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Radiative Transfer in Combustion Systems: Fundamentals & Applications

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Raymond Viskanta

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Radiative Transfer of Combustion Systems: Fundamentals and Applications

by

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Dedication

Birutei, su meile.

This volume is dedicated to my wife Birute B., the woman in my life, for her love, patience, continuous source of support, and for creating a family environment that was conducive for me to do my work.

About the Author

Raymond Viskanta is currently a W.F.M. Goss Distinguished Professor Emeritus of Engineering at Purdue University. The author of about 500 technical papers published in technical and scientific journals and in proceedings of conferences and symposia, he has guided the doctoral research of over 60 doctoral and over 40 master's candidates. Viskanta received his BSME degree from the University of Illinois and his MSME and PhD degrees from Purdue University. He held visiting appointments at the University of California–Berkeley, Technical University of Munich, Tokyo Institute of Technology, and University of Karlsruhe.

He served as a technical editor of the *ASME Journal of Heat Transfer* and Associate Editor of the *Journal of Quantitative Spectroscopy and Radiative Transfer* and *Experimental Heat Transfer*. Viskanta has been and continues to be a member of editorial advisory boards of numerous journals, including the *AIAA Journal*, *AIAA Journal of Thermophysics and Heat Transfer*, *International Journal of Heat and Mass Transfer*, *International Journal of Heat and Fluid Flow*, and others. He is a Fellow of ASME and AIAA and has received numerous professional recognitions, including the ASME Heat Transfer Memorial Award, ASME/AIChE Max Jakob Memorial Award, AIAA Thermophysics Award, ASEE Senior Research Award, Alexander von Humboldt U.S. Senior Research Award, JSME Thermal Engineering Award, Nusselt-Reynolds Prize, among others. He has also received a Distinguished Engineering Alumnus Award from the University of Illinois. He has been elected as a Member of the National Academy of Engineering and a Foreign Member of the Academy of Engineering Sciences of the Russian Federation and of the Lithuanian Academy of Sciences. He was also awarded Dr.-Ing. E. h. (Doctor Honoris Causa) by the Technical University of Munich.

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PREFACE

Fossil-fuel utilization, primarily in the form of combustion transformations, has been the backbone of worldwide industrial development for about two centuries. The reliance on such fuels is not likely to change in the foreseeable future as the remaining supplies of coal, oil, gas, shale oil, tar sands, etc. appear to be adequate for decades. Another reason for this belief is that alternative technologies, including renewable systems, have not proven to be economically competitive in the past. In view of the anticipated continuing cost advantage of fossil-fuel-based combustion technologies, there are research, development and design requirements for sustainable technological advances discussed in the paragraphs to follow.

Numerous respected petroleum geologists have pointed out that worldwide discovery of oil peaked decades ago, and the only question is whether other fossil fuels (including hydrogen) will replace "cheap" oil in time for needs in propulsion, power generation, chemical goods, etc. which are made from petroleum, or will the world run "out of gas." Goodstein* has recently argued that there is no "single magic bullet" in sight that will solve the world's energy problems. To quote him, "There is no existing technology capable of replacing the oil we will soon be without, nor is there any on the horizon that we can depend on to replace the remaining fossil fuels when they are exhausted." Somehow during the next several decades, new energy sources will have to be found that can produce sufficient, clean, and cheap energy on a sustainable basis. The best hope for the future of our civilization lies in new technologies based on scientific discoveries that have not yet been made. In the meantime, while the world will start running out of conventionally produced cheap oil and natural gas, the burden is on the combustion scientist/engineer to design and operate fossil-fuel-fired combustion systems that are much more energy efficient and environment friendly.

Combustion of fossil fuels is a polluting process, and in today's environmental era (from about 1970 to the present) combustion research, process improvements, and new process developments are motivated mainly by the challenge of reducing pollutant emissions. Gaseous pollutants, such as oxides of sulfur and nitrogen, polycyclic aromatic compounds, greenhouse gases, and nitrogen oxides, as well as fine inorganic aerosols and soot, require special attention because of their wide-ranging effects on the environment. These pollutants contribute to reduction of atmospheric visibility, acid rain, production of tropospheric ozone, and to depletion of stratospheric ozone in the case of water. Increases in heat extraction efficiency from the flame or heat transfer from the flame to the bounding surfaces/load, and thereby eventual decreases and complete elimination of greenhouse gas emissions to the atmosphere, is a grand challenge for the 21st century. The goal of fossil combustion research

* D. Goodstein, *Out of Gas*, W.W. Norton & Co., New York (2004).

and development is to create high-efficiency and clean combustion technology options that can mitigate adverse atmosphere climate changes, reduce pollutant emissions, and simultaneously increase fossil fuel utilization efficiencies.

Today's combustion engineers and scientists are often confronted with complex combustion phenomena that depend on interrelated processes of thermodynamics, chemical kinetics, fluid mechanics, heat and mass transfer, and turbulence. Thermal radiation transport in combustion systems at high temperatures is an important process that has been receiving increased attention in the last few decades because of environmental, energy efficiency, and economic considerations. Understanding of fundamental radiative transfer concepts as they impact coupled processes in flames and combustion systems should provide engineers and scientists with the technical background and training to solve various current and future practical combustion problems. During the transition from present to indefinitely sustainable technologies, fossil-fuel utilization technologies may include hydrogen technologies coupled to renewable energy supplies in biomass forms (e.g., special crops, plant residues, etc.). Combustion of biomass is expected to be an important combustion technology that will require understanding and all of the necessary controls.

Market demands and federal regulations on controlling combustion performance have led and continue to drive the development of more efficient combustion devices. Increased use of natural gas will continue in the U.S. largely due to its availability and price. Changes in Title IV of the Clean Air Act of 1990 have made natural gas a more desirable alternative fuel. However, global warming concerns may in the future restrict not only the use of a desirable fuel, such as natural gas, but other fossil fuels as well. Computational design tools will be needed for burner and combustion system designs to determine the effects of fuels, burner position and orientation, and geometry on combustion system performance. Hence, one of the main tasks of a research worker or a designer in the combustion field will be to develop and use computational methods that describe important phenomena in practical industrial systems that are expected to drive the combustion technology.

Energy for high-temperature processes is usually derived directly from fossil fuel; therefore, combustion is an integral part of many "hot" systems. The rapidly developing discipline of Computational Fluid Dynamics (CFD) is being used to help understand, design, optimize, and operate high-temperature processes. These processes involve the transfer of heat, mass, species, and momentum in a very hostile environment. Combustion and heat transfer are closely linked disciplines and together they form the theme of this volume. At high temperature, radiation is either a very important or the dominant mode of heat transfer. Radiative transfer differs from conduction and convection in its fundamental laws and formulation and is a special focus in this volume because of its conceptual and computational difficulties. The emphasis in the book is on those combustion situations in which radiative transfer has been identified as an important or a dominant phenomenon influencing physicochemical processes and energy transport.

The aim of the book is: 1) to lay the foundations of radiative transfer for inclusion of the process in modeling of combustion phenomena and in predicting radiation heat transfer in chemically reacting and combusting systems, 2) to collect relevant information on the effects of thermal radiation on chemical processes in combustion devices, and 3) to identify and discuss radiation and total heat transfer in important combustion applications.

The book is basically organized in two parts. The first part (Chapters 1 through 7) deals with the fundamentals of radiative transfer (e.g., concepts, thermodynamics and physics of radiation, phenomenological description of radiative transfer, radiation characteristics of combustion gases, radiation characteristics of particulates, and methods for solving the radiative transfer equation and integrating over the spectrum). The second part (Chapters 8 through 15) of the book deals with combustion phenomena that are affected by radiative transfer and discussion of combustion devices in which radiation transport plays a significant or major role and impacts the system performance. Specific applications include modeling of radiative transfer in isolated, individual flames and industrial combustion devices ranging from burners to industrial furnaces. The volume includes a chapter on wildland fires (Chapter 14) in which radiation plays a dominant role in the spread of fire and represents a hazard to humans as well as property. The book concludes with a chapter on premixed combustion in porous media (Chapter 15), a promising technology for reducing pollutant emissions and improving energy utilization efficiency for a variety of applications.

Many textbooks have been written on combustion and on radiation heat transfer, but both types of books contain limited information on combination radiative transfer and how it impacts combustion processes and performance of combustion devices. The key difference between this book and others is that it examines each application from a somewhat narrow scope to learn how radiative transfer affects the combustion processes and on the performance of combustion systems. The basics of combustion are considered, but from a limited perspective as to how combustion is influenced by radiative transfer and how the performance of a combustion device or system is affected by radiation. There is very little discussion of combustion kinetics because this subject has been more than adequately covered in combustion books and because the kinetics of the chemical reactions have significant impact on radiative transfer only in special circumstances. Rather, the book attempts to narrowly discuss those topics in regard to how radiative transfer affects the flame structure (e.g., temperature and species concentrations), and how the temperature impacts physicochemical processes during combustion.

As with any book on combustion and radiative transfer, there are many topics that are not covered and others that are treated only superficially. This work does not cover many topics relevant to radiative transfer in infrared radiating gases or in dispersed systems. The book also does not deal with applications of radiative transfer in many combustion systems, which are very important technologically in power and industrial steam generation (boilers, fluidized bed combustion, packed bed combustion), propulsion (internal combustion, gas turbines, rocket propulsion), industrial processing, and many other specialized combustion devices and applications, such as nonintrusive diagnostics in combustion systems. Some topics, such as combustion and heat transfer in furnaces, are discussed in a cursory manner; others, such as radiative transfer in gas turbine combustors, are discussed by way of example. The focus is on radiative transfer fundamentals and applications to simple combustion systems and devices.

The book discusses how to construct, use, and interpret numerical results of combustion system simulations. Radiation transport must be a part of comprehensive models used in interpreting, analyzing, and optimizing combustion systems. Computer models can reduce the number of costly and time-consuming experiments in designing combustion devices. Modeling of radiation and its interaction with other processes (i.e., turbulence) needs to be treated for realistic description of chemical kinetics and computational procedures to quantify description of transport phenomena in combustion devices.

I have liberally used the published literature. While I am indebted to these scholars and to those colleagues who shaped my thinking, I am of course responsible for errors and omissions in interpreting their work. Many individuals have contributed to the development

of this book. Sections of the volume were used for years as notes in a graduate-level radiation heat transfer course at Purdue University, and the comments of students are greatly appreciated, as are the comments of over 100 former graduate students and postdoctoral researchers who worked with me in the past and provided technical comments and critique. Of these, I would especially like to mention Professor M. Pinar Mengüç, University of Kentucky. I am indebted to my Purdue University colleagues Professor J.P. Gore, Professor F.P. Incropera, and Professor S. Ramadhyani for many enlightening discussions on radiative transfer and heat transfer in combustion systems.

Finally, the book could not have been written without the expert typing of the manuscript by Francesca Beard and Lori Gardner. The figures were prepared by Michael Black and Charles Tseng. I am indebted to Peter and Donna Thompson for their editorial assistance in removing errors, inconsistencies, and ambiguities from the text.

R. Viskanta

LIST OF SYMBOLS

a	particle radius (m)
a	weight function (–)
a_i	weight function for sum-of-gray-gases model (–)
A	area (m^2)
A	total band absorptance (–)
A^*	dimensionless band absorptance (= A/ω) (–)
$\overline{A}$	spectrum integrated absorptance (–)
A_{ij}, B_{ij}	Einstein probability coefficients (–)
b	line half-width (–)
B	rotational constant (–)
Bo	Boltzmann number (convection-to-radiation parameter) (–)
c	speed of light (m/s)
c_o	speed of light in vacuum (m/s)
C_1, C_2	Planck's first and second constants (see Table 2.1)
C_3	constant in Wien's displacement law (see Table 2.1)
C_f	molar fuel concentration (N/m^3)
d	line spacing (–)
d	particle diameter (m)
D	diameter (m)
$\mathfrak{D}$	binary diffusion coefficient (m^2/s)
E	emitted flux (W/m^2)
$\mathbf{E}$	electric field vector (N/C)
$\mathcal{E}$	net (emission – absorption) volumetric radiant energy loss/gain (W/m^3)
E_b	blackbody emitted flux (W/m^2)
$E_n(x)$	exponential integral function (–)
f_v	volume fraction (–)
f_ν	photon distribution function (–)
$\mathfrak{F}$	radiation flux vector (W/m^2)
$F_{0-\lambda T}$	fractional blackbody function (–)
F_{i-j}	configuration (view, angle) factor between finite area i and area j (–)
G	irradiation (incident radiation flux) on a surface (W/m^2)
$\mathcal{G}$	irradiance (radiation incident on a volume of matter, from all possible directions) (W/m^2)
h	enthalpy (J/kg)
h	convective heat transfer coefficient (W/m^{2}K)
h	Planck's constant (= 6.626×10^{-34}Js)

$\mathbf{H}$	magnetic field vector (–)
ΔH_{fg}	latent heat of vaporization (J/kg)
$\mathbf{i}$	unit vector in the x-direction (–)
I	intensity of radiation (radiance) ($W/m^2 \cdot sr$)
I_b	blackbody intensity of radiation ($= \sigma T^4/\pi$) ($W/m^2 \cdot sr$)
$\mathbf{j}$	unit vector in the y-direction (–)
J	rotational quantum number (–)
J	radiosity (radiation flux leaving a surface) (W/m^2)
k	thermal conductivity (W/m K)
k	Boltzmann constant ($= 1.3807 \times 10^{-23}$ J/K)
k	imaginary part of complex index of refraction (–)
$\mathbf{k}$	unit vector in the z-direction (–)
l,m,n	direction cosines with x-, y-, z-axis (–)
L	length (m)
L_m	mean beam length (m)
L_o	geometric mean beam length (m)
m	mass flux (kg/m^2s)
m	complex index of refraction (–)
n	real part of complex index of refraction (–)
n	self-broadening exponent in Eq. (4.58) (–)
$\mathbf{n}$	unit vector normal to real or imaginary surface (–)
N	number of particles per unit volume ($\#/m^3$)
Nu	Nusselt umber (–)
p	pressure (N/m^2)
$\mathcal{P}$	radiation pressure (N/m^2)
P_l	Legendre polynominals (–)
Pr	Prandtl number (–)
q	heat flux (W/m^2)
$\mathbf{q}$	heat flux vector (W/m^2)
Q	heat transfer rate (W)
Q	Mie efficiency factor (–)
r	radial coordinate (m)
$\mathbf{r}$	position vector (m)
R	radius (m)
$\mathfrak{R}$	universal gas constant (= 8.3145J/mol K)
Re	Reynolds number (–)
s	distance measured along the direction of ray propagation (m)
$\mathbf{s}$	unit vector in the direction of ray propagation (–)
S	line-integrated absorption coefficient (line strength) (–)
S	source function (W/m^3)
S	distance between two points in the medium (m)
S	flame speed (m/s)
$\mathbf{S}$	Poynting vector (W/m^2)
St	Stanton number (–)
$\overline{S_iS_j}, \overline{S_iG_k}$	total exchange area in zone method (m^2)
t	time (s)
T	temperature (K)

u	internal energy (J/kg)
u	velocity in the x-direction (m/s)
u	scaling function for absorption coefficient (–)
U	overall heat transfer coefficient (W/m^2K)
$\mathcal{U}$	radiant energy density (J/m^3)
v	vibrational quantum number (–)
v	velocity in the y-direction (m/s)
$\mathbf{v}$	velocity vector (m/s)
V	volume (m^3)
w_i	quadrature weight (–)
W	equivalent line width (–)
W	molecular weight (–)
x,y,z	Cartesian coordinates (m)
X	optical length (–)
X_i	mole fraction of species i (–)
Y_l^m	spherical harmonics (–)
Y_i	mass fraction of species I (–)

Greek Symbols

α	absorptivity or absorptance (–)
α	band-integrated absorption coefficient (band strength parameter) (–)
α	thermal diffusivity ($= k/\rho c_p$) (m^2/s)
β	extinction coefficient ($= \kappa + \sigma$) (m^{-1})
β	line overlap (structure) parameter (–)
Γ	generalized diffusion coefficient (m^2/s)
δ	Dirac-delta function (–)
δ_{ij}	Kronecker delta function (–)
ε	emissivity or emittance (–)
ε	electrical permittivity of matter (C^2/Nm^2)
ε	complex dielectric function ($= \varepsilon' - \varepsilon''$) (–)
θ	polar angle (rad)
Θ	scattering angle (rad)
κ	absorption coefficient (m^{-1})
λ	wavelength (μm)
μ	dynamic viscosity (kg/ms)
μ	magnetic permeability (Ns^2/C^2)
μ	direction cosine ($= \cos\theta$) (–)
ν	frequency (Hz)
ν	kinematic viscosity (m^2/s)
ξ	direction cosine (–)
ξ	dimensionless coordinate (–)
ρ	reflectivity or reflectance (–)
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant ($= 5.670 \times 10^{-8} W/m^2\,K^4$)
σ	scattering coefficient (m^{-1})
τ	transmissivity (–)

τ	optical distance or optical coordinate (–)
Υ	transmittance (–)
ϕ	azimuthal angle (rad)
ϕ	porosity (–)
ϕ	general scalar variable (ρ, u, v, w, t_ρ, T, h,Y_i . . .)
Φ	scattering phase function (–)
ω	single scattering albedo (= σ/β) (–)
ω	wave number (1/cm)
ω	angular frequency (rad/s)
$\dot{\omega}_i$	mass rate production of species l (kg/m^{3}s)
Ω	solid angle (sr)
χ	particle size parameter (–)
χ_R	radiant fraction (–)

Subscripts

1,2	at location "1" or "2"
a	absorption
amb	ambient
av	average
b	blackbody
c	chemical
c	collimated or beam flux
C	collision or convection
d	diffuse flux or droplet
D	Doppler or based on diameter
e	effective
e	extinction
eff	effective
f	fuel or flame
g	gas
i	incident or dummy counter
j	rotational sate or dummy counter
k	absorption coefficient variable or dummy counter
ℓ	leaving
L	at length
mix	mixture
n	normal direction
o	reference value or in vacuum
p	particle
P	Planck-mean
r	reflected
R	reflected component or radiation
R	Rosseland-mean or at $r = R$
s	along the path s or at surface
s	solid or surroundings
s	scattering

t	transmitted component
u	upper limit
v	at a vibrational state or at constant volume
w	wall value
x,y,z	components in the x,y,z directions
θ,ϕ	in a given direction
λ	at a given wavelength or per unit of wavelength
ν	at a given frequency or per unit frequency
ω	at a given wave number or per unit wave number
$\|\|$	polarization component or situated in plane of incidence
$\perp$	polarization component or situated in plane perpendicular to the plane of incidence

Superscripts

o	external
$'$, $''$	real and imaginary parts of a complex number
$\cap$	hemisphere of solid angle
$+, -$	into “positive” and “negative” directions
d	diffusive
s	specular
$-$	average value or spectrum integrated
$\sim$	Favre average or effective

LIST OF ACRONYMS

ADF	Absorption distribution function model
ADFFG	Absorption distribution function fictitious gas model
BEM	Boundary element method
CFD	Computational fluid dynamics
CK	Correlated-k model
CKFG	Correlated-k fictitious gas model
DNS	Direct numerical simulation
DOM	Discrete ordinates method
DTM	Discrete transfer method
EBU	Eddy break up model
EDC	Eddy dissipation chemical equilibrium model
EM	Electromagnetic wave theory
EPF	Even parity formulation
EWB	Exponential wide-band model
FSCK	Full-spectrum correlated-k model
FVM	Finite volume method
LBL	Line-by-line model
LES	Large eddy simulation
LTE	Local thermodynamic equilibrium
MCM	Monte Carlo method
MFM	Multiflux method
MSFCK	Multiscale full-spectrum correlated-k model
NB	Narrow-band model
PDF	Probability density function
PIM	Porous inert medium
PMMA	Polymethylmethacrylate
PPMC	Premixed porous medium combustor
PSIC	Particle source in cell method
RADCAL	Computer program for calculating radiance along the line-of-sight based on SNB data
RANS	Reynolds-averaged Navier-Stokes equations
RTE	Radiative transfer equation
SLW	Spectral line weighted-sum-of-gray gases model
SNB	Statistical narrow-band model
TRI	Turbulence/radiation interaction
TTNH	Total transmittance non-homogeneous model
WB	Wide-band model
WSGG	Weighted sum-of-gray-gases model
YIX	Numerical method for solving exact integral form of RTE
ZM	Zone method

CHAPTER 1

Introduction

1.1 Combustion in Nature and Technology

Fires fascinated prehistoric man, and unwanted wildland, building, urban, and large-scale industrial fires have preoccupied modern man for centuries [1]. Fossil-fuel utilization, primarily in the form of combustion transformations, has been the focus of worldwide developments for about two centuries. The utilization of combustion systems for power generation, propulsion, process industry, materials processing and manufacturing, domestic use, and others have occupied man until present. During the pre-environmental era the objectives were to complete combustion with a minimum of excess air and absence of carbon emissions. In the present environmental era (since about 1970) attention is being turned toward pollutant emission control technologies and reduction of CO_2 emissions to mitigate their effects on global warming. During the last two decades several factors have emerged that continue to influence the development of combustion systems. As a result of the international greenhouse gas debate, emission control is gaining increased acceptance and is adding the task of raising the energy efficiency of systems to the existing demands for reduced pollutant and CO_2 emissions. A number of technological fixes that have been proposed to alleviate further global warming are discussed by Hoffert *et al.* [2].

The combustion systems of interest in this volume range from aerospace propulsion to wildland (forest) fires. At the high temperatures encountered in most of the applications of interest, the flow is turbulent and radiative transfer is, if not the dominant, at least an important, desirable or undesirable mode of energy transfer controlling the processes or performance of the system. For example, in combustion technologies related to power generation, radiation from the flame/combustion products to the tubes in the steam boiler is desirable [3]. Whereas radiation coupled to turbulent convection is often undesirable in an aerospace propulsion system using a solid propellant as a fuel. In a solid propellant engine high specific impulse is generally achieved by adding to the oxidant and to the polymeric binder a metal fuel, such as aluminum. Metal combustion increases the temperature and pressure inside the chamber. The high temperature and pressure combustion products (gases and particles) result in high radiant fluxes to the chamber walls, which require cooling [4].

In combustion systems, radiation is an important mode of energy transport for several reasons. First, high temperature combustion devices require consideration of heat transfer by diffusion, convection, and radiation, and energy losses from the reaction region govern processes, such as flame quenching, flame evolution near walls, and others. Second, the heat transfer rate from the reactants and/or postreaction combustion products to the load and/or

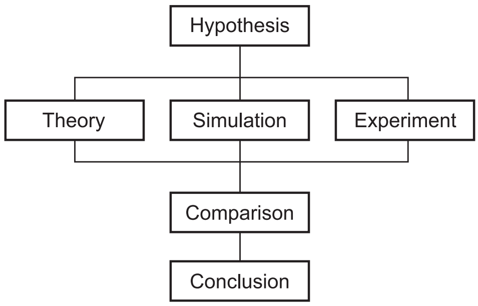

Figure 1.1 Schematic representation of the current scientific method.

containment walls of the chamber is determined by convection and radiation. Third, in combustion systems, where the primary function of the process is to convert chemical energy to thermal energy of the products, there is a need to keep temperatures low so as to reduce pollutant emissions. Fourth, understanding of radiative transport in combustion devices is needed for development of versatile computational tools in which radiation is accounted for in predicting the combustion process and/or heat transfer to the load in the system.

The current scientific method in science and engineering is shown schematically in Fig. 1.1. In addition to theory and experiment, simulation has emerged as the "third leg" of the method. Simulation is neither experimentation in the traditional sense of the word nor theoretical analysis. Theoretical studies are limited by analytical constraints and experiments are limited by the bounds of cost, hazard, measurement techniques, and time. With simulation, however, analysis can be extended by numerical calculations and experiments are augmented by simulations. Some parameters can now be more accurately simulated than they can be measured. Full-scale simulations are often feasible, whereas full-scale experiments are usually too costly or too risky to perform. In summary, with the availability of computers today, the scope and extent of the scientific method is vastly enhanced.

To facilitate simulation, a physical/mathematical model is needed. The model could be of the full-scale system, prototype, or component. As a concrete example, consider the first step in the construction of a mathematical model for an industrial combustion chamber. The analysis begins with the simplification of the physicochemical processes occurring in the system. Figure 1.2 shows a schematic of the processes and their interactions taking place in a combustion chamber with a diffusion flame. The relevance of radiative transfer in combustion systems has been recognized [5–8], but sufficiently detailed models for radiative

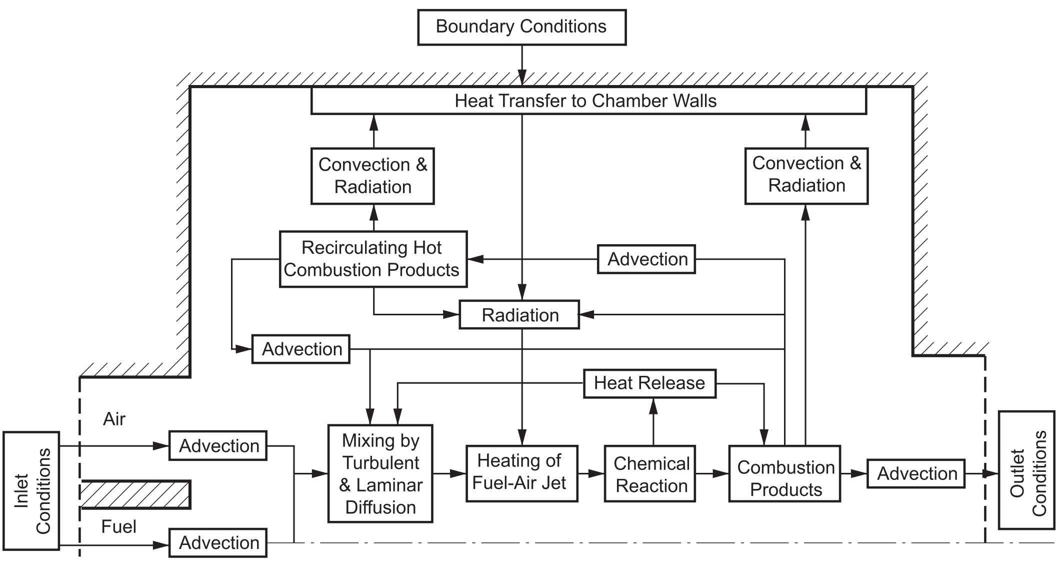

Figure 1.2 Schematic of physical and chemical processes taking place in a diffusion flame in a combustion chamber.

transfer require complicated descriptions of the spectral radiation characteristics of the main chemical species and particles (if any), the solution of the radiative transfer equation, integration of the equation over the spectrum, and solution of the transport equations with a radiation term accounted for in the thermal energy equation. In the past, radiative transfer has been neglected in analyzing combustion phenomena and in calculating system performance. Currently, however, serious efforts are being made to account for radiation in practical combustion systems [9,10]. Radiation transport is a major scientific field in its own right and has received significant research attention and organization during the last century, with many books and treatises written on it.

In this chapter, important concepts and definitions are introduced to lay the foundation for the discussion of the physics and thermodynamics of radiation. The different concepts, together with the fundamental laws of modern physics, are then used in conjunction with the radiative transfer theory to construct models for the radiation characteristics of gases and particles and to develop analysis to simulate radiative transfer in flames and different combustion systems.

1.2 Physical Nature of Radiation

1.2.1 Duality of radiation phenomena

Energy can be propagated either by moving matter or by a wave disturbance through a medium that does not move itself. One will immediately recall the rise in temperature that results from absorption of the sun's rays, as well as other manifestations of energy due to the same cause. It is apparent that only two general theories are possible because energy can be transmitted from one place to another by only one of two means. In general, since energy can be propagated either by moving matter or by a wave disturbance through a medium that does not itself move as a whole, two general (i.e., wave and corpuscular or quantum) theories have been formulated [11–13]. According to the electromagnetic wave theory, a disturbance travels from the source of radiation through the surrounding medium; according to the corpuscular theory, radiation consists of a flight of invisible rapidly moving particles (photons) whose size varies with the wavelength emitted from the radiation source [11]. One important difference between the two theories may be noted. In the wave theory, at all points on a surface through which an ordinary beam of radiation is passing, energy is uniformly and continuously distributed; whereas in the other, the energy distribution is discontinuous, being concentrated at points. Only when the beam of particles is so intense that it seems to be continuous must it in some way become equivalent to what is described as a light wave in classical physics.

There exists a mutually complementary dualism between the wave and the corpuscular concept. Both theories are complementary and both models are valid. Which one is to be emphasized depends on occasion, although both may serve equally well for phenomena in which the wave nature is prominent as well as for phenomena in which the particle character is manifested [11].

A theory is satisfactory only in so far as it provides an explanation of physical facts. As it is impossible for most people to think of waves without a medium to carry the wave motion, and as matter is not necessary for propagation of radiation, a hypothetical ether was to be postulated although no such postulate is necessary in the corpuscular theory. For generations, the attention of physicists has been directed toward problems connected with the emission and absorption of light. This work has shown that there are many facts for which an adequate explanation cannot be given in terms of simple wave theory [11–13]. One of the most important of these facts was discovered by Hertz. He noted that light, when incident on a metal plate, may cause an emission of electrons that is independent of the intensity of the radiation. The simplest interpretation of this phenomenon is that light consists of particles that, because they are localized objects, can transfer all their energy to the photoelectrons during a collision. When the laws governing the photoelectrons were later discovered, it was found that the corpuscular or quantum theory, which postulates the emission of light discontinuously in isolated bundles of quanta, provided the explanation, whereas the continuous wave front of the wave theory failed to do so. Although the assumption that light is made up of localized particles enables us to explain the photoelectric effect in a very simple way, it cannot be made consistent with the extremely wide range of experiments leading to the conclusion that light is a form of wave motion. An example of the physical phenomenon that calls for wave interpretation is interference. Interference can be both qualitatively and quantitatively explained by the assumption that light is made of waves that can interfere either constructively or destructively so that under some circumstances the waves may cancel each other [13].

There are certain phenomena, therefore, that can be interpreted only by thinking of radiation as having a corpuscular nature or a kind of atomicity, the fundamental unit possessing a quantum of energy. One must not forget, too, that other phenomena, such as interference and diffraction, find a complete and satisfactory explanation by an ordinary (classical) wave theory. The modern position, then, is that radiation has a dual aspect. Sometimes one must think in terms of waves, sometimes in terms of photons. Thus, these two points of view are complimentary.

1.2.2 Identity of radiant energy and light

It can be demonstrated experimentally that radiant energy and light obey identical laws and have identical properties [12,13]. So far as their physical properties are concerned, heat rays are identical with light rays of the same wavelength. The term "thermal radiation" or more simply "radiation," then, will be applied to all physical phenomena of the same nature as light rays. As a further consequence of this resemblance, one can mention here some of the fundamental optical processes that pertain to heat transfer by thermal radiation. They are emission, absorption, scattering, and transmission, and their discussion is left for a later section.

Fundamental laws of geometric optics theory are: 1) the law of the rectilinear propagation of light; 2) the law of the independence of the different portions of a beam of light; 3) the law of reflection; and 4) the law of refraction. The rectilinear propagation of light, for example, is shown by the shadow of an opaque body that a point light source casts upon a screen [13]. Physical optics is concerned with such phenomena as light diffraction, interference, polarization, and dispersion. Experiments show, for example, that under certain conditions two parallel or nearly parallel beams of light do not produce increased intensity when superposed, but rather disturb each other's effects in such a way that darkness results [13]. This modification in intensity obtained by superposition of two or more beams of light is called interference. If the resultant intensity is zero or in general less than one expects from the separate intensities, we have destructive interference, while if it is greater we have constructive interference.

The passage of radiation from one medium to another causes the change in wavelength in the same proportion as it does in velocity since the frequency of propagation is not altered. Inasmuch as the wave front represents a surface on which the phase of motion is constant, it should be clear that regardless of any changes in velocity two different wave fronts are

0), and for highly scattering media when $\kappa_\lambda << \sigma_\lambda$, the medium and the albedo approach unity ($\omega_\lambda \rightarrow 1$). The single scattering albedo is an important characteristic scaling parameter in radiative transfer problems in the presence of scattering.

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