Modelling of Radiative Heat Transfer of a Square Trihedral Design Radiator Panel on the Lunar Surface

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Introduction

• Power requirements for telecommunication satellites has increased from 2-5 kW to 20-30 kW since the 2000’s.
• Increased miniaturisation of electronics and rapid growth of smallsat industry.
• This has led to greater heat dissipation requirements for spacecraft radiators.
• New concepts have been developed in recent years in order to enhance radiator performance.
Trihedral Design Radiator

- Definition: “Three plane faces which meet at a common apex point”.
- Aims to minimise effects of environmental radiation sources and increase the surface area visible to deep space.
- Single trihedral element can be tiled into an array.
- Similar geometry to corner cube retro-reflectors used in radar and optical industries.

\[ \phi = 60^\circ \quad \phi = 90^\circ \quad \phi = 110^\circ \]
Model Description

- Geometry on lunar surface with coordinates at Apollo 17 landing site (20°N, 31°E).
- Develop **radiative** model which takes into account all environmental sources of heat:
  - Direct solar flux
  - Indirect solar flux reflections
  - Albedo flux
  - Lunar infra-red flux
  - Internal heating
- Determine radiative heat transfer from each radiator surface.
Model Description

• Solar UV flux
  – Direct incident irradiation:
    \[ q''_{\text{solar, direct}} = G_{SC} \cos \theta \]
  – Direct incident irradiation per surface:
    \[ q''_{solar, direct,i} = \frac{1}{A_i} \sum_{k}^{k} q''_{solar, direct,k} a_{k} \]
Model Description

- Solar UV flux
  - Indirect (diffuse) reflections and lunar Albedo by Radiation Network Methodology.
  - For each surface:

\[
I_i(1 - F_{it}) - \sum_{i \neq j} F_{ij}J_j = (1 - \alpha_i)q''_{solar\ direct,i}
\]

<table>
<thead>
<tr>
<th></th>
<th>(\alpha_{UV})</th>
<th>(\varepsilon_{IR})</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSR(^{(1)})</td>
<td>0.12</td>
<td>0.8</td>
</tr>
<tr>
<td>Moon(^{(2)})</td>
<td>1-0.12</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Model Description

• Lunar IR flux
  – Diffuse Infra-red heat radiated from lunar surface.
  – Lunar surface temperature varies as a function of location, time and surface properties (2).
  – As before, apply Radiation Network Methodology to IR sources:
    \[ J_i [1 - F_{ii} (1 - \varepsilon_i)] - (1 - \varepsilon_i) \sum_{i \neq j} F_{ij} J_j = \varepsilon_i \sigma T_i^4 \]
  – Setting \( T \) here for all radiator surfaces to a maximum allowable temperature of 40°C.
Model Description

- Net radiative heat transfer per surface
  - Difference of outgoing less incoming sources of heat:
    \[ q_{net,i} = (q_{solar_{out,i}} + q_{IR_{out,i}}) - (q_{solar_{in,i}} + q_{IR_{in,i}}) \]
    \[ = \left[ \frac{\varepsilon_i A_i}{1 - \varepsilon_i} (\sigma T_i^4 - J_i) \right] - \alpha_i (q_{solar_{direct,i}} + q_{solar_{indirect,i}}) \]

- Total radiator heat transfer rate:
  \[ q_{rad} = \sum_{i=1}^{21} q_{net,i} \]
Model Description

- **View Factor Determination**
  - Monte Carlo based Ray Tracing.
  - Shoots $N$ rays originating from face centroid with a distribution defined by Lambert’s cosine Law:

\[
y_n = \sin^{-1} \sqrt{R y_n} \\
\phi_n = 2\pi R \phi_n
\]

- where:
  \[
  0 \leq y_n \leq \frac{\pi}{2} \\
  0 \leq \phi_n \leq 2\pi \\
  0 \leq R \leq 1
\]

- Then:
  \[
  F_{ij} = \frac{n_{ij}}{N_i}
  \]
Model Description

• View Factor Determination (Validation)

1. Comparison with analytical solution\(^{(3)}\) for “Perpendicular rectangles with a common edge”.

Model Description

- **View Factor Determination (Validation)**
  2. Comparison with analytical solution$^{(3)}$ for “*Parallel, equal, directly opposed rectangles*”.

\[
F_{\text{hot, top}} \quad y/d = 0.5, 1.0, 2.0, 3.0
\]

\[
x/d \quad 10^{-1}, 10^{0}, 10^{1}, 10^{2}
\]

- Analytical
- Monte Carlo ($N=1000$)
Model Description

- **View Factor Determination**
  - Effect of Lunar disc diameter ($D$) on $F_{i,lunar}$
Results

• Comparison with commercial software
  – SYSTEMA/THERMICA v4 by Airbus.
  – FloTHERM XT v3.3 by Mentor.

• Test case at Apollo 17 landing site for $\varphi = 90^\circ$
Results

• Comparison with commercial software
  – Direct solar heat flux:

<table>
<thead>
<tr>
<th>Time</th>
<th>RMSE w. THERMICA (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>06:30</td>
<td>7.96</td>
</tr>
<tr>
<td>09:00</td>
<td>7.27</td>
</tr>
<tr>
<td>12:00</td>
<td>8.44</td>
</tr>
</tbody>
</table>
Results

- Comparison with commercial software
  - Direct and indirect absorbed solar heat flux:

<table>
<thead>
<tr>
<th>Time</th>
<th>RMSE w. THERMICA (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>06:30</td>
<td>2.87</td>
</tr>
<tr>
<td>09:00</td>
<td>3.22</td>
</tr>
<tr>
<td>12:00</td>
<td>1.65</td>
</tr>
</tbody>
</table>
Results

- Radiative Heat Transfer of Trihedral Radiator
  - Effect of Apex Angle ($\phi$)

Compared to flat plate ($\phi \equiv 120^\circ$):

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>Best case (sunrise/sunset)</th>
<th>Worst case (noon)</th>
<th>Full day</th>
</tr>
</thead>
<tbody>
<tr>
<td>60$^\circ$</td>
<td>+84.2%</td>
<td>-40.2%</td>
<td>+15.0%</td>
</tr>
<tr>
<td>90$^\circ$</td>
<td>+31.7%</td>
<td>-11.8%</td>
<td>+8.4%</td>
</tr>
<tr>
<td>110$^\circ$</td>
<td>+8.8%</td>
<td>-0.6%</td>
<td>+4.4%</td>
</tr>
</tbody>
</table>
Results

- Radiative Heat Transfer of Trihedral Radiator
  - Effect of Azimuth Angle ($\phi$)
Results

- Radiative Heat Transfer of Trihedral Radiator
  - Effect of Inclination Angle ($\beta$)

![Graph showing the total radiator dissipating power (W) vs. lunar hour for different inclination angles.](image)

Compared to flat plate ($\phi \equiv 120^\circ$):

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>Best case (sunrise/sunset)</th>
<th>Worst case (noon)</th>
<th>Full day</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$</td>
<td>+31.5%</td>
<td>-11.8%</td>
<td>+8.4%</td>
</tr>
<tr>
<td>$45^\circ$</td>
<td>+31.5%</td>
<td>-28.3%</td>
<td>+8.8%</td>
</tr>
<tr>
<td>$90^\circ$</td>
<td>-96.2%</td>
<td>+2.7%</td>
<td></td>
</tr>
</tbody>
</table>
Manufacturability

• Honeycomb Panel

![Honeycomb Panel Diagram]

• Metal 3D printing
  – Sample array of 4 Trihedral elements additively manufactured with AlSi10Mg.

![Metal 3D Printing Diagram]
Conclusions

- Developed model with can predict radiative heat transfer of a radiator panel on lunar surface.
- Shows excellent agreement with commercial software.
- Initial results show that trihedral geometry offers good potential for most conditions studied here.
- Smaller apex angles dissipate more heat in morning compared to a flat plate, whereas larger apex angles reduce difference around noon.
- Azimuth angle has little impact on heat transfer, whereas as Inclination angle rotates towards vertical, net heat transfer is reduced significantly.
Future Work

• Expand the array to include greater number of elements.
  – Reduce impact of lunar IR heat flux on central surfaces

• Add thermal conduction to model
  – Improve prediction to real-world behaviour and smooth discontinuities between connecting faces.
Acknowledgements

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Thank You

Questions...?