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Thermal & Fluids Analysis Workshop
TFAWS 2018
August 20-24, 2018
NASA Johnson Space Center
Houston, TX
Outline

• Introduction
  – Motivation and background
  – Properties of vanadium dioxide (VO₂)
  – Variable emitter design and initial results

• Preliminary MATLAB modeling
  – Objectives
  – Representative spacecraft system definition
  – Modeling approach and cases considered
  – Model results

• Additional Geometries
  – Radial flow radiators
  – Bypass valve

• Comparison with Thermal Desktop

• Conclusions
Background: Ideal Performance

High Temperature – High Heat Rejection

Low Temperature – Low Heat Rejection

Ideal Broadband Emittance

- High Temp: $\varepsilon \approx 1$
- Low Temp: $\varepsilon \approx 0$
Background: Characteristics of VO$_2$

- VO$_2$ is an insulator-to-metal thermochromic material
- Changes phase at 341 K (68 ºC)

Silicon is only 54% transparent in the mid-infrared
- Incorporate VO$_2$ in a multilayer structure to get variable $\varepsilon$

Taylor et al., Thin Solid Films, submitted
Background: Emitter Design

\[ d_f = 25 \text{ nm} \]
\[ d_s = 730 \text{ nm} \]

• Consistent results for the last 3 samples fabricated
• ~0.55 change in emissivity over short wavelengths
• ~0.30 change in emissivity over longer wavelengths

Presented as a poster at ICES2018
Modeling Objectives:

1. Determine what transition temperature range is required for human spaceflight applications

2. Determine the minimum emittance change required for the coating to have an appreciable turn down

3. Identify what types of missions would or would not benefit from variable emittance

4. Identify which radiator designs seem to be the most effective when using a variable emissivity coating
Body-mounted radiators that are discretized into $N = 360$ panels

Each panel is discretized into $K$ blocks, each with their own independent emissivity $\varepsilon_1, \varepsilon_2, \varepsilon_3, \ldots, \varepsilon_n$

1. Fluid picks up heat from HX
2. Flow separates into 360 lines with equal flow rates
3. Heat is rejected by each separate fluid line/radiator panel
4. Flow is mixed to give average $T_{\text{outlet}}$
MATLAB Approach

\[ T_i = \text{Radiator Inlet T} \]

Determine \( T_{i+1} \) from:

\[ \dot{m}c_p(T_i - T_{i+1}) = \varepsilon \sigma A \left( \frac{T_i + T_{i+1}}{2} \right)^4 - A \alpha q_{sol} \]

Flow in

\[ \varepsilon_1 \]
\[ \varepsilon_2 \]
\[ \varepsilon_3 \]
\[ \ldots \]
\[ \varepsilon_n \]

Flow out

Flow in

Flow out

Iterate enough times to reach steady state

\[ i++ \]

\[ i = K? \]

No

\[ j = N? \]

No

\[ j++ \]

Yes

Yes

Average outlet temperature from lines

Determine new inlet temperature:

\[ T_{in} = \frac{\dot{Q}_{S/C+crew}}{\dot{m}c_p + T_{avg}} \]

Output: Steady State \( T_{outlet} \)
Initial Cases Considered

**Hot Case**
- Full Heat Load
- $Q_{FHL} = 8500$ W

**Cold Case**
- Partial Heat Load

- **Requirement 1**: Average outlet temperature must be between 0 °C and 10 °C
- **Requirement 2**: The temperature of each radiator panel must be above -10 °C

- Turndown percentage $TD = \text{lowest percentage of full load that can be reduced to while still meeting requirements}$
Radiator Area Sizing

\[ T_{Rad} = \frac{T_{in} - T_{out}}{2} \]

\[ T_{\infty} = \left( \frac{1}{\sigma} \left( \frac{\alpha}{\varepsilon} q_{sol} + q_{IR} \right) \right)^{1/4} \]

\[ A_{Rad} = \frac{Q_{load}}{(\varepsilon \sigma (T_{Rad}^4 - T_{\infty}^4))} \]

where \( q_{sol} = 432.5 \text{ W/m}^2 \)

Panel Discretization

Results for both the hot case and cold case stop changing significantly after \( K = 10 \)
1. No hysteresis considered
2. $\varepsilon_{\text{low}}$ can vary between 0.3 and 0.6
3. $\varepsilon_{\text{high}}$ can vary between 0.6 and 0.9
4. $T_{\text{high}}$ must be between 4 and 20 degrees higher than $T_{\text{low}}$

$\Rightarrow$ (2), (3), and (4) are based on fabrication limitations
Initial Results: Same Area

- \( A = 28.8 \, \text{m}^2 \)
- \( T_{\text{low}} = 7 \, ^\circ\text{C} \)
- \( T_{\text{high}} = 11 \, ^\circ\text{C} \)
- \( T_{\text{out,desired}} = 4 \, ^\circ\text{C} \)
- Turndown = 40%

**Hot Case (0.3 \leq \varepsilon \leq 0.9)**

\[
T_{\text{out}} = 9.80 \, ^\circ\text{C}
\]

**Cold Case (0.3 \leq \varepsilon \leq 0.9)**

\[
T_{\text{out}} = 0.13 \, ^\circ\text{C}
\]

**Hot Case (\varepsilon = 0.9)**

\[
T_{\text{out}} = 4.65 \, ^\circ\text{C}
\]

**Cold Case (\varepsilon = 0.9)**

\[
T_{\text{out}} = -58.61 \, ^\circ\text{C}
\]
Initial Results: Same Outlet Temperature

- $A_{\text{static}} = 27.8 \text{ m}^2$
- $A_{\text{variable}} = 32.2 \text{ m}^2$
- Mass $\uparrow$: 24 kg
- $T_{\text{low}} = 7 \, ^\circ\text{C}$
- $T_{\text{high}} = 12 \, ^\circ\text{C}$
- $T_{\text{out,desired}} = 8 \, ^\circ\text{C}$
- Turndown = 40%

- Study optimum tradeoff between increased mass and cold case turn down percentage

**Hot Case ($0.3 \leq \varepsilon \leq 0.9$)**
- $T_{\text{out}} = 8.46 \, ^\circ\text{C}$

**Cold Case ($0.3 \leq \varepsilon \leq 0.9$)**
- $T_{\text{out}} = -0.01 \, ^\circ\text{C}$

**Hot Case ($\varepsilon = 0.9$)**
- $T_{\text{out}} = 8.46 \, ^\circ\text{C}$

**Cold Case ($\varepsilon = 0.9$)**
- $T_{\text{out}} = -55.99 \, ^\circ\text{C}$
Optimized Case: Majority of blocks in hot case are $\varepsilon = 0.90$ and cold case has mainly $\varepsilon = 0.30$
Intermediate Case: Cold case slowly changes from $\varepsilon = 0.9$ to $\varepsilon = 0.30$
Maximum turn down percentage of 40% occurs when $T_{\text{low}} = 7 \, ^\circ\text{C}$ and $T_{\text{high}} = 11 \, ^\circ\text{C}$.

Minimum surface emissivity $\varepsilon_{\text{low}} = 0.30$

Maximum surface emissivity $\varepsilon_{\text{high}} = 0.90$

Surface area $A_{\text{rad}} = 28.8 \, \text{m}^2$
Transition Range Optimization

- \( T_{\text{high}} = T_{\text{low}} + 13 \degree \text{C} \)
- \( T_{\text{high}} = T_{\text{low}} + 3 \degree \text{C} \)
- \( T_{\text{out}} > 10 \degree \text{C} \)
- \( T_{\text{out}} < 0 \degree \text{C} \)

- Optimization ends due to \( T_{\text{out}} \) going out of bounds
- No cases with freezing as the exit condition
• Only 86% turn down percentage achieved → represents lower limit for emissivity change

\[ \varepsilon_{\text{low}} = 0.60 \]
\[ \varepsilon_{\text{high}} = 0.90 \]
\[ A_{\text{rad}} = 28.8 \text{ m}^2 \]
**Objective:** Help improve turndown ratio by spreading the heat more evenly over the fluid lines

MATLAB implementation is similar to previous model where “blocks” are now discretized areas along the cylinder circumference and “panels” are the radial segments.
• \( A = 28.8 \text{ m}^2 \)
• \( T_{\text{low}} = 8 \text{ °C} \)
• \( T_{\text{high}} = 13 \text{ °C} \)
• Turndown = 35%
• Pointing Angle = 180°

\[ T_{\text{out}} = 9.91 \text{ °C} \]

\[ T_{\text{out}} = 0.07 \text{ °C} \]
Objective: Improve the turndown by only flowing a portion of fluid through radiator, yielding higher average outlet temperature

Implemented in the code by:
(1) Solving the radiator with \((1 – BPR)\) percentage of mass flow
(2) Weighted average of the inlet temperature and the radiator exit temperature

\[
T_{\text{outlet}} = T_{\text{in}} \times BPR + T_{\text{rad,avg out}} \times (1 - BPR)
\]
- Did not provide expected benefit
- Turn down was 50% rather than 40% with all else being equal
- Might be able to optimize to a better solution or change BPV configuration

**Hot Case (0.3 ≤ ε ≤ 0.9)**

\[ T_{out} = 9.53 \, ^\circ C \]

**Cold Case (0.3 ≤ ε ≤ 0.9)**

\[ T_{out} = -0.07 \, ^\circ C \]
Thermal Desktop Model Set-up

- No conduction is assumed
- Mass flow is chosen from MATLAB to correlate with $c_p$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>S/C Heat Load</td>
<td>6000 W</td>
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<tr>
<td>Crew Heat Load</td>
<td>8500 W</td>
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<tr>
<td>Fluid</td>
<td>Water</td>
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<tr>
<td>Mass Flow Rate</td>
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<tr>
<td>Spacecraft Diameter</td>
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<tr>
<td>Rad Panel Length</td>
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<tr>
<td>Solar Absorptivity</td>
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<tr>
<td>IR Emissivity Range</td>
<td>0.3 to 0.9</td>
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<tr>
<td>Temperature</td>
<td>7 °C to 13 °C</td>
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<tr>
<td>Radiator Panels</td>
<td>18</td>
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<tr>
<td>Panel Blocks</td>
<td>5</td>
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<td>UA considered</td>
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Hot Case Considered
Earth Orbit

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<th>Parameter</th>
<th>Value</th>
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<td>Altitude</td>
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<td>Albedo</td>
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<tr>
<td>Planet IR</td>
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</tbody>
</table>

No Vehicle Rotation
Thermal Desktop Results

\[ T_{\text{in}} = 35.22 \, ^\circ\text{C} \]
\[ T_{\text{out}} = 8.35 \, ^\circ\text{C} \]

→ This agrees reasonably well with MATLAB results

→ Need to set up and run cold case
Conclusions

• Variable radiator runs hotter than static radiator
• Optimum transition range is approximately 7 °C to 11 °C
• 4 °C radiator outlet temperature was very difficult to achieve → effectively no turn down
• Tradeoff between added radiator mass and minimum turn down percentage that can be reached
• Smaller width for transition temperature range is better
• Radial geometry radiator performs the best so far
• Radial radiator doesn’t seem to be as attitude dependent as we initially thought
Acknowledgements

• Thanks to Thomas Gross for help with the Thermal Desktop modeling
• Thanks to Rubik Sheth and EC6 for input on the MATLAB model
• This work is supported by a NASA Space Technology Research Fellowship (NNX16AM63H)
Questions?