## MICHAEL F. MODEST

# THIRD EDITION RADIATIVE HEATTRANSFER



# RADIATIVE HEAT TRANSFER

#### Third Edition

TANIME RAL COT CONS NO	SEP IS HOS
LEUNS REPTING OF	FRU VEN
07-07	
03634	

Michael F. Modest The University of California at Merced



GIFT OF THE ASIA FOUNDATION NOT FOR RE-SALE QUÀ TẶNG CỦA QUỸ CHÂU Á KHÔNG ĐƯỢC BÁN LẠI

**Academic Press** 

New York San Francisco London

Academic Press is an imprint of Elsevier The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK Radarweg 29, PO Box 211, 1000 AE Amsterdam, The Netherlands

First edition 1993 Second edition 2003 Third edition 2013

Copyright © 2013 Elsevier Inc. All rights reserved

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.

Permissions may be sought directly from Elseviers Science & Technology Rights Department in Oxford, UK: phone (+44) (0) 1865 843830; fax (+44) (0) 1865 853333; email: permissions@elsevier.com. Alternatively you can submit your request online by visiting the Elsevier web site at http://elsevier.com/locate/permissions, and selecting Obtaining permission to use Elsevier material.

#### Notices

No responsibility is assumed by the publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein.

#### Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

#### British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

#### ISBN: 978-0-12-386944-9

For information on all Academic Press publications visit our website at store.elsevier.com

Printed and bound in USA

13 14 15 16 17 10 9 8 7 6 5 4 3 2 1



**BOOK AID** International Sabre Foundation

### ABOUT THE AUTHOR

Michael F. Modest was born in Berlin and spent the first 25 years of his life in Germany. After receiving his Dipl.-Ing. degree from the Technical University in Munich, he came to the United States, and in 1972 obtained his M.S. and Ph.D. in Mechanical Engineering from the University of California at Berkeley, where he was first introduced to theory and experiment in thermal radiation. Since then, he has carried out many research projects in all areas of radiative heat transfer (measurement of surface, liquid, and gas properties; theoretical modeling for surface transport and within participating media). Since many laser beams are a form of thermal radiation, his work also encompasses the heat transfer aspects in the field of laser processing of materials.

For several years he has taught at Rensselaer Polytechnic Institute and the University of Southern California, and for 24 years was a Professor of Mechanical Engineering at the Pennsylvania State University. Today Dr. Modest is the Shaffer and George Professor of Engineering at the University of California, Merced, the 10th campus of the University of California system, and the first newly established research university of the 21st century. He is a fellow of the American Society of Mechanical Engineers, and an associate fellow of the American Institute of Aeronautics and Astronautics. Dr. Modest and his wife Monika reside in Merced, CA.

## CONTENTS

Prefa	ce to the Third Edition	xiv
List o	of Symbols	xvii
1 F1	undamentals of Thermal Radiation	1
1.1	Introduction	. 1
1.2	The Nature of Thermal Radiation	. 3
1.3	Basic Laws of Thermal Radiation	. 4
1.4	Emissive Power	. 5
1.5	Solid Angles	. 11
1.6	Radiative Intensity	. 13
1.7	Radiative Heat Flux	. 15
1.8	Radiation Pressure	. 17
1.9	Visible Radiation (Luminance)	. 18
1.10	Radiative Intensity in Vacuum	. 20
1.11	Introduction to Radiation Characteristics of Opaque Surfaces	. 21
1.12	Introduction to Radiation Characteristics of Gases	. 23
1.13	Introduction to Radiation Characteristics of Solids and Liquids	. 24
1.14	Introduction to Radiation Characteristics of Particles	. 25
1.15	The Radiative Transfer Equation	. 26
1.16	Outline of Radiative Transport Theory	. 27
Refer	ences	. 28
Probl	ems	. 29
2 P.	adiative Property Predictions from	
Z No	remeanatic Ways Theory	~
Elect.	Introduction	31
2.1		. 31
2.2	The Macroscopic Maxwell Equations	. 32
2.3	Electromagnetic Wave Propagation in Unbounded Media	. 32
2.4	Polarization	. 37
2.5	Reflection and Transmission	. 42
2.6	Theories for Optical Constants	. 57
Refere	ences	. 60
Proble	ems	. 60

3	Radiative Properties of Real Surfaces	61
3.1	Introduction	. 6
3.2	Definitions	. 62
3.3	Predictions from Electromagnetic Wave Theory	. 73
3.4	Radiative Properties of Metals	. 75
3.5	Radiative Properties of Nonconductors	. 83
3.6	Effects of Surface Roughness	. 89
3.7	Effects of Surface Damage and Oxide Films	. 93
3.8	Radiative Properties of Semitransparent Sheets	. 95
3.9	Special Surfaces	. 101
3.1	0 Experimental Methods	. 105
Re	ferences	. 118
Pro	oblems	. 123
A	View Factors	129
4.1	Introduction	120
4.2	Definition of View Factors	131
43	Methods for the Evaluation of View Factors	134
4.4	Area Integration	135
4.5	Contour Integration	. 138
4.6	View Factor Algebra	. 143
4.7	The Crossed-Strings Method	. 147
4.8	The Inside Sphere Method	. 151
4.9	The Unit Sphere Method	. 153
Re	ferences	154
		104
Pro	blems	154
Pro	Padiativa Exchange Between Crev Diffuse Surfaces	155
Pro <b>5</b>	Radiative Exchange Between Gray, Diffuse Surfaces	154 155 160
Pro 5 5.1	Radiative Exchange Between Gray, Diffuse Surfaces	154 155 160 160
Pro 5 5.1 5.2 5.3	Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray Diffuse Surfaces	<b>160</b> 160 160
Pro 5 5.1 5.2 5.3 5.4	Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy	154 155 160 160 165 173
Pro 5 5.1 5.2 5.3 5.4 5.5	Biblems       Introduction         Radiative Exchange Between Black Surfaces       Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces       Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy       Radiation Shields	104 155 160 160 165 173 176
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6	Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations	104 155 160 160 165 173 176 178
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref	Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations	104 155 160 160 160 165 173 176 178 188
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro	<b>Radiative Exchange Between Gray, Diffuse Surfaces</b> Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems	104 155 160 160 165 173 176 178 188 188
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro	Biblems         Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems	104 155 160 160 165 173 176 178 188 188
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6	Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems         Radiative Exchange Between Partially Specular	104 155 160 160 165 173 176 178 188 188
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6 Graa	Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems         Radiative Exchange Between Partially Specular         y Surfaces         Introduction	104 155 160 160 165 173 176 178 188 188 188
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6 Gra 6.1 6.2 6.1	Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         Elems         Radiative Exchange Between Partially Specular         y Surfaces         Introduction         Solution Methods For the Governing Integral Equations	104 155 160 160 160 165 173 176 178 188 188 188 188
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6 Gra 6.1 6.2 6.3	Adiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems         Radiative Exchange Between Partially Specular         ty Surfaces         Introduction         Specular View Factors         Enclosures with Partially Specular Surfaces	104 155 160 160 160 165 173 176 178 188 188 188 188 188 197 197 198
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6 Gra 6.1 6.2 6.3 6.4	Biblems         Radiative Exchange Between Gray, Diffuse Surfaces         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems         Radiative Exchange Between Partially Specular         ty Surfaces         Introduction         Specular View Factors         Enclosures with Partially Specular Surfaces         Electrical Network Analogy	104 155 160 160 160 165 173 176 178 188 188 188 188 188 197 197 198 202
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6 Gra 6.1 6.2 6.3 6.4 6.5	Biblems         Radiative Exchange Between Gray, Diffuse Surfaces         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems         Radiative Exchange Between Partially Specular         ty Surfaces         Introduction         Specular View Factors         Enclosures with Partially Specular Surfaces         Electrical Network Analogy         Radiation Shields	104 155 160 160 165 173 176 178 188 188 188 188 188 197 197 198 202 214 215
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6 Gra 6.1 6.2 6.3 6.4 6.5 6.6	Billion         Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems         Radiative Exchange Between Partially Specular         ty Surfaces         Introduction         Specular View Factors         Enclosures with Partially Specular Surfaces         Electrical Network Analogy         Radiation Shields	104 155 160 160 160 165 173 176 178 188 188 188 188 197 197 198 202 214 215 216
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6 Gra 6.1 6.2 6.3 6.4 6.5 6.6 6.7	Billion         Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems         Radiative Exchange Between Partially Specular         ty Surfaces         Introduction         Specular View Factors         Enclosures with Partially Specular Surfaces         Electrical Network Analogy         Radiation Shields         Semitransparent Sheets (Windows)         Solution of the Governing Integral Equation	104 155 160 160 160 165 173 176 178 188 188 188 188 188 197 197 198 202 214 215 216 220
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6 Gra 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8	<b>Radiative Exchange Between Gray, Diffuse Surfaces</b> Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems <b>Radiative Exchange Between Partially Specular</b> ty Surfaces         Introduction         Specular View Factors         Enclosures with Partially Specular Surfaces         Electrical Network Analogy         Radiation Shields         Semitransparent Sheets (Windows)         Solution of the Governing Integral Equation         Concluding Remarks	104 155 160 160 160 165 173 176 178 188 188 188 188 188 188 197 197 198 202 214 215 216 220 222
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6 Gra 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8 Ref	Adiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems         Radiative Exchange Between Partially Specular         ty Surfaces         Introduction         Specular View Factors         Enclosures with Partially Specular Surfaces         Electrical Network Analogy         Radiation Shields         Semitransparent Sheets (Windows)         Solution of the Governing Integral Equation         Concluding Remarks	104 155 160 160 160 165 173 176 178 188 188 188 188 188 188 197 197 198 202 214 215 216 220 222 222
Pro 5 5.1 5.2 5.3 5.4 5.5 5.6 Ref Pro 6 Gra 6.1 6.2 6.3 6.4 6.5 6.6 6.7 6.8 Ref Pro	Radiative Exchange Between Gray, Diffuse Surfaces         Introduction         Radiative Exchange Between Black Surfaces         Radiative Exchange Between Gray, Diffuse Surfaces         Electrical Network Analogy         Radiation Shields         Solution Methods for the Governing Integral Equations         erences         blems         Radiative Exchange Between Partially Specular         ty Surfaces         Introduction         Specular View Factors         Enclosures with Partially Specular Surfaces         Electrical Network Analogy         Radiation Shields         Semitransparent Sheets (Windows)         Solution of the Governing Integral Equation         Concluding Remarks	104 155 155 160 160 160 165 173 176 178 188 188 188 188 188 197 197 198 202 214 215 216 220 222 222 223

7 Ra 7.1 7.2 7.3 7.4 Refere Proble	Adiative Exchange Between Nonideal Surfaces Introduction Radiative Exchange Between Nongray Surfaces Directionally Nonideal Surfaces Analysis for Arbitrary Surface Characteristics ences ems	229 230 234 242 243 243
8.1 8.2	Introduction Numerical Quadrature by Monte Carlo	247 251
8.3	Heat Transfer Relations for Radiative Exchange Between Surfaces	252
8.4	Random Number Relations for Surface Exchange	254
8.6	Ray Tracing	259
8.7	Efficiency Considerations	261
Refere	ences	263
Proble	ems	264
9 S1	urface Radiative Exchange in the Presence of	
Cond	uction and Convection	267
9.1	Introduction	267
9.2	Conduction and Surface Radiation—Fins	268
Refer	ences.	275
Proble	ems	277
10 7	The Radiative Transfer Equation in Participating	
10 T Medi	The Radiative Transfer Equation in Participating a (RTE)	279
<b>10</b> 7 <b>Medi</b> 10.1	The Radiative Transfer Equation in Participating a (RTE) Introduction	<b>279</b> 279
<b>10</b> 7 <b>Medi</b> 10.1 10.2	The Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering	<b>279</b> 279 280
<b>10</b> 7 <b>Medi</b> 10.1 10.2 10.3	Che Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering	<b>279</b> 279 280 281
<b>10</b> 7 <b>Medi</b> 10.1 10.2 10.3 10.4	Che Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation	279 279 280 281 283 285
<b>10</b> 7 <b>Medi</b> 10.1 10.2 10.3 10.4 10.5 10.6	Che Radiative Transfer Equation in Participating         (A (RTE))         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation	279 279 280 281 283 285 285 288
<b>10 7 Medi</b> 10.1 10.2 10.3 10.4 10.5 10.6 10.7	Che Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiation Energy Density	279 279 280 281 283 285 285 288 291
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8	Che Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiation Energy Density         Radiative Heat Flux	279 279 280 281 283 285 285 288 291 292
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9	Che Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiative Heat Flux         Divergence of the Radiative Heat Flux	279 279 280 281 283 285 288 291 292 292
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11	Che Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation	279 279 280 281 283 285 288 291 292 293 295 207
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11 10.12	Che Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation         Overall Energy Conservation         Solution Methods for the Radiative Transfer Equation	279 279 280 281 283 285 288 291 292 293 295 297 299
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11 10.12 Refer	The Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         Augmentation by Emission and Scattering         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiation Energy Density         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation         Overall Energy Conservation         Solution Methods for the Radiative Transfer Equation	279 280 281 283 285 288 291 292 293 295 297 299 300
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11 10.12 Refer Probl	The Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiation Energy Density         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation         Overall Energy Conservation         Solution Methods for the Radiative Transfer Equation         ences	279 280 281 283 285 288 291 292 293 295 297 299 300 301
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11 10.12 Refer Probl	The Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         Augmentation by Emission and Scattering         Formal Solution to the Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation         Solution Methods for the Radiative Transfer Equation         ences         ences         ems	279 280 281 283 285 288 291 292 293 295 297 299 300 301
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11 10.12 Refer Probl 11 1 11.1	The Radiative Transfer Equation in Participating a (RTE)         Introduction         Augmentation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation         Solution Methods for the Radiative Transfer Equation         ences         ems         Mathematical Energy Conservation         Solution Methods for the Radiative Transfer Equation         Ences	279 280 281 283 285 288 291 292 293 295 297 299 300 301 <b>303</b>
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11 10.12 Refer Probl 11 1 11.1 11.2	The Radiative Transfer Equation in Participating a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation         Overall Energy Conservation         Solution Methods for the Radiative Transfer Equation         ences         ems         Solution Methods for the Radiative Transfer Equation         ences         Enditive Properties of Molecular Gases         Fundamental Principles         Emission and Absorption Probabilities	279 280 281 283 285 288 291 292 293 295 297 299 300 301 <b>303</b> 303 304
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11 10.12 Refer Probl 11.1 11.2 11.3	The Radiative Transfer Equation in Participating a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation         Overall Energy Conservation         Solution Methods for the Radiative Transfer Equation         ences         ems         Addiative Properties of Molecular Gases         Fundamental Principles         Emission and Absorption Probabilities         Atomic and Molecular Spectra	279 280 281 283 285 288 291 292 293 295 297 299 300 301 303 303 303 304 308
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11 10.12 Refer Probl 11.1 11.2 11.3 11.4	The Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiation Energy Density         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation         Overall Energy Conservation         Solution Methods for the Radiative Transfer Equation         ences         ems         Adiative Properties of Molecular Gases         Fundamental Principles         Emission and Absorption Probabilities         Atomic and Molecular Spectra         Line Radiation	279 280 281 283 285 288 291 292 293 295 297 299 300 301 <b>303</b> 303 304 308 315
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11 10.12 Refer Probl 11.1 11.2 11.3 11.4 11.5 11.6	The Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiation Energy Density         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation         Overall Energy Conservation         Overall Energy Conservation         Solution Methods for the Radiative Transfer Equation         ences         ems         Adiative Properties of Molecular Gases         Fundamental Principles         Emission and Absorption Probabilities         Atomic and Molecular Spectra         Line Radiation         Nonequilibrium Radiation	279 280 281 283 285 288 291 292 293 295 297 299 300 301 <b>303</b> 303 304 303 304 308 315 321
10 7 Medi 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11 10.12 Refer Probl 11 1 11.1 11.2 11.3 11.4 11.5 11.6 11.7	The Radiative Transfer Equation in Participating         a (RTE)         Introduction         Attenuation by Absorption and Scattering         Augmentation by Emission and Scattering         The Radiative Transfer Equation         Formal Solution to the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Boundary Conditions for the Radiative Transfer Equation         Radiative Heat Flux         Divergence of the Radiative Heat Flux         Integral Formulation of the Radiative Transfer Equation         Overall Energy Conservation         Solution Methods for the Radiative Transfer Equation         ences         ens         Solution Methods for the Radiative Transfer Equation         Nonequil Energy Conservation         Solution Methods for the Radiative Transfer Equation         ences         ens         Magnental Principles         Emission and Absorption Probabilities         Atomic and Molecular Spectra         Line Radiation         Nonequilibrium Radiation         High-Resolution Spectroscopic Databases         Spectral Models for Radiative Transfer Calculations	279 280 281 283 285 288 291 292 293 295 297 299 300 301 <b>303</b> 304 303 304 308 315 321 325

11.9Narrow Band k-Distributions3311.10Wide Band Models3411.11Total Emissivity and Mean Absorption Coefficient3611.12Experimental Methods36References37Problems38	36 19 52 59 75 32
12Radiative Properties of Particulate Media3812.1Introduction3612.2Absorption and Scattering from a Single Sphere3612.3Radiative Properties of a Particle Cloud3912.4Radiative Properties of Small Spheres (Rayleigh Scattering)3912.5Rayleigh-Gans Scattering4012.6Anomalous Diffraction4012.7Radiative Properties of Large Spheres4012.8Absorption and Scattering by Long Cylinders4012.9Approximate Scattering Phase Functions4112.10Radiative Properties of Irregular Particles and Aggregates4112.11Radiative Properties of Combustion Particles42References43Problems43	77383381112810342631 37
13Radiative Properties of Semitransparent Media4413.1Introduction4413.2Absorption by Semitransparent Solids4413.3Absorption by Semitransparent Liquids4413.4Radiative Properties of Porous Solids4413.5Experimental Methods44References45Problems45	0 10 10 12 14 17 51
14Exact Solutions for One-Dimensional Gray Media4514.1Introduction4514.2General Formulation for a Plane-Parallel Medium4514.3Plane Layer of a Nonscattering Medium4514.4Plane Layer of a Scattering Medium4614.5Radiative Transfer in Spherical Media4614.6Radiative Transfer in Cylindrical Media4714.7Numerical Solution of the Governing Integral Equations47Problems47	4 4 4 9 5 7 1 75 76 77
15Approximate Solution Methods forOne-Dimensional Media4815.1The Optically Thin Approximation4815.2The Optically Thick Approximation (Diffusion Approximation)4815.3The Schuster-Schwarzschild Approximation4815.4The Milne-Eddington Approximation (Moment Method)4815.5The Exponential Kernel Approximation49References49Problems49	0 30 32 36 38 91 93

#### x

	e Method of Spherical Harmonics	105
(P <sub>N</sub> -A	proximation)	105
16.1	ntroduction	495
16.2	Seneral Formulation of the $P_N$ -Approximation $\dots \dots \dots$	490
16.3	The P <sub>N</sub> -Approximation for a One-Dimensional Slab	497
16.4	Soundary Conditions for the $P_N$ -Method	502
16.5	The P <sub>1</sub> -Approximation	502
16.6	<sup>3</sup> - and Higher-Order Approximations	509
16.7	Simplified P <sub>N</sub> -Approximation	522
16.8	The Modified Differential Approximation	521
16.9	Comparison of Methods	531
Referer	ICes	527
Problei	ns	557
17 TI	ne Method of Discrete Ordinates	= 11
(SN-AL	proximation)	541
17.1	ntroduction	541
17.2	General Relations	542
17.3	The One-Dimensional Slab	545
17.4	One-Dimensional Concentric Spheres and Cylinders	550
17.5	Multidimensional Problems	556
17.6	The Finite Volume Method	566
17.7	The Modified Discrete Ordinates Method	572
17.8	Even-Parity Formulation	573
17.9	Other Related Methods	574
17.10	Concluding Remarks	576
Referen	nces	576
Proble	ns	582
18 T	he Zonal Method	585
18.1	Introduction	585
18.1 18.2	Introduction	585 585
18.1 18.2 18.3	Introduction	585 585 590
18.1 18.2 18.3 18.4	Introduction	585 585 590 596
18.1 18.2 18.3 18.4 18.5	Introduction	585 585 590 596 603
18.1 18.2 18.3 18.4 18.5 18.6	Introduction	585 585 590 596 603 606
18.1 18.2 18.3 18.4 18.5 18.6 Refere	Introduction	585 585 590 596 603 606 606
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble	Introduction	585 585 590 596 603 606 606 606
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble	Introduction	585 585 590 596 603 606 606 606 607
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble	Introduction       Introduction         Surface Exchange — No Participating Medium       Surface Exchange in Gray Absorbing/Emitting Media         Radiative Exchange in Gray Media with Isotropic Scattering       Radiative Exchange in Gray Media with Isotropic Scattering         Radiative Exchange through a Nongray Medium       Radiative Exchange through a Nongray Medium         Determination of Direct Exchange Areas       Radiative Exchange Areas         Intersection       Intersection         Ms       Interadiation and Transient Phenomena	585 585 590 596 603 606 606 606 607 <b>510</b>
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble <b>19 C</b> 19.1	Introduction	585 585 590 596 603 606 606 606 607 <b>510</b> 610 613
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble <b>19 C</b> 19.1 19.2	Introduction	585 585 590 596 603 606 606 606 607 610 610 613 616
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble <b>19 C</b> 19.1 19.2 19.3 10.4	Introduction	585 585 590 596 603 606 606 607 610 610 613 616 616
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble <b>19 C</b> 19.1 19.2 19.3 19.4	Introduction	585 585 590 596 603 606 606 606 606 607 610 613 616 619 622
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble <b>19 C</b> 19.1 19.2 19.3 19.4 Refere Prefere	Introduction	585 585 590 596 603 606 606 606 607 <b>610</b> 613 616 619 622 624
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble <b>19 C</b> 19.1 19.2 19.3 19.4 Refere Proble	Introduction	585 585 590 596 603 606 607 610 610 613 616 619 622 624
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble 19.0 19.1 19.2 19.3 19.4 Refere Proble 20 S	Introduction	585 585 590 596 603 606 606 606 607 610 610 613 616 619 622 624
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble <b>19 C</b> 19.1 19.2 19.3 19.4 Refere Proble <b>20 S</b> <b>Coeffi</b>	Introduction	585 585 590 596 603 606 606 607 610 610 613 616 619 622 624 626
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble <b>19 C</b> 19.1 19.2 19.3 19.4 Refere Proble <b>20 S</b> <b>Coeffi</b> 20.1	Introduction	585 585 590 596 603 606 606 607 610 613 616 619 622 624 626 626
18.1 18.2 18.3 18.4 18.5 18.6 Refere Proble <b>19 C</b> 19.1 19.2 19.3 19.4 Refere Proble <b>20 S</b> <b>Coeffi</b> 20.1 20.2	Introduction	585 585 590 596 603 606 606 607 610 613 616 619 622 624 624 626 626
<ul> <li>18.1</li> <li>18.2</li> <li>18.3</li> <li>18.4</li> <li>18.5</li> <li>18.6</li> <li>Referee</li> <li>Proble</li> <li>19 C</li> <li>19.1</li> <li>19.2</li> <li>19.3</li> <li>19.4</li> <li>Referee</li> <li>Proble</li> <li>20 S</li> <li>Coeffi</li> <li>20.1</li> <li>20.2</li> <li>20.3</li> </ul>	Introduction	585 585 590 596 603 606 606 607 610 613 616 619 622 624 626 626 628 634

xi

20.5 General Band Model Formulation	. 643
20.6 The Weighted-Sum-of- Gray-Gases (WSGG) Model	. 649
20.7 k-Distribution Models	. 654
20.8 The Full Spectrum k-Distribution (FSK) Method for Homogeneous Media	. 656
20.9 The Spectral-Line-Based Weighted Sum of Gray Gases (SLW)	. 659
20.10 The FSK Method for Nonhomogeneous Media	. 660
20.11 Evaluation of <i>k</i> -Distributions	. 668
20.12 Higher Order <i>k</i> -Distribution Methods	. 679
References	. 686
Problems	. 691
21 The Monte Carlo Method for Participating Media	694
21.1 Introduction	. 694
21.2 Heat Transfer Relations for Participating Media	. 694
21.3 Random Number Relations for Participating Media	. 695
21.4 Treatment of Spectral Line Structure Effects	. 700
21.5 Overall Energy Conservation	. 705
21.6 Discrete Particle Fields	. 706
21.7 Efficiency Considerations	. 712
21.8 Backward Monte Carlo	. 713
21.9 Direct Exchange Monte Carlo	. 717
21.10 Example Problems	. 717
References	. 720
Problems	. 722
22 Radiation Combined with Conduction and	
Convection	724
22.1 Introduction	724
22.2 Combined Radiation and Conduction	. 724
22.3 Melting and Solidification with Internal Radiation	. 733
22.4 Combined Radiation and Convection in Boundary Lavers	. 738
22.5 Combined Radiation and Free Convection	. 743
22.6 Combined Radiation and Convection in Internal Flow	. 744
22.7 Combined Radiation and Combustion	. 748
22.8 Interfacing Between Turbulent Flow Fields and Radiation	. 751
22.9 Interaction of Radiation with Turbulence	. 753
22.10 Radiation in Concentrating Solar Energy Systems	. 759
References	. 763
Problems	. 777
22 Lange De listing H & T (	
23 Inverse Radiative Heat Transfer	779
23.1 Introduction	. 779
23.2 Solution Methods	. 780
23.5 Regularization	. 785
23.4 Gradient-based Optimization	. 788
12.5 Motobourgistice	
23.5 Metaheuristics	. 794
23.5 Metaheuristics	. 794 . 795
23.5 Metaheuristics	. 794 . 795 . 797

xii

24 Nanoscale Radiative Transfer	803
24.1 Introduction	803
24.2 Coherence of Light	803
24.3 Evanescent Waves	804
24.4 Radiation Tunneling	805
24.5 Surface Waves (Polaritons)	807
24.6 Fluctuational Electrodynamics	809
24.7 Heat Transfer Between Parallel Plates	811
24.8 Experiments on Nanoscale Radiation	814
References	816
Problems	817
A Constants and Conversion Factors	818
B Tables for Radiative Properties of Opaque Surfaces	820
References	820
C Blackbody Emissive Power Table	833
D View Factor Catalogue	836
References	846
E Exponential Integral Functions	852
References	853
F Computer Codes 8	855
References	861
Acknowledgments	363

Index

867