Spacecraft Thermal Control Systems

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Lesson Objectives:

1. The student will understand thermal control processes
2. The student will be able to calculate thermal balances and equilibrium temperatures
3. The student will be able to size and select thermal control systems.

Outline

- Purpose of thermal control systems
- Review of heat transfer fundamentals
- Space system thermal analysis
  - Equations
  - Models
  - Analysis programs
- Thermal control sub-systems

Purposes of Thermal Control

- To control the operating temperature environment of spacecraft systems
  - Most systems become less reliable when operated outside their design operating environment
  - Propellant freezes
  - Thermal cycling damage
  - Instrument/antenna/camera alignment
  - Instrument requirements for very cold temperatures
- Example operating temperatures – SMAD Table 11-43

Temperature Requirements

- Operating temperature ranges
- Switch-on temperatures
- Non-operating temperature ranges
- Temperature stability
- Temperature uniformity

Typical Spacecraft Design Temperatures

Component/ System	Operating Temperature (C)	Survival Temperature (C)
Digital electronics	0 to 50	-20 to 70
Analog electronics	0 to 40	-20 to 70
Batteries	10 to 20	0 to 35
IR detectors	-269 to –173	-269 to 35
Solid-state particle detectors	-35 to 0	-35 to 35
Momentum wheels	0 to 50	-20 to 70
Solar panels	-100 to 125	-100 to 125

Review of Heat Transfer Fundamentals

- Convection – heat transfer via flowing fluids
- Conduction – heat transfer within materials other than flowing fluids
- Radiation – heat transfer via electromagnetic waves

Convection

$$q = h * A * \Delta T$$

- h = heat transfer coefficient
- Important to spacecraft during launch after fairing separation
- Convective heat transfer is used in some pumped-liquid thermal control systems, especially in manned spacecraft

Conduction

$$q = \frac{kA}{\Delta x}(T_1 - T_2)$$

$$q = \frac{2k\pi L(T_1 - T_2)}{\ln(D_o / D_i)}$$

$$q = \frac{4\pi k R_i R_o (T_1 - T_2)}{(R_o - R_i)}$$

- Rectangular
- Cylindrical
- Spherical
- k is the thermal conductivity

Radiation

$$q = \varepsilon \sigma T^4$$

ε=emissivity at the wavelength mix corresponding to temperature T

σ=Stefan-Bolzmann's constant

= 5.670×10^{-8} W/m^2-K^4

T is temperature in Kelvin

Primary energy transfer mechanism for spacecraft.

Most spacecraft have large radiators to rid themselves of heat.

q is the heat transfer per unit area and T is the surface temperature.

Planck's Equation

$$E_{b\lambda} = \frac{2\pi hc^2}{\lambda^5} * \frac{1}{e^{ch/k\lambda T} - 1}$$

λ=wavelength

h=Planck's constant

c=speed of light

k=Bolzmann's constant

At any temperature above absolute zero, all materials emit thermal (blackbody) radiation.

For a perfect blackbody, the rate of total energy emission and the energy distribution across all wavelengths is strictly a function of the absolute temperature T.

For spacecraft and atmosphere covered planets these distributions are modified, but we usually use the perfect blackbody energy distribution at least as an initial estimate.

Planck's equation gives us the spectral energy distribution of a perfect blackbody. E_b is the energy per unit wavelength of a blackbody.

h=6.6260755e-34 Ws^2 k=1.380658e-23 Ws/K

Kirchoff’s Law

- Monochromatic emissivity = monochromatic absorptivity
- However, emissivity and absorptivity for a given material vary with wavelength
- E.g., white paint α_s=0.4, ε_{IR}=0.8

At a given frequency, Kirchoff’s law says that the emissivity and absorbtivity will be the same.

White paint on spacecraft will have a low equilibrium temperature because it absorbs little energy in the frequencies of the solar spectra, but may have a high emissivity at the IR frequencies associated with the bodies temperature.

Called a selective surface

View Factor

- F_{1-2} is the view factor from surface 1 with area A_1 to surface 2 with area A_2
- $A_1 F_{1-2} = A_2 F_{2-1}$

The view factor is a function of the size, geometry, relative position, and orientation of two surfaces.

Assume a diffuse gray surface condition, I.e., that a particular surface emits equally in all directions and emmissivity and absorptivity are not strong functions of wavelength.

Radiation Equation

- Into deep space $q=\sigma\varepsilon AT^4$
- Between two surfaces

$$q=\sigma\varepsilon_1\varepsilon_2 A_1 F_{1\text{-}2} (T_1^4 - T_2^4)$$

- If one surface is Earth, assume $\varepsilon=1$ and $T=250$ to 260 K

Technically, q= $A(T^4- T^4)$ but T deep space is 4K, $<<T^4$

We can use these equations to calculate the heat transfer between two surfaces, once we calculate the view factor.

Thermal Analysis

- Conservation of energy

$$q_{in} - q_{out} + q_{dissipated} = \frac{\partial E_{\mathrm{int}}}{\partial t}$$

- And $q_{incident}=q_{absorbed} + q_{reflected} + q_{transmitted}$ for transparent materials with no internal dissipation

Thermal balance

energy absorbed + energy dissipated – energy emitted = 0 in steady state.

Dissipated energy is primarily referring to the heat generated by electrical equipment

For transparent materials with no internal dissipation, energy is either absorbed, reflected or transmitted

Steady State Temperature of Insulated Surfaces

$q_{in}=G_s A_p \alpha * \cos\theta$

$q_{out}=\varepsilon\sigma T^4 A_r$

$$T=\left(\frac{G_s\alpha\cos\theta}{\varepsilon\sigma}\right)^{\frac{1}{4}}$$

G_s=solar flux (1418 W/m^2)

The absorbed energy is the solar flux times the area times the absorbtivity times the cosine of the incidence angle.

The solar flux is 1418 W/m^2 on average around earth, but it depends on the distance from the sun and other factors.

The emitted energy is proportional to the area and the surface temperature to the fourth power.

With no internal dissipation, the bottom equation gives us the equilibrium temperature of a surface. Note the relationship of emissivity in the denominator and absorptivity in the numerator.

Space Radiators

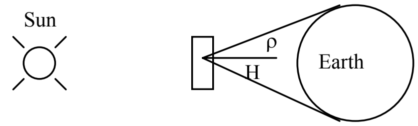
$G_s \alpha * \cos(\theta) + Q_W/A_R - \sigma \varepsilon T^4 = 0$

Q_W is the heat to be rejected

Q_W is the waste heat we are trying to get rid of in a space radiator. We generally orient radiators to minimize the incident radiation.

Using this equation we can determine the temperature of a radiator that is used to eliminate a given amount of energy, or we can determine the amount of energy that will be removed for a radiator at a particular temperature.

Solar Array/Flat Plate Max/Min Temperatures



Energy absorbed includes energy:

- From sun on top surface $Q_{sa}=G_s A \alpha_t \cos\theta$
- Plus Earth IR
- Plus sunlight reflected from Earth

Earth IR Analysis

q_I= Energy flux at Earth's surface
= 237 ± 21 W/m^2

G_I=Energy flux at spacecraft altitude
= $q_I(4\pi R_E^2)/(4\pi(H+R_E)^2) = q_I \sin^2\rho$

$q_{Ia} = q_I \sin^2\rho A \varepsilon_b$ = energy absorbed on the bottom surface

The energy flux at a given altitude is lower than at the surface of the earth by the ratio of the area of the surface of the earth to the area of a sphere with a radius equal to the spacecraft's altitude plus the radius of the earth.

The energy absorbed by the spacecraft is given by the bottom equation. Note that we used the emissivity in this equation because the radiant energy is IR.

Choose the + or the – based on whether you are calculating the maximum or minimum temperature.

Solar Energy Reflected from Earth

$Q_{Aa}=G_s a A \alpha_b K_a \sin^2\rho$

$K_a=0.664+0.521\rho+0.203\rho^2$

a=albedo (percentage of direct solar energy reflected off the Earth = 30 % $\pm$ 5%

The Earth also reflects the sun's energy, called albedo, and it's a strong function of the altitude of the spacecraft, as represented by rho.

Solar Array/Flat Plate Energy Balance

Absorbed energy
$Q_a = G_s A \alpha_t + q_I A \varepsilon_b \sin^2\rho + G_s a A \alpha_b K_a \sin^2\rho$

Emitted energy $Q_e = \sigma \varepsilon_b A T^4 + \sigma \varepsilon_t A T^4$

$q_{absorbed} - q_{emitted} - q_{power\ generated} = 0$

$q_{power\ generated} = G_s A \eta$ where η is the solar array installed efficiency

Summing up

The emitted energy includes emissions from both the top and bottom of the array, which may have different emissivities.

In the energy balance we subtract out the energy produced by the solar array, which is a fraction of the incident solar energy (eta)

Solar Array Maximum/Minimum Temperatures

$$T_{\max} = \left[\frac{G_s \alpha_t + q_I \varepsilon_b \sin^2 \rho + G_s a \alpha_b K_a \sin^2 \rho - \eta G_s}{\sigma(\varepsilon_b + \varepsilon_t)} \right]^{\frac{1}{4}}$$

$$T_{\min} = \left[\frac{q_I \varepsilon_b \sin^2 \rho}{\sigma(\varepsilon_b + \varepsilon_t)} \right]^{\frac{1}{4}}$$

Rearranging the equations, we solve for the equilibrium temperature of the array

The maximum is in full sun

The minimum is for eclipse conditions.

For a given altitude, functions of the absorbtivity and emissivity of the array, and its efficiency.

Spherical Satellite Max/Min Temperatures

$$T_{\max_s} = \left[\frac{A_C G_s \alpha + AFq_I \varepsilon + AFG_s a \alpha K_a + Q_W}{A \sigma \varepsilon} \right]^{\frac{1}{4}}$$

$$T_{\min_s} = \left[\frac{AFq_I \varepsilon + Q_W}{A \sigma \varepsilon} \right]^{\frac{1}{4}}$$

Where A=satellite surface area, A_C is the satellite cross-sectional area, and F is the view factor = (1-cos ρ)/2

Similar analysis

Thermal Property Degradation

- UV radiation degrades solar absorptivity with time
  - Absorptivity increases and reaches an upper limit exponentially with time
- Outgassing, contamination, material instability affect thermo-optical properties

Most surfaces approach a gray-brown color after some time in space.

As absorptivity increases, the spacecraft heats up.

Must consider end of life absorptivity in equilibrium temperature calculations.

Thermal Capacity

- Variation of temperature with time

$$Q = mc_p \frac{\Delta T}{\Delta t} \; or = mc_p \frac{\partial T}{\partial t}$$

- c_p=specific heat capacity of the material

The temperature rise of a material in a given amount of time is called its heat capacity and the proportionality constant is c_p (the specific heat capacity of the material.)

Equation not applicable to phase change situations.

Thermal Control Components

- Materials and coatings
  - Selective surfaces (α_s does not equal ε_{IR})
  - Paints, mirrors, silvered plastics, anodized materials
  - Optical Solar Reflectors (OSR)
    - Second surface mirror (reflector) under a transparent cover (emitter)
  - Silver coated Teflon is much tougher and less expensive, although not as effective

OSRs work because the cover has a very high emissivity, and the metalized reflector reflects a large percentage of the incident radiation (the reflector by itself has a low emissivity)

Quartz over silver

Silver coated teflon is much more commonly used because of its lower cost and higher ruggedness.

Multi-layer Insulation

- Minimizes radiative heat transfer from/to a spacecraft component
- Made of alternate layers of aluminized Mylar or Kapton with a thin net of material between
  - Without air the primary coupling between layers is radiative, not conductive

Multi-layer Insulation

- Modeled at an effective emissivity

$$q = \sigma\varepsilon_{effective}(T_h^4 - T_c^4)$$

- Larger MLI systems generally have lower effective emissivity
- In thermal vacuum tests we must wait until all air has escaped from the MLI blankets (several hours)

Larger MLI systems are more effective because they have fewer seams and penetrations per unit area.

It takes a long time to get the air out of MLI systems during tests and on orbit.

Thermal Control Components (continued)

- Electric heaters
  - Used in cold-biased equipment
  - Controlled by thermostats (local or central)
  - Flat sheet heaters use the Joule effect
- Space radiators
  - Heat exchanger on outer surface radiates waste heat into space

Joule effect

Thermal Control Components (continued)

- Cold plates
  - Structural mount for electronic equipment
  - May use flowing fluids for convective heat transfer
- Doublers
  - Passive aluminum plates that increase heat exchange surface area

Doubler is just an aluminum plate attached to a heat dissipator and a radiator. It provides a heat flow path between the two and increases the area for heat exchange. Works similar to a heat pipe but not as effectively.

Thermal Control Components (continued)

- Phase change devices
  - Used when heat is generated in short bursts
  - Solid absorbs energy while melting

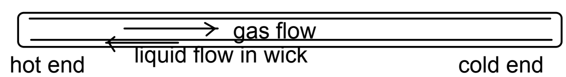
$$q_{pc} = \dot{m}_{pc} H_{pc}$$

Materials absorb and release large amounts of energy during phase changes.

Phase change devices might be used in conjunction with a transmitter that is used infrequently.

Thermal Control Components (continued)

- Heat pipes
  - Used to transfer heat from one area to another
  - Heat at one end evaporates the working fluid, absorbing heat
  - Vaporized working fluid flows to cold end and condenses, releasing heat
  - Wicking material returns fluid to hot end
  - Provide high heat transfer rates even with small temperature differences
  - Difficult to test in one-g environment



Thermal Control Components (continued)

- Louvers
  - Shield radiator surfaces to moderate heat flow to space
- Temperature sensors
  - Thermistors – Semiconductors whose resistance varies with temperature
  - Resistance thermometers – Pure platinum conductor whose resistance changes with temperature

Thermal Control Components (continued)

- Adhesive tapes
- Fillers – increase the heat transfer between contacting surfaces
  - Thin sheets of metal oxide in elastomeric binders
  - Fills voids between contacting surfaces

Adhesive tape is used in the manufacture of MLI

Also used to modify directly the thermo-optical property of a material or structural member

Filler is critical for creating a thermal path, but is difficult to test in the atmosphere.

Thermal Control Components (continued)

- Thermal isolators
  - Low conductivity materials used to isolate instruments and other components from the spacecraft body
- Thermoelectric coolers
  - Electric current induces cooling of junction between dissimilar metals
  - Relatively low efficiency

Thermal Control Components (continued)

- Cryogenic systems
  - Low noise amplifiers, super-conducting materials, and IR detectors require extremely low temperatures (<100 K)
  - Active cooler systems use Stirling or Brayton cycle pumps
  - Passive systems use cryogenic liquids (e.g., liquid Helium) to cool instruments for short missions

Thermal Analyses

- Finite difference models are used for non-linear analysis
  - Temperature prediction
  - Interface heat flux
  - Thermal gradients
  - Temperature vs time plots
- Electrical units often are modeled by Finite Element method (based on the structural FEM) for internal conduction

Thermal Analysis

- Model and analyze the radiation environment first
  - Based on operational attitudes and orientation relative to sun, Earth and on-board equipment
  - Software programs include
    - NEVADA (Turner Associates Consultants)
    - TRASYS (JSC/LMSC, COSMIC)
    - THERMICA (Matra Marconi Space)
    - ESARAD (ALSTROM)

Thermal Analysis (continued)

- Heat transfer model
  - Lumped parameter model of spacecraft components
  - Discrete network of nodes (thermal capacitance) linked by conductors
  - Analogous to electric circuit model
    - Heat flow maps to electrical current
    - Temperature maps to voltage
  - Permits prediction of temperatures within the spacecraft as a function of time

Thermal Analysis (continued)

- Heat transfer models
  - Inputs are geometry, radiation heat flux, electrical power dissipation, conduction and thermal control system performance
  - Prediction models
    - BETA (Boeing)
    - MITAS (LM)
    - SINDA (JSC/LM, COSMIC)
    - ESATAN (ALSTOM)

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