

Radiation Heat Transfer Notes

D. K. Edwards

A Hemisphere Engineering Paperback

8263556

TIC 124
E1

RADIATION HEAT TRANSFER NOTES

D. K. EDWARDS

University of California, Los Angeles



E8263556

● **HEMISPHERE PUBLISHING CORPORATION**
Washington New York London

906

00000000

RADIATION HEAT TRANSFER NOTES

Copyright © 1981 by Hemisphere Publishing Corporation. All rights reserved.
Printed in the United States of America. No part of this publication may be
reproduced, stored in a retrieval system, or transmitted, in any form or by
any means, electronic, mechanical, photocopying, recording, or otherwise,
without the prior written permission of the publisher.

1 2 3 4 5 6 7 8 9 0 B C B C 8 9 8 7 6 5 4 3 2 1

Library of Congress Cataloging in Publication Data

Edwards, D. K. (Donald Kenneth), date
Radiation heat transfer notes.

Includes bibliographies and index.

1. Heat—Radiation and absorption. I. Title.

TJ260.E318 621.402'2 81-4539

ISBN 0-89116-231-3 AACR2

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.

Grateful acknowledgment is made to Mrs. Phyllis Gilbert, who typed the Notes. Professor Frank W. Schmidt reviewed the text for incorporation into the *Heat Exchanger Design Handbook* and made several helpful suggestions. Messrs. J. C. McMurrin and W. A. Menard helped considerably in proofreading

the typescript. Mr. Patrick Hubbard assisted with the drafting of many of the illustrations. The help of graduate students who participated in the radiation heat transfer course at UCLA over the past several years is also gratefully acknowledged.

D. K. Edwards

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 k th band, cm^{-1}
A_k^*	band absorptance at k th 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, $\text{W}/\text{m}^2 \text{ cm}^{-1}$ or $\text{W}/\text{m}^2 \mu\text{m}$; also the rotational constant, cm^{-1}
\underline{B}	magnetic induction
c	velocity of light, $2.997925 \times 10^8 \text{ m/s}$
c_1	first radiation constant, $3.7415 \times 10^{-16} \text{ J m}^2/\text{s}$
c_2	second radiation constant, 1.4388 cm K
c_f	skin friction coefficient
c_p	specific heat at constant pressure, $\text{J}/\text{kg K}$
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
\mathcal{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
\mathcal{G}_{i-j}	area-transfer-factor product $A_i \mathcal{F}_{i-j}$; 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
H	magnetic field strength
I	intensity, W/m^2 sr; also the spectral intensity, $W/m^2 \text{ cm}^{-1}$ sr or $W/m^2 \text{ }\mu\text{m}$ 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, $W/m \text{ K}$; also the second moment of the radiant intensity, also von Karman's constant, 0.4
K_R	radiation conductivity, $W/m \text{ K}$
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
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

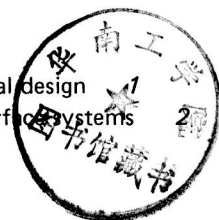
r_e	electrical resistivity, ohm cm
r_{WL}	wall-layer thickness-to-hydraulic diameter ratio, dimensionless
R	radius, m
R_t	turbulent Reynolds number
Re	Reynolds number based upon hydraulic diameter
s	slant path length, m
S	integrated line intensity; also mean radiant intensity
t	time, s; also optical 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	$\sec \theta$; also $\cos \theta$; also velocity in x-direction, m/s
U	unit step function; also average velocity in x-direction, m/s
v	$\cos \theta$
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, $\text{cm}^{-1}/(\text{g}/\text{m}^2)$
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, $(\text{kg}/\text{m}^2)^{-1}$
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 charge density
σ	Stefan-Boltzmann constant, $5.67 \times 10^{-8} \text{ W}/\text{m}^2 \text{ K}^4$

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

Preface	<i>vii</i>
Principal Symbols	<i>ix</i>
1 INTRODUCTION	1
1.A Radiation heat transfer in thermal design	
1.B Thermodynamic surfaces and surface systems	
1.C Radiant intensity and flux	5
1.D Black-body radiation	8
1.E Fractional functions	11
References	16
Exercises	17
2 SURFACE RADIATION CHARACTERISTICS	19
2.A Introduction to surface characteristics	19
2.B Absorption and emission characteristics	20
2.C Measurement of absorption and emission characteristics	25
2.D Reflection and transmission characteristics	29
2.E Measurement of reflection and transmission characteristics	33
2.F Electromagnetic theory and the Fresnel relations	36
2.G Some useful approximations	46
2.H Polarization	54
2.I Thermal radiation characteristics in thermal design	61
References	80
Exercises	86
3 RADIATION TRANSFER BETWEEN PERFECTLY DIFFUSE SURFACES	93
3.A Shape Factors	93
3.B Radiosity-irradiation formulations	107
3.C Refractory surfaces	116
3.D The radiation network	117
3.E Selected working relations	123
3.F Diffuse-walled passages	137
References	146
Exercises	149



4 RADIATION TRANSFER BETWEEN NONDIFFUSE WALLS 157

- 4.A Specular and imperfectly diffuse surfaces 157
- 4.B The mirror image concept 158
- 4.C The Monte Carlo algorithm 161
- 4.D Specular-walled passages 167
- 4.E Surface models 177
- 4.F Rough-walled passages 184
- References 187
- Exercises 191

5 GAS RADIATION PROPERTIES 195

- 5.A The equation of transfer 195
- 5.B Measurement of gas radiation properties 200
- 5.C Qualitative remarks on the physics of gas radiation 206
- 5.D Spectral, band, and total property definitions 209
- 5.E Molecular gas radiation properties 220
- 5.F Gas mixtures 232
- References 236
- Exercises 239

6 RADIATION TRANSFER WITH AN ISOTHERMAL GAS 245

- 6.A Heat transfer at a black wall 245
- 6.B The mean beam length concept 246
- 6.C Wall layer transmission 253
- 6.D Radiosity-irradiation formulation at an isothermal gas-filled-enclosure wall 254
- 6.E The radiation network with a gas 256
- 6.F Some useful results 260
- 6.G Sample calculation 266
- 6.H Monte Carlo solution 269
- References 274
- Exercises 276

7 NONISOTHERMAL GAS RADIATION 281

- 7.A Solution of the equation of transfer 281
- 7.B Geometrical considerations 286
- 7.C The slab geometry 289
- 7.D Differential formulations 294
- 7.E Spectral considerations, scaling approximations 307
- 7.F Molecular gas radiation in the slab 311
- References 321
- Exercises 323

8 RADIATION ACTING WITH CONDUCTION OR CONVECTION 329

- 8.A Combined phenomena 329**
- 8.B Thermal network analysis 330**
- 8.C Radiation-cooled transient heating or cooling 338**
- 8.D Radiant heat exchanger 339**
- 8.E The radiating fin 341**
- 8.F Linearized radiation and conduction around the hollow cylinder 346**
- 8.G Convection of a radiation molecular gas 353**
 - References 363**
 - Exercises 366**

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 $5.6697 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$. 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 $6 \text{ W/m}^2 \text{ K}$ (circa $1 \text{ Btu/hr ft}^2 \text{ R}$) on the same order as a natural convection heat transfer coefficient. At $T_m = 2000 \text{ K}$ the value is nearly 300 times greater. From such a value, $1800 \text{ W/m}^2 \text{ K}$, 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

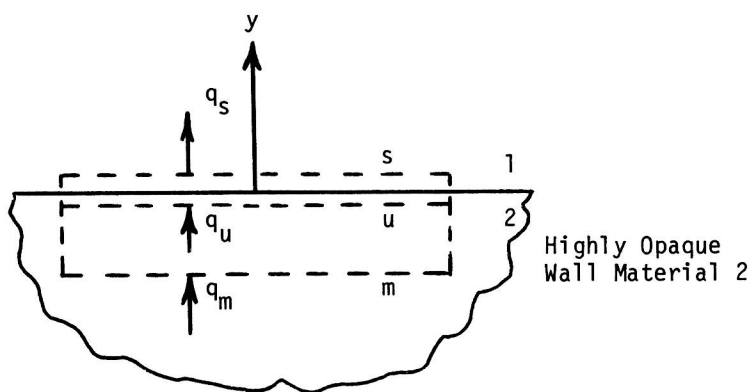


FIGURE 1-1

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