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.

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