

Introduction to Spacecraft Thermal Design

Develop a fundamental understanding of heat transfer analysis techniques as applied to Earth-based spacecraft with this practical guide. This essential text is written in a tutorial style and provides a how-to manual tailored for those who wish to understand and develop spacecraft thermal analyses. Providing an overview of basic heat transfer analysis fundamentals such as thermal circuits, limiting resistance, MLI, environmental thermal sources and sinks, as well as contemporary space-based thermal technologies, and the distinctions between design considerations inherent to room temperature and cryogenic temperature applications, this is the perfect tool for graduate students, professionals, and academic researchers.

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This work is dedicated to the two women that delivered me to my undergraduate educational institution (freshman year) where this journey began: my mother Rachel Silk and my aunt Maple Skinner.

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Nomenclature

A	Area [m^2]
A	Amps
Alb	Albedo, fraction of Earth-reflected solar energy
A_p	Projected surface area [m^2]
$B_{i,j}$	Fraction of gray body radiation transfer and absorption between surface i and j
Bo	Bond number [$g(\rho_l - \rho_v) \cdot l_c^2 / \sigma_l$]
C	Thermal conductance [W/K], Vacuum line conductance [$\text{Pa} \cdot \text{m}^3/\text{s}$]
CC	Compensation chamber
$^\circ\text{C}$	Degrees Celsius
CHF	Critical heat flux [W/m^2]
COP	Coefficient of performance
CTE	Coefficient of thermal expansion [K^{-1}]
D	Diameter [m]
\dot{E}	Rate of energy transfer [W]
E	Energy [J]
E_b	Blackbody emissive power [W/m^2]
E_{mod}	Modulus of elasticity [MPa]
$E_{\lambda b}$	Blackbody spectral emissive power [$\text{W/m}^2 \cdot \mu\text{m}$]
Eff	Effectiveness [$0 \Leftrightarrow 1.0$]
EIR	Earth IR energy [W/m^2]
$F_{i,j}$	View factor
$\hat{F}_{i,j}$	Fraction of gray body radiation transfer between surface i and j
\mathcal{F}	Radiative transfer factor
FOM	Figure of merit
G	Irradiation [W/m^2]
G_λ	Spectral irradiation [$\text{W/m}^2 \cdot \mu\text{m}$]
H	Magnetic field intensity [$\text{A} \cdot N_{turns}/\text{m}$]
HP	Heat pipe
Hz	Hertz
I	Intensity [$\text{W}/\text{sr} \cdot \text{m}^2$], Current [A]
I_b	Blackbody intensity [W/m^2]
I_λ	Spectral intensity [$\text{W}/\text{sr} \cdot \text{m}^2 \cdot \mu\text{m}$]
IR	Infrared
J	Radiosity [W/m^2]

J	Joules
J_e	Current density [A/m^2]
J_λ	Spectral radiosity [$W/m^2 \cdot \mu m$]
K	Permeability [m^2]
K	Kelvin
KE	Kinetic energy [J]
km	Kilometers
L	Length vector [m]
L, l	Length [m], Honeycomb panel length [m]
L_o	Lorenz number 2.45×10^{-8} [$W \cdot Ohms/K^2$]
LHP	Loop heat pipe
M	Million
N	Newtons, Number
NCG	Non-condensable gas
<i>O</i>	On the order of
<i>OP</i>	Orbital period [minutes]
Q	Energy [J]
\dot{Q}	Heat transfer [W]
\dot{Q}''	Heat flux [W/m^2]
P	Pressure [kPa], Power [W]
PRT	Platinum resistance thermometer
R	Thermal resistance [K/W], Radius [m]
R	Radius on virtual hemisphere
Re	Reynolds number [$\rho \cdot d_h \cdot Vell/\mu$]
R_e	Electrical resistance [Ohms, Ω]
R_{Flow}	Fluid flow resistance [$m^{-1} \cdot s^{-1}$]
R_m	Radius of molecule [m]
RRR	Residual resistivity ratio
S	Shape factor [m]
S_y	Yield strength [MPa]
<i>S.P.</i>	Specific power
STC	Strength-to-thermal-conductivity ratio [MPa/W/m · K]
T	Temperature °C or K
T	Honeycomb panel thickness [m], Tesla [$N/A \cdot m$]
T_c	Transition temperature for super-conducting state [K]
TC	Thermocouple
Torr	0.133322 kPa
TM	Thermistor
<i>TP</i>	Transmission probability
U	Overall heat transfer coefficient [$W/m^2 \cdot K$]
USD	United States dollars
UV	Ultraviolet
V	Voltage
V	Volts

Vel	Velocity [m/s]
Vol	Volume [m ³]
\dot{Vol}	Volume flow rate [m ³ /s]
w, W	Width [m], Honeycomb panel width [m]
W	Watts [J/s]
\dot{W}	Work input [W]
Wb	Weber [T · m ²]
We	Weber number $\left[\rho_v \cdot Vel_{avg}^2 \cdot d_h / \sigma_l \right]$
X_{leak}	Leak rate [Pa · m ³ /s]
\dot{Z}	Throughput [Pa · m ³ /s]
a	Semi-major axis
c_o	Speed of light [2.9979×10^8 m/s]
c_p	Specific heat [J/kg · K]
cm	0.01 meters
dA	Differential surface area [m ²]
d_h	Hydraulic diameter [m]
d_s	Sphere diameter [m]
dB	Decibels
$d\Omega$	Differential solid angle [sr]
e^-	Charge of an electron [-1.602×10^{-19} Coulombs]
f	Friction factor
g	Earth gravitational acceleration [9.8 m/s]
\dot{g}	Energy generation [W]
\dot{g}'''	Energy generation per unit volume [W/m ³]
h	Height [m]
	Fluid enthalpy [kJ/kg], Planck's Constant [6.6256×10^{-34} J · s]
h_{conv}	Convection coefficient [W/m ² · K]
h_f	Head loss [m], Liquid phase enthalpy [kJ/kg]
h_{fg}	Enthalpy of vaporization [kJ/kg]
h_s	Solid phase enthalpy [kJ/kg]
h_{sf}	Enthalpy of fusion [kJ/kg]
k	Thermal conductivity [W/m · K]
k_B	Boltzmann's Constant [1.381×10^{-23} J/K]
k_{eff}	Effective thermal conductivity [W/m · K]
kg	Kilograms
kPa	1,000 N/m ²
l_c	Characteristic length [m]
lbs	Pounds
\dot{m}	Rate of mass change [kg/s], Mass flow rate [kg/s]
m	Mass [kg]
m	Meters
mil	1/100th of an inch
mV	millivolts

mK	milli-Kelvin
$\hat{\mathbf{n}}, n$	Surface normal direction
\dot{q}	Heat transfer [W]
\dot{q}''	Heat flux [W/m^2]
r	Radial length [m]
r_b	Average bubble radius [m]
r_p	Pore radius [m]
s	Seconds
s	Entropy [$\text{J}/\text{kg} \cdot \text{K}$]
s_{arc}	Arc length
sr	Steradians
t	Time [seconds]
th	Thickness [m]
x	Length [m], Fluid quality [$0 \Leftrightarrow 1.0$]
x_{MSR}	Melt-to-solidification ratio [$0 \Leftrightarrow 1.0$]
y	Length [m]
z	Longitudinal length [m]
Ξ	Balance equations coefficient matrix
Φ	Balance equations solution vector
Φ_v	Viscous dissipation
Δ	Difference in value
Λ	Thomson coefficient [V/K]
Ω	Solid angle [sr], Ohms
Π	Peltier coefficient [V]
Γ	Seebeck coefficient [V/K]
α	Absorptivity
β	Beta angle
δ	Ribbon thickness [m], Error
δ_F	Foil thickness [mils]
η	Efficiency
θ	Azimuthal angle [Degs, $^\circ$], Inclination angle [Degs, $^\circ$]
ε	Emissivity
ε^*	Effective emissivity
γ	Solar constant to surface normal angle [Degs, $^\circ$]
λ	Wavelength [μm], Lambda point for transition of He into the superfluid state
λ_{MFP}	Mean free path [m]
ζ_{load}	Duty cycle for environmental thermal loading
ρ	Density [kg/m^3], Reflectivity
ρ_e	Electrical resistivity [$\Omega \cdot \text{m}$]
ρ_l	Liquid density [kg/m^3]
ρ_v	Vapor density [kg/m^3]
ω	Honeycomb cell size [m]

τ	Transmissivity
ϕ	Cylindrical circumferential direction, Circumferential angle [Degs, °]
ϕ	Porosity [0 \leftrightarrow 1.0], Electrostatic voltage [V]
μ_l	Liquid viscosity [kg/m · s]
μ	Product of universal gravitational constant and mass of earth [3.98603 $\times 10^{14}$ m ³ /s ²]
μ -g	Microgravity
μ_{J-T}	Joule–Thomson coefficient [K/kPa]
μ_o	Magnetic permeability [Wb/A · m]
μm	Microns [10^{-6} m]
π	3.14159265359
σ	Stefan Boltzmann constant [5.67×10^{-8} W/m ² · K ⁴], Honeycomb ribbon extension factor
σ_{dc}	DC electrical conductivity [$\Omega^{-1} \cdot \text{m}^{-1}$]
σ_e	Electrical conductivity [$\Omega^{-1} \cdot \text{m}^{-1}$]
σ_l	Liquid surface tension [N · m]

Subscripts

<i>Adia</i>	Adiabatic
<i>C,c</i>	Cold
<i>CC</i>	Compensation chamber
<i>CHF</i>	Critical heat flux
<i>E</i>	Endpoint
<i>EIR</i>	Earth-IR
<i>F</i>	Foils
<i>FB</i>	Film boiling
<i>FE</i>	Finite element
<i>Fermi</i>	Fermi-based value
<i>H,h</i>	Hot, High
<i>HL</i>	Heat leak
<i>HX</i>	Heat exchanger
<i>Iso</i>	Isothermal
<i>L</i>	Honeycomb panel height,Low
<i>LHP</i>	Loop heat pipe
<i>LRL</i>	Liquid return line
<i>MHF</i>	Minimum heat flux
<i>MLI</i>	Multi-layer insulation
<i>NC</i>	Natural convection
<i>OFF</i>	Off operating state
<i>ON</i>	On operating state
<i>ONB</i>	Onset of nucleate boiling
<i>P</i>	Packing
<i>PCM</i>	Phase-change material
<i>PEL</i>	Peltier
<i>PV</i>	Photovoltaic
<i>RNB</i>	Rapid nucleate boiling
<i>S</i>	Shape, Solar
<i>T</i>	Temperature, Honeycomb panel thickness
<i>Thom</i>	Thomson effect
<i>TS</i>	Thermal strap
<i>VL</i>	Vapor line
<i>W</i>	Honeycomb panel width
<i>a</i>	Apogee

<i>a,b,c</i>	Nodal position in planar grid
<i>abs</i>	Absorption, absorber
<i>actual</i>	Actual value
<i>avg</i>	Average
<i>b</i>	Blackbody, Perigee
<i>boil</i>	Boiling
<i>cap</i>	Capillary
<i>comp</i>	Compressor
<i>con</i>	Condenser
<i>cond</i>	Conduction
<i>couple</i>	Couple level
<i>eff</i>	Effective
<i>elec</i>	Electrical
<i>emb</i>	Embedded
<i>ent</i>	Entrainment
<i>end</i>	Endpoint
<i>env</i>	Environmental
<i>evap</i>	Evaporator
<i>exit</i>	At outlet location
<i>final</i>	Final or end state
<i>g</i>	Generated, Gravitational
<i>h</i>	Convection, Isenthalpic
<i>high</i>	High value, high end
<i>i</i>	Inner
<i>in</i>	Inflow/Ingoing
<i>init</i>	Initial
<i>inlet</i>	Entrance
<i>int</i>	Interface
<i>isen</i>	Isentropic
<i>joule</i>	Joule heating
<i>k</i>	Conductivity
<i>l,liq</i>	Liquid
<i>lat</i>	Lattice
<i>link</i>	Thermal coupling
<i>load</i>	Heat load value
<i>low</i>	Lower value
<i>lower</i>	Lower end
<i>m</i>	Mean
<i>max</i>	Maximum
<i>melt</i>	Value during melting
<i>min</i>	Minimum
<i>mod</i>	Module level
<i>net</i>	Net difference
<i>o</i>	Outer
<i>out</i>	Outwards, rejected, outflow/outgoing

<i>p</i>	Projected
<i>par</i>	Particle
<i>para</i>	Parallel
<i>pri</i>	Primary
<i>pump</i>	At mechanical pump
<i>r</i>	Real, Radial direction
<i>rad</i>	Radiator, radiation
<i>recup</i>	Recuperator
<i>ref</i>	Reflected
<i>rej</i>	Rejected
<i>s</i>	Isentropic value
<i>sat</i>	Saturation
<i>sec</i>	Secondary
<i>ser</i>	Serial
<i>sink</i>	Circuit cold temperature location
<i>sol</i>	Solid
<i>st</i>	Stored
<i>sup</i>	Superheat
<i>surf</i>	Surface
<i>tot</i>	Total
<i>tp</i>	Triple point
<i>tran</i>	Transition point
<i>trans</i>	Transmitted
<i>turb</i>	Turbine
<i>upper</i>	Higher end
<i>v,vap</i>	Vapor
<i>wall</i>	At wall location
<i>waste</i>	Excess, non-usable
<i>wick</i>	Wick structure
<i>wire</i>	Wire/s
<i>x</i>	Cartesian <i>x</i> direction
<i>y</i>	Cartesian <i>y</i> direction
<i>z</i>	Cartesian <i>z</i> direction, Cylindrical longitudinal direction
λ	Spectral
2- Φ	Multiphase
θ	Cylindrical circumferential direction
∞	Infinite distance
+	Positive value
–	Negative value