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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Tables

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 $\left[g(\rho_l - \rho_v) \cdot l_c^2/\sigma_l\right]$
C	Thermal conductance [W/K], Vacuum line conductance [Pa · m^3/s]
CC	Compensation chamber
°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 [W/m^2 · μm]
Eff	Effectiveness [0 ⇔ 1.0]
EIR	Earth IR energy [W/m^2]
$\mathrm{F}_{i,\,j}$	View factor
$\hat{\mathrm{F}}_{i,j}$	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 [W/m^2 · μm]
H	Magnetic field intensity [A · N_{turns}/m]
HP	Heat pipe
Hz	Hertz
I	Intensity [W/sr · m^2], Current [A]
I_b	Blackbody intensity [W/m^2]
I_λ	Spectral intensity [W/sr · m^2 · μm]
IR	Infrared
J	Radiosity [W/m^2]

J	Joules
J_e	Current density [A/m^2]
J_λ	Spectral radiosity [W/m^2 · μm]
$\boldsymbol{K}$	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 · Ohms/K^2]
LHP	Loop heat pipe
M	Million
N	Newtons, Number
NCG	Non-condensable gas
O	On the order of
OP	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 [$\rho \cdot d_h \cdot Vel/\mu$]
R_e	Electrical resistance [Ohms, Ω]
R_{Flow}	Fluid flow resistance [m^{-1} · s^{-1}]
R_m	Radius of molecule [m]
RRR	Residual resistivity ratio
S	Shape factor [m]
S_y	Yield strength [MPa]
$S.P.$	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 · m]
T_c	Transition temperature for super-conducting state [K]
TC	Thermocouple
Torr	0.133322 kPa
TM	Thermistor
TP	Transmission probability
U	Overall heat transfer coefficient [W/m^2 · 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 [$T \cdot m^2$]
We	Weber number $\left[\rho_v \cdot Vel_{avg}^2 \cdot d_h/\sigma_l\right]$
X_{leak}	Leak rate [$Pa \cdot m^3/s$]
$\dot{Z}$	Throughput [$Pa \cdot m^3/s$]
a	Semi-major axis
c_o	Speed of light [2.9979×10^8 m/s]
c_p	Specific heat [$J/kg \cdot K$]
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 [$W/m^2 \cdot K$]
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 [$W/m \cdot K$]
k_B	Boltzmann's Constant [1.381×10^{-23} J/K]
k_{eff}	Effective thermal conductivity [$W/m \cdot K$]
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 [J/kg · K]
s_{arc}	Arc length
sr	Steradians
t	Time [seconds]
th	Thickness [m]
x	Length [m], Fluid quality [0 ⇔ 1.0]
x_{MSR}	Melt-to-solidification ratio [0 ⇔ 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, °], Inclination angle [Degs, °]
ε	Emissivity
ε^*	Effective emissivity
γ	Solar constant to surface normal angle [Degs, °]
λ	Wavelength [μm], Lambda point for transition of He into the superfluid state
λ_{MFP}	Mean free path [m]
ξ_{load}	Duty cycle for environmental thermal loading
ρ	Density [kg/m^3], Reflectivity
ρ_e	Electrical resistivity [Ω · 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 ⇔ 1.0], Electrostatic voltage [V]
μ_l	Liquid viscosity [kg/m · s]
μ	Product of universal gravitational constant and mass of earth [3.98603×10^{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} $W/m^2 \cdot K^4$], Honeycomb ribbon extension factor
σ_{dc}	DC electrical conductivity [$\Omega^{-1} \cdot m^{-1}$]
σ_e	Electrical conductivity [$\Omega^{-1} \cdot m^{-1}$]
σ_l	Liquid surface tension [N · m]

Subscripts

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

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

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