Thermal Systems Design

- Fundamentals of heat transfer
- Radiative equilibrium
- Surface properties
- Non-ideal effects
  - Internal power generation
  - Environmental temperatures
- Conduction
- Thermal system components
Classical Methods of Heat Transfer

• Convection
  - Heat transferred to cooler surrounding gas, which creates currents to remove hot gas and supply new cool gas
  - Don't (in general) have surrounding gas or gravity for convective currents

• Conduction
  - Direct heat transfer between touching components
  - Primary heat flow mechanism internal to vehicle

• Radiation
  - Heat transferred by infrared radiation
  - Only mechanism for dumping heat external to vehicle
Thermal Systems Design

Principles of Space Systems Design

University of Maryland

Ideal Radiative Heat Transfer

Planck’s equation gives energy emitted in a specific frequency by a black body as a function of temperature

\[ e_{\lambda b} = \frac{2\pi h C_0^2}{\lambda^5 \left[ \exp\left(\frac{-h C_0}{\lambda kT}\right) - 1 \right]} \]

(Don’t worry, we won’t actually use this equation for anything…)

• Stefan-Boltzmann equation integrates Planck’s equation over entire spectrum

\[ P_{rad} = \sigma T^4 \]

\[ \sigma = 5.67 \times 10^{-8} \frac{W}{m^2 \circ K^4} \]

(“Stefan-Boltzmann Constant”)
Thermodynamic Equilibrium

• First Law of Thermodynamics

\[ Q - W = \frac{dU}{dt} \]

heat in - heat out = work done internally

• Heat in = incident energy absorbed

• Heat out = radiated energy

• Work done internally = internal power used (negative work in this sense - adds to total heat in the system)
Radiative Equilibrium Temperature

- Assume a spherical black body of radius \( r \)
- Heat in due to intercepted solar flux
  \[ Q_{in} = I_s \pi r^2 \]
- Heat out due to radiation (from total surface area)
  \[ Q_{out} = 4\pi r^2 \sigma T^4 \]
- For equilibrium, set equal
  \[ I_s \pi r^2 = 4\pi r^2 \sigma T^4 \Rightarrow I_s = 4\sigma T^4 \]
- 1 AU: \( I_s = 1394 \text{ W/m}^2 \); \( T_{eq} = 280^\circ \text{K} \)

\[ T_{eq} = \left( \frac{I_s}{4\sigma} \right)^{1/4} \]
Effect of Distance on Equilibrium Temp

Distance from Sun (AU) vs. Black Body Equilibrium Temperature (°K)
Shape and Radiative Equilibrium

- A shape absorbs energy only via illuminated faces
- A shape radiates energy via all surface area
- Basic assumption made is that black bodies are intrinsically isothermal (perfect and instantaneous conduction of heat internally to all faces)
Effect of Shape on Black Body Temps

![Graph showing the effect of shape on black body temperatures. The graph plots black body equilibrium temperature (°K) against distance from the Sun (AU). There are three lines representing different shapes: Spherical Black Body, Adiabatic Black Wall, and Double-Sided Wall. The temperature decreases as the distance from the Sun increases.]
Incident Radiation on Non-Ideal Bodies

Kirchhoff’s Law for total incident energy flux on solid bodies:

\[ Q_{\text{Incident}} = Q_{\text{absorbed}} + Q_{\text{reflected}} + Q_{\text{transmitted}} \]

\[ \frac{Q_{\text{absorbed}}}{Q_{\text{Incident}}} + \frac{Q_{\text{reflected}}}{Q_{\text{Incident}}} + \frac{Q_{\text{transmitted}}}{Q_{\text{Incident}}} = 1 \]

\[ \alpha \equiv \frac{Q_{\text{absorbed}}}{Q_{\text{Incident}}}; \quad \rho \equiv \frac{Q_{\text{reflected}}}{Q_{\text{Incident}}}; \quad \tau \equiv \frac{Q_{\text{transmitted}}}{Q_{\text{Incident}}} \]

where

- \( \alpha \) = absorptance (or absorptivity)
- \( \rho \) = reflectance (or reflectivity)
- \( \tau \) = transmittance (or transmissivity)
Non-Ideal Radiative Equilibrium Temp

- Assume a spherical black body of radius $r$
- Heat in due to intercepted solar flux
  \[ Q_{in} = I_s \alpha \pi r^2 \]
- Heat out due to radiation (from total surface area)
  \[ Q_{out} = 4\pi r^2 \varepsilon \sigma T^4 \]
  ($\varepsilon$ = "emissivity" - efficiency of surface at radiating heat)
- For equilibrium, set equal
  \[ I_s \alpha \pi r^2 = 4\pi r^2 \varepsilon \sigma T^4 \Rightarrow I_s = 4 \frac{\varepsilon}{\alpha} \sigma T^4 \]

\[ T_{eq} = \left( \frac{\alpha}{\varepsilon} \frac{I_s}{4\sigma} \right)^{1/4} \]
Effect of Surface Coating on Temperature

- Teq=560°K (a/e=4)
- Teq=471°K (a/e=2)
- Teq=396°K (a/e=1)
- Teq=333°K (a/e=0.5)
- Teq=280°K (a/e=0.25)

- Black Ni, Cr, Cu
- Black Paint
- Polished Metals
- Aluminum Paint
- White Paint
- Optical Surface Reflector
Non-Ideal Radiative Heat Transfer

- Full form of the Stefan-Boltzmann equation

\[ P_{rad} = \varepsilon \sigma A(T^4 - T_{env}^4) \]

where \( T_{env} \) = environmental temperature (≈4°K for space)

- Also take into account power used internally

\[ I_s \alpha A_s + P_{int} = \varepsilon \sigma A_{rad}(T^4 - T_{env}^4) \]
Example: AERCam/SPRINT

- 30 cm diameter sphere
- $\alpha = 0.2; \ \varepsilon = 0.8$
- $P_{\text{int}} = 200\text{W}$
- $T_{\text{env}} = 280^\circ\text{K}$ (cargo bay below; Earth above)

Analysis cases:
- Free space w/o sun
- Free space w/sun
- Earth orbit w/o sun
- Earth orbit w/sun
AERCam/SPRINT Analysis (Free Space)

- \( A_s = 0.0707 \, \text{m}^2; \ A_{\text{rad}} = 0.2827 \, \text{m}^2 \)
- Free space, no sun

\[
P_{\text{int}} = \varepsilon \sigma A_{\text{rad}} T^4 \Rightarrow T = \left( \frac{200W}{0.8 \left( 5.67 \times 10^{-8} \frac{W}{m^2 \cdot K^4} \right) \left( 0.2827 m^2 \right)} \right)^{1/4} = 354^\circ K
\]
AERCam/SPRINT Analysis (Free Space)

- \( A_s = 0.0707 \text{ m}^2; A_{rad} = 0.2827 \text{ m}^2 \)
- Free space with sun

\[
I_s \alpha A_s + P_{int} = \varepsilon \sigma A_{rad} T^4 \quad \Rightarrow \quad T = \left( \frac{I_s \alpha A_s + P_{int}}{\varepsilon \sigma A_{rad}} \right)^{1/4} = 362^\circ K
\]
AERCam/SPRINT Analysis (LEO Cargo Bay)

• $T_{\text{env}} = 280^\circ\text{K}$
• LEO cargo bay, no sun

\[
P_{\text{int}} = \varepsilon\sigma A_{\text{rad}} \left(T^4 - T_{\text{env}}^4\right) \Rightarrow T = \left(\frac{200\text{W}}{0.8 \left(5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4}\right) \left(0.2827\text{m}^2\right)} + (280^\circ\text{K})^4\right)^{1/4} = 384^\circ\text{K}
\]

• LEO cargo bay with sun

\[
I_s \alpha A_s + P_{\text{int}} = \varepsilon\sigma A_{\text{rad}} \left(T^4 - T_{\text{env}}^4\right) \Rightarrow T = \left(\frac{I_s \alpha A_s + P_{\text{int}}}{\varepsilon\sigma A_{\text{rad}}} + T_{\text{env}}^4\right)^{1/4} = 391^\circ\text{K}
\]
Radiative Insulation

- Thin sheet (mylar/kapton with surface coatings) used to isolate panel from solar flux
- Panel reaches equilibrium with radiation from sheet and from itself reflected from sheet
- Sheet reaches equilibrium with radiation from sun and panel, and from itself reflected off panel
Multi-Layer Insulation (MLI)

- Multiple insulation layers to cut down on radiative transfer
- Gets computationally intensive quickly
- Highly effective means of insulation
- Biggest problem is existence of conductive leak paths (physical connections to insulated components)
1D Conduction

• Basic law of one-dimensional heat conduction (Fourier 1822)

\[ Q = -KA \frac{dT}{dx} \]

where

\( K = \text{thermal conductivity (W/m}°\text{K)} \)
\( A = \text{area} \)
\( \frac{dT}{dx} = \text{thermal gradient} \)
3D Conduction

General differential equation for heat flow in a solid

\[ \nabla^2 T(\vec{r},t) + \frac{g(\vec{r},t)}{K} = \frac{\rho c}{K} \frac{\partial T(\vec{r},t)}{\partial t} \]

where

- \( g(\vec{r},t) \) = internally generated heat
- \( \rho \) = density (kg/m\(^3\))
- \( c \) = specific heat (J/kg\(^\circ\)K)
- \( K/\rho c \) = thermal diffusivity
Simple Analytical Conduction Model

- Heat flowing from \((i-1)\) into \((i)\)

\[
Q_{in} = -KA \frac{T_i - T_{i-1}}{\Delta x}
\]

- Heat flowing from \((i)\) into \((i+1)\)

\[
Q_{out} = -KA \frac{T_{i+1} - T_i}{\Delta x}
\]

- Heat remaining in cell

\[
Q_{out} - Q_{in} = \frac{\rho c}{K} \frac{T_i(j + 1) - T_i(j)}{\Delta t}
\]
Heat Pipe Schematic
Shuttle Thermal Control Components

Typical Radiator Panel
Physical Characteristics

Space Shuttle Active
Thermal Control Subsystem

68 Parallel Flow Tubes
0.131 in. I.D.
SilverTeflon Coating Both Sides
h = 11, e = .76

(One Loop Shown)
Shuttle Thermal Control System Schematic
ISS Radiator Assembly