Radiation Heat Transfer Notes

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PREFACE

These Notes are intended for a 40-lecture-hour course in radiation heat transfer. The emphasis is on developing the information and skills to formulate and solve engineering heat transfer problems. The Notes are in two main parts. After an introduction to the fundamental concepts of spectral and total intensity and flux and fractional functions, the first part develops the subject of surface-to-surface radiation heat transfer. Surface radiation characteristics needed to incorporate radiation heat transfer rates into a first law of thermodynamics heat balance are defined and related to fundamental physical properties where appropriate via electromagnetic theory. The experimental techniques developed to measure the characteristics are briefly described. Then the engineering enclosure problem is addressed. Radiosity-irradiation formulations, the network method, the mirror-image concept, and the powerful Monte Carlo algorithm are described. The second part considers the subject of radiation transfer in a participating medium. Gas radiation properties are defined, and their measurement described. The engineering enclosure problem with a well-stirred and thus homogeneous absorbing-emitting medium is treated using radiosity-irradiation and network representations. The Monte Carlo algorithm is extended to cover an absorbing-emitting-scattering medium that can be homogeneous or inhomogeneous. Geometrical and spectral complexities and simplifications are considered, primarily for the slab. Differential formulations are briefly described. Narrow- and wide-band scaling for inhomogeneous molecular gases complete the second part concerned with gas radiation. The Notes conclude with a short section on heat transfer by radiation and conduction or convection.

To keep within the confines of a 40-hour course, the Notes keep to the engineering radiation heat transfer discipline. Even so, there is an attempt to develop two levels of problem-solving skills. The first level, of great importance to practicing engineers, is what may be termed finite-element thermal system analysis. This skill is emphasized first in the development, in Sections 3 and 6, and in the early portion of Section 8. The second level is differential-element or so-called exact analysis. While this level is almost totally absent from Sections 3 and 6, the bulk of Sections 7 and 8 are devoted to it.

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PRINCIPAL SYMBOLS

a	length between surface roughness asperities, μm
A, A_i, A_j	area, m^2
A_c	cross-sectional area, m^2
A_k	band absorption of kth band, cm^{-1}
A_k^*	band absorptance at kth band, dimensionless
A^+	Van Driest's constant, 26
b	thickness, m; also Mei and Squire constant, 3.4
B	black body heat flux, W/m^2, or the spectral black body heat flux, $W/m^2\ cm^{-1}$ or W/m^2 μm; also the rotational constant, cm^{-1}
$\underline{B}$	magnetic induction
c	velocity of light, 2.997925×10^8 m/s
c_1	first radiation constant, 3.7415×10^{-16} J m^2/s
c_2	second radiation constant, 1.4388 cm K
c_f	skin friction coefficient
c_p	specific heat at constant pressure, J/kg K
C^*	channel emissivity, dimensionless
d	spectral line spacing, cm^{-1}
D	diameter, m; also optical collision diameter
$\underline{D}$	electric induction
E	energy, J or eV
E_n	exponential integral of order n
$\underline{E}$	electric field strength
f	function of fractional function; also friction factor
f_e	external fractional function, dimensionless

f_i	internal fractional function, dimensionless
F	collision frequency, s^{-1}; also entry length factor
F_{i-j}	shape factor from area i to area j, dimensionless
$\mathscr{F}_{i-j}$	transfer factor from area i to area j, dimensionless
g	statistical weight
G	normal irradiation of a beam, $\int I d\Omega$, W/m^2
G_{i-j}	area-shape-factor product, $A_i F_{i-j}$, m^2
$\mathscr{G}_{i-j}$	area-transfer-factor product $A_i \mathscr{F}_{i-j}$; also the area-to-volume or volume-to-volume quantity, m^2
h	Planck's constant, 6.6256×10^{-34} Js
h_c	convective heat transfer coefficient
h_r	radiative heat transfer coefficient
$\hat{h}$	specific enthalpy, J/kg
$\underline{H}$	magnetic field strength
I	intensity, W/m^2 sr; also the spectral intensity, W/m^2 cm^{-1} sr or W/m^2 μm sr
I_b	black body intensity (units as above)
$\underline{j}$	electric current density
k	absorptive index; also Boltzmann's constant, 1.38054×10^{-23} J/K
k_a	absorption coefficient, m^{-1}
k_e	extinction coefficient, m^{-1}
k_s	scattering coefficient, m^{-1}
K	thermal conductivity, W/m K; also the second moment of the radiant intensity, also von Karman's constant, 0.4
K_R	radiation conductivity, W/m K
K*	radiation kernel

L	length, m
L_{mb}	mean beam length, m
L_{mbg}	geometric mean beam length, m
m	mass, kg
$\dot{m}$	mass flow rate, kg/s
n	refractive index
N	radiation conductivity to molecular conductivity ratio, dimensionless
N_v	number density, m^{-3}
Nu	Nusselt number
P	pressure, N/m^2 or atm
$\mathcal{P}$	perimeter, m
P_e	dimensionless equivalent line broadening pressure
P_i	partial pressure of species i
Pr_m	Prandtl number
Pr_t	turbulent Prandtl number
q	heat flux, W/m^2
q^+	radiosity, W/m^2
q^-	irradiation, W/m^2
Q	heat energy, J
$\dot{Q}$	heat flow, W
Q_a	absorption efficiency
Q_e	extinction efficiency
Q_s	scattering efficiency

r_e	electrical resistivity, ohm cm
r_{WL}	wall-layer thickness-to-hydraulic diameter ratio, dimensionless
R	radius, m
R_t	turbulent Reynolds number
Re	Reynolds number based upon hydraulic diameter
s	slant path length, m
S	integrated line intensity; also mean radiant intensity
t	time, s; also optical depth, dimensionless
t_H	optical depth at band head, dimensionless
T	temperature, K
T_e	environmental temperature or equivalent mean temperature, K
T_g	gas temperature, K
T_r	mean radiant temperature, K
T_w	wall temperature, K
u	sec θ; also cos θ; also velocity in x-direction, m/s
U	unit step function; also average velocity in x-direction, m/s
v	cos θ
V	detector signal, volts
x	length coordinate, m; also mole fraction
X	density-path-length product, kg/m^2 or g/m^2
y	length coordinate, m
z	length coordinate, m
α	absorptivity; also thermal diffusivity, m^2/s

α_k	integrated band intensity, $cm^{-1}/(g/m^2)$
α_m	molecular thermal diffusivity, m^2/s
β	line-width-to-spacing parameter; also dimensionless temperature ratio
γ	line half-width, cm^{-1}; also Euler's constant 0.5772156...
δ	thickness or half thickness, m; also vibrational quantum number change
ε	emissivity
ε_{eff}	heat exchanger effectiveness
ε_H	eddy diffusivity for heat
ε_M	eddy diffusivity for momentum
η	line-width-to-spacing parameter; also fin effectiveness
θ	polar angle
κ	mass absorption coefficient, $(kg/m^2)^{-1}$
λ	wavelength, μm
μ	$\cos\theta$
μ_m	magnetic permeability
ν	wavenumber, cm^{-1}; also kinematic viscosity, m^2/s
ν_f	frequency, s^{-1}
ν_m	molecular kinematic viscosity, m^2/s
π	3.1415926...
ρ	reflectivity; also density kg/m^3
ρ_a	absorber partial density, kg/m^3
ρ_e	electric change density
σ	Stefan-Boltzmann constant, 5.67×10^{-8} $W/m^2\ K^4$

σ_e	electrical conductivity
σ_r	surface roughness, μm
τ	transmissivity
$\tau_{H,k}$	optical depth at band head
τ_{WL}	wall layer transmissivity
ϕ	azimuthal angle
Φ	hot band line spacing parameter, dimensionless
Ψ	hot band intensity parameter, dimensionless
ω	exponential band width, cm^{-1}
ω_s	albedo for single scatter
Ω	solid angle, sr

CONTENTS

1 *INTRODUCTION*

1.A Radiation Heat Transfer in Thermal Design. When does one consider radiation heat transfer, and when does one not? One does not consider radiation inside of a fluid that is highly opaque to the source spectrum. In a fluid such as water, the radiation is merely a contributor to what we know as thermal conductivity. Similarly one does not consider radiation inside a fluid that is perfectly transparent to the source spectrum. If there is no physical mechanism by which the fluid can absorb energy from radiation passing through it, then it follows from thermodynamics that it cannot emit radiation either, and it cannot be either heated or cooled by radiation. Such a fluid is said to be diathermanous. The walls surrounding such a fluid, however, may exchange heat radiation, but only if they are not isothermal. Thus one does not ordinarily consider radiation within the passages of a heat exchanger containing oil, water, or air. The first two are opaque. The last is diathermanous.

When two walls at different temperatures are in view of one another or one wall is in view of a participating medium (one neither opaque nor diathermanous) the radiation heat flux (W/m^2) tends to be high when $\Delta\sigma T^4$ is high, where σ is the Stefan-Boltzmann constant 5.6697×10^{-8} $W/m^2 K^4$. When ΔT is small compared to the absolute temperature level, $\Delta\sigma T^4$ can be written $4\sigma T_m^{\ 3}\Delta T$ where T_m is the mean temperature level.

At 300 K the value for $4\sigma T_m^3$ is slightly over 6 W/m^2 K (circa 1 Btu/hr ft^2 R) on the same order as a natural convection heat transfer coefficient. At T_m = 2000 K the value is nearly 300 times greater. From such a value, 1800 W/m^2 K, one can see why radiation contributes to film boiling heat transfer. Radiation is important when temperatures are high, distances are large (because convective heat transfer coefficients go like passage size D as $D^{-1/5}$ for turbulent flow or D^{-1} for laminar flow), or under vacuum conditions when convective heat transfer coefficients are low because of the low fluid density.

1.B Thermodynamic Surfaces and Surface Systems. The thermal designer needs to know surface heat fluxes adjacent to the interface between phases. When one phase is highly opaque, and the other is not, the opaque surface system concept is used. Figure 1-1 depicts a surface system. The s-surface lies just outside the highly opaque phase; the u-surface lies just within it. The m-surface lies sufficiently below the phase interface so that (1) no radiation crossing the s and u surfaces is transmitted to the m-surface, and (2) the radiation flux crossing the m-surface is given by the radiation-diffusion equation and is included with the conduction. For no flow through the surfaces and negligible transient heat storage in the mass between the m and u surfaces, one has

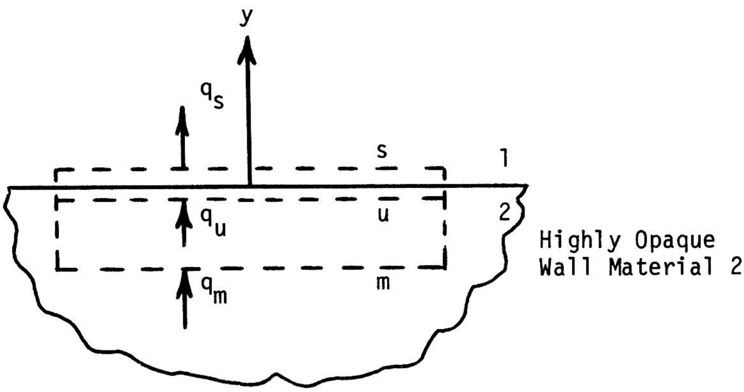

FIGURE 1-1

The s, u, and m Thermodynamic Boundaries
for a Surface System