Thermal radiation in the cryogenic regime

NASA Glenn Research Center
Thermal Systems Branch (LTT)

Presented By
Justin P. Elchert

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

• Review of multilayer insulation (also called superinsulation) fundamentals
  – Basic construction
  – Types of MLI models

• Introduction of advanced concepts
  – Non-gray
  – Seams
  – Validating Thermal Desktop

• Incorporating these concepts into Thermal Desktop models

• Discussion of results
Types of MLI models

- Numerical (commercial code, or custom code)
- Floating shields analytical model

\[
q = \frac{\sigma(T_1^4 - T_2^4)}{1/\epsilon_1 + 1/\epsilon_2 - 1 + \sum_{n=1}^{N-1} (1/\epsilon_{n+1}) - 1) + 1/\epsilon_{N2} + 1/\epsilon_2 - 1}
\]  

(22)

- Semi-empirical models

\[
q = \frac{c''}{t} N^m T_m (T_h - T_c) + \frac{3 b_2 n^3 \sigma}{7 N_o} (T_h^{14/3} - T_c^{14/3})
\]  

(38)

- Polynomial fits

\[
q = h(T_h - T_c) + \epsilon'_{eff} \sigma (T_h^4 - T_c^4)
\]

\[
q = c_3 (T_h^2 - T_c^2) + c_4 (T_h^3 - T_c^3) + c_5 (T_h^{0.67} - T_c^{0.67})
\]

- Iterative separated mode
Validation case: floating shields

<table>
<thead>
<tr>
<th>Analytical solution</th>
<th>Thermal Desktop solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>90.0000</td>
</tr>
<tr>
<td>128.494</td>
<td>128.9190</td>
</tr>
<tr>
<td>147.986</td>
<td>148.4690</td>
</tr>
<tr>
<td>161.873</td>
<td>162.3760</td>
</tr>
<tr>
<td>172.896</td>
<td>173.4180</td>
</tr>
<tr>
<td>182.14</td>
<td>182.6130</td>
</tr>
<tr>
<td>190.159</td>
<td>190.5390</td>
</tr>
<tr>
<td>197.275</td>
<td>197.5990</td>
</tr>
<tr>
<td>203.695</td>
<td>203.9480</td>
</tr>
<tr>
<td>209.56</td>
<td>209.7310</td>
</tr>
<tr>
<td>214.97</td>
<td>215.0610</td>
</tr>
<tr>
<td>220</td>
<td>220.0000</td>
</tr>
</tbody>
</table>

-5.34 W/m²

TFAWS 2018 – August 20-24, 2018
Reminder: check ray tracing assumptions

Correct
Reminder: check ray tracing assumptions

Incorrect
A gray surface has the simplifying property that the absorptivity may be reasonably assumed to equal the emissivity.

Pre-requisites:
1. Either the irradiation is diffuse or the surface is diffuse.
2. Spectral properties of surface are nearly constant over spectral region of interest.
3. Irradiation and surface emission occur in the bounds of the spectral region of interest.

\[
\epsilon(T) = \frac{\int_0^\infty \epsilon_\lambda(\lambda, T) E_\lambda(b, \lambda, T) d\lambda}{E_b(T)}
\]
Non-gray validation case

Siegel & Howell
Problem 8-2

Solution: 140,500 W/m$^2$

Figure 8-4 Example of heat transfer across space between infinite parallel plates having spectrally dependent emissivities.
Non-gray validation case

Note: To avoid a runtime error, the temperatures must be monotonically increasing in the bivariate table.
Non-gray validation case
Srinivasan’s Paradox

• J. Srinivasan [24] observed that their dewar suffered roughly **66% more heat leak** when filled with LN2 than with LH2 (no blanket, just a thermos type setup)

• I.A. Black and P.E. Glaser [27] reported **41% more heat transfer** with a 1 inch thick blanket in their 35-liter dewar

• Thermal desktop gray analysis 10 layer cylinder showed the same heat leak for either the 77K or the 20K boundary condition

• **What’s going on here?** The hydrogen is colder and the surroundings are the same temperature. Why is liquid nitrogen losing more heat?
Srinivasan’s approach (Hagen-Rubens eq)

\[ n = \kappa = \sqrt{\frac{\lambda_o \mu_o c_o}{4\pi r_e}} = \sqrt{\frac{0.003\lambda_o}{r_e}} \]

\[ \epsilon'_n = \frac{4n}{(n + 1)^2 + \kappa^2} \implies \epsilon'_{\lambda,n}(\lambda) = \frac{4n}{2n^2 + 2n + 1} = \frac{2}{n} - \frac{2}{n^2} + \frac{1}{n^3} - \frac{1}{2n^5} + \frac{1}{2n^6} - \ldots \]

\[ \epsilon'_n(\lambda) = \frac{2}{\sqrt{0.003}} \sqrt{\frac{r_e}{\lambda_o}} - \frac{2}{0.003} \frac{r_e}{\lambda_o} + \ldots \approx 36.5 \sqrt{\frac{r_e}{\lambda_o}} - 464 \frac{r_e}{\lambda_o} \]

\[ q(T_1, T_2) = \int_{5}^{10000} \frac{E_{\lambda_b}(\lambda, T_1) - E_{\lambda_b}(\lambda, T_2)}{\epsilon_h(\lambda, T_1) + \frac{1}{\epsilon_h(\lambda, T_2)} - 1} d\lambda \]

TFAWS 2018 – August 20-24, 2018
Predicted temperature dependent spectral emissivities as calculated with the two term Hagen-Rubens approximation.
Plotting flux as function of boundary temps

Non-gray aluminumized cryogenic dewar

- $q_a(300K, T_0)$
- $q_a(300K, 90K)$
- $q_a(300K, 77K)$
- $q_a(300K, 20K)$
- $q_a(220K, T_0)$

[Temperature vs. Flux]
Paradox solved in Thermal Desktop

• Two concentric spheres, each with one boundary node
  – Outer boundary node at 300K, inner at either 77K (LN2) or 20K (LH2)
  – Radius 1m and 1.1m

• Solution:
  – 16.86 W @ LH2
  – **28.24 W @ LN2!!**
  – This works out to 68% increase, matching the expected results
Non-gray MLI in the cryogenic regime

Heat flux should be roughly constant, if gray assumption holds

HEAT FLUX [W/M²]

0 0.02 0.04 0.06 0.08 0.1 0.12

0 2 4 6 8 10 12

LAYER

TFAWS 2018 – August 20-24, 2018
Is the gray assumption justified?

Cylinder non-gray vs gray

![Graph showing temperature vs layer comparison between non-gray and gray cases.](image)

- **Non-gray case** vs **Gray case**

**Temperature [K] vs Layer**

**Layers (0 to 12)** vs **Temperature (0 to 250 K)**

TFAWS 2018 – August 20-24, 2018
Modeling MLI with Thermal Desktop

• Inner cold surface area was 1 square meter
• Layer thickness $2.5 \times 10^{-5}$ m
• Ten layers of insulation
• Layer spacing 1 mm
• Two fixed dirichlet (prescribed) conditions at 90K and 220K unless otherwise stated
• 1,000,000 rays (chosen after finding at least 100,000 rays were acceptable based on test runs)
• Aluminized kapton, 1 mil, BOL with IR emissivity of 0.61 (inner surface matches this value), unless otherwise stated
Heat flux changes with aspect ratio

Floating shields, large isothermal surroundings, gray-diffuse

\[ y = -0.0224x + 85.649 \]
The effectiveness of using a patch

- Surroundings added as a very closely spaced surface near the outer layer of the MLI stack
- Same emissivity of 0.61
- Resulting heat leak -5.78 W/m²
  - Close to ideal, floating shields case with no seams
  - Suggests that patching over seams ought to be very effective
References


[27] I.A. Black & Glaser “Progress report on development of high-efficiency insulation.” (Advances in Cryogenic Engineering volume 6, proceedings of the 1960 Cryogenic Engineering Conference)
Table 1. Superinsulation System Equations

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-Aluminized Mylar-Silk Netting (2 layers)</td>
<td>( k_e = 1.12 \times 10^{-3} N T_m + \frac{\sigma (T_h^2 + T_c^2)} {N-1} \left( \frac{1} {\epsilon} - 1 \right) )</td>
</tr>
<tr>
<td>NRC-2</td>
<td>( k_e = 5.90 \times 10^{-12} (S)^2 T_m + \frac{\sigma (T_h^2 + T_c^2)} {N-1} \left( \frac{1} {\epsilon} - 1 \right) )</td>
</tr>
<tr>
<td>Superflow</td>
<td>( k_e = 3.23 \times 10^{-11} (S)^2 T_m + \frac{\sigma (T_h^2 + T_c^2)} {N-1} \left( \frac{1} {\epsilon} - 1 \right) )</td>
</tr>
<tr>
<td>Double-Aluminized Mylar-Nylon Net (1 layer)</td>
<td>( k_e = 6.0 \times 10^{-11} (S)^2 T_m + \frac{\sigma (T_h^2 + T_c^2)} {N-1} \left( \frac{1} {\epsilon} - 1 \right) )</td>
</tr>
<tr>
<td>Double-Aluminized Mylar-Dexiglas</td>
<td>( k_e = 4.58 \times 10^{-12} (S)^2 T_m + \frac{2.1 \sigma (T_h^2 + T_c^2)} {N-1} \left( \frac{1} {\epsilon} - 1 \right) )</td>
</tr>
<tr>
<td>Double-Aluminized Mylar-Tissuglas</td>
<td>( k_e = 1.83 \times 10^{-12} (S)^2 T_m + \frac{1.7 \sigma (T_h^2 + T_c^2)} {N-1} \left( \frac{1} {\epsilon} - 1 \right) )</td>
</tr>
<tr>
<td>Double-Aluminized Crinkled Mylar-Tissuglas</td>
<td>( k_e = 4.6 \times 10^{-12} (S)^2 T_m + \frac{1.7 \sigma (T_h^2 + T_c^2)} {N-1} \left( \frac{1} {\epsilon} - 1 \right) )</td>
</tr>
<tr>
<td>Double-Aluminized Mylar-Open-Cell Foam</td>
<td>( k_e = 1.26 \times 10^{-14} (S)^2 T_m + \frac{\sigma (T_h^2 + T_c^2)} {N-1} \left( \frac{1} {\epsilon} - 1 \right) )</td>
</tr>
<tr>
<td>Double-Aluminized Mylar-Closed-Cell Foam</td>
<td>( k_e = 3.5 \times 10^{-15} (S)^2 T_m + \frac{\sigma (T_h^2 + T_c^2)} {N-1} \left( \frac{1} {\epsilon} - 1 \right) )</td>
</tr>
</tbody>
</table>

- \( k_e \) = effective thermal conductivity
- \( N \) = no. of radiation shields/unit thickness
- \( T_m \) = mean temperature
- \( \sigma \) = Stefan-Boltzmann constant
- \( \epsilon \) = emissivity
- \( T_c \) = cold temperature
- \( T_h \) = hot temperature

TFAWS 2018 – August 20-24, 2018

24
Simulating infinite parallel planes using reflecting surfaces
Adding contact conductance

- Contacting shields, 3 degree opening, large isothermal surroundings, gray-diffuse
  - Contact conductance 0.05 W/m²/K
  - Resulting heat leak -6.66 W/m² (roughly 10% more than floating)

**Figure 75:** Case 7, layer 1.

**Figure 41:** Case 1, layer 1.
More contact!

- Contact conductance increased by order of magnitude to 0.5 W/m²/K
  - Resulting heat leak -11.97 W/m²

**Figure 86:** Case 8, layer 1.

**Figure 41:** Case 1, layer 1.
Review

Thermal radiation occurs between $10^{-3}$ μm and $10^8$ μm. This encompasses part of the ultraviolet spectrum, the entire visible light spectrum, and the entire infrared spectrum. To understand thermal radiation, the concept of the blackbody and its properties should be defined as follows.

1. A blackbody absorbs all incident radiation, regardless of wavelength and direction.
2. For a prescribed temperature and wavelength, no surface can emit more energy than a blackbody.
3. Although the radiation emitted by a blackbody is a function of wavelength and temperature, it is independent of direction. That is, the blackbody is a diffuse emitter.

The blackbody spectral intensity is well known, having first been determined by Planck:

$$I_{\lambda}(\lambda, T) = \frac{2hc^2}{\lambda^5(e^{hc/\lambda kT} - 1)}$$

Since the blackbody is by definition a diffuse emitter, it follows that the spectral emissive power, after integration, is simply the spectral intensity multiplied by π.

$$E_{\lambda}(\lambda, T) = \pi I_{\lambda}(\lambda, T)$$

An example of the Planck distribution plotted for a temperature of 20K is shown in 2.

By integrating 3 over the wavelength from zero to infinity, the Stefan-Boltzmann Law is obtained.

$$E_{\lambda}(T) = \sigma T^4$$

As an example, for 90K, considering a band up to 250μm would account for 99% of the energy emitted. For 220K, a band up to 102μm needs to be considered to account for 99% of the energy (these results are shown in Figure 3).

Relevant to cryogenic superinsulation heat transfer, consider that, in Figure 3, less than 1% of the energy is in the band from 250μm to 1000μm for the 90K case. The wavelength here is on the order of the spacing of the insulation (roughly 10 layers per centimeter means layer spacing is on the order of 0.1cm

$$F_{\lambda_1,\lambda_2}(\lambda_1,\lambda_2, T) = \int_{\lambda_1}^{\lambda_2} \frac{E_{\lambda}(\lambda, T)}{\sigma T^4} d\lambda$$

Figure 3: A computer algebra system, like MathCAD, is very useful to avoid the table lookup typically associated with band fractions.

which equals 1000μm). At 20K, the energy in the 250μm to 1000μm band jumps drastically to 85%, with 1% of the energy having a wavelength between 1000μm and 10000μm, which is greater than the spacing the layers. At 2K, 92% of the energy has a wavelength in this very long band from 1000μm and 10000μm which is equivalent to 0.1cm and 1cm.
Figure 21: Solution to the nongray dewar problem following the approach of Srinivasan [24] which keeps a two term approximation of the Hagen-Rubens relation.