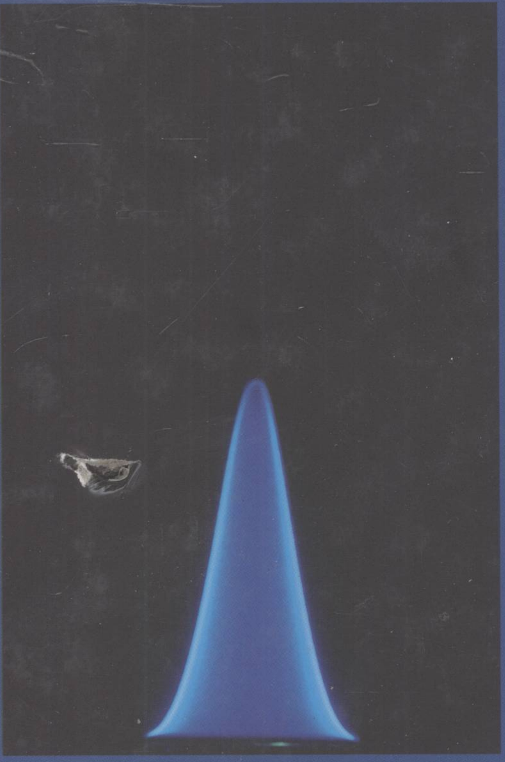
COMBUSTION PHYSICS



CHUNG K. LAW

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In the past several decades, combustion has evolved from a scientific discipline that was largely empirical to one that is quantitative and predictive. These advances are characterized by the canonical formulation of the theoretical foundation; the strong interplay between theory, experiment, and computation; and the unified description of the roles of fluid mechanics and chemical kinetics. This graduate-level text incorporates these advances in a comprehensive treatment of the fundamental principles of combustion physics. The presentation emphasizes analytical proficiency and physical insight, with the former achieved through complete, though abbreviated, derivations at different levels of rigor, and the latter through physical interpretations of analytical solutions, experimental observations, and computational simulations. Exercises are designed to strengthen the student's mastery of the theory. Implications of the fundamental knowledge on practical phenomena are discussed whenever appropriate. These distinguishing features provide a solid foundation for an academic program in combustion science and engineering.

Chung K. Law is the Robert H. Goddard Professor of Mechanical and Aerospace Engineering at Princeton University. He obtained his doctorate in engineering physics from the University of California at San Diego in 1973. His research interests are in combustion, propulsion, heat and mass transfer, and issues on energy and the environment. For his research accomplishments, he received the Curtis W. McGraw Research Award of the American Society for Engineering Education (ASEE) in 1984 for outstanding early achievement in research, a silver medal of the Combustion Institute in 1990, the Propellants and Combustion Award of the American Institute of Aeronautics and Astronautics (AIAA) in 1994, the Heat Transfer Memorial Award, in science, of the American Society of Mechanical Engineers (ASME) in 1997, the Energy Systems Award and the Pendray Literature Award of the AIAA in 1999 and 2004, respectively, and several awards for best conference papers. He is an original member of the Highly Cited Researchers database of the Institute for Scientific Information (ISI).

Professor Law is a former president of the Combustion Institute, a Fellow of the AIAA and the ASME, and a member of the U.S. National Academy of Engineering.

To my wife Helen
and to our children
Jonathan, Jennifer, and Jeffrey

Preface

Since the mid-1970s there has been truly significant advancement in combustion science, spurred by the dual societal concerns for energy sufficiency and environmental quality, and enabled by the rapid increase in the sophistication of mathematical analysis, computational simulation, and experimental techniques. Consequently, we have witnessed the evolvement of combustion from a scientific discipline that was largely empirical to one that is quantitative and predictive, leading to its useful applications in combustion-related engineering devices and practices.

This text reflects my desire to incorporate these advances in my lectures on combustion. As a result, its preparation has been guided by the three distinguishing themes characterizing recent developments in combustion research, namely the canonical formulation of the theoretical foundation; the strong interplay between experiment, theory, and computation; and the description of combustion phenomena from the unified viewpoint of fluid mechanics and chemical kinetics.

The text also emphasizes analytical proficiency by presenting complete, albeit abbreviated, derivations that can be followed by the student with a modest effort. Alternate solutions are sometimes presented to demonstrate that a phenomenon can often be analyzed using different approaches and at different levels of rigor. I hope that through this gentle guidance the student can acquire the needed confidence to tackle more difficult problems on his or her own.

This text grew out of the lecture material prepared for a one-year graduate course that I have given at several academic institutions. No prerequisite in mathematics, fluid mechanics, and chemistry is expected apart from the usual undergraduate education in the physical sciences or mechanical, aerospace, or chemical engineering. The text consists of three parts: Chapters 1 through 4 cover the basic components required to describe chemically reacting flows, namely thermodynamics, chemical kinetics, and transport phenomena; Chapters 5 through 10 cover descriptions of the basic combustion phenomena—those of governing equations, nonpremixed and premixed flames, the limit phenomena of ignition, extinction, and flame stabilization, and the aerodynamics of flames; Chapters 11 through 14 cover combustion in the four major classes of flows, namely turbulent, boundary-layer, two-phase, and supersonic flows. Since the amount of material treated in this text is substantial, the instructor may be more selective in the choice of topics. For example, discussion on reaction mechanisms, especially most of Chapter 3, can be omitted if chemistry is not emphasized in the course. Similarly, much of the materials that require extensive mathematical derivations, especially those of Chapter 9, can be omitted if strong mathematical experience is not intended. Furthermore, a one-semester course can be structured by abstracting materials from individual chapters, leaving the rest of the text for the enrichment of individual students.

While a serious attempt was made to make the text comprehensive in its coverage, it is nevertheless inevitable that some important topics were either excluded or inadequately presented. Feedback from readers on possible improvements in future editions will be very much appreciated. Similarly, because of the extensive literature in existence, it is also unavoidable that important references were inadvertently left out. Forbearance of the authors of these articles is requested.

In the preparation of this text I have been ably assisted by many of my present and former graduate students and research associates. In particular, I acknowledge with appreciation the following who have contributed substantially in this effort: John K. Becktold, Beei-Huan Chao, Peck Cho, Suk-Ho Chung, Fokion N. Egolfopoulos, Hong G. Im, Tianfeng Lu, Atsushi Makino, Matei I. Radulescu, Chih-Jen Sung, Hai Wang, Heyang Wang, and Delin Zhu. The manuscript was read in part or in whole by Professor Craig T. Bowman of Stanford University, Professor Sau-Hai Lam of Princeton University, and Professor Forman A. Williams of the University of California at San Diego. Their comments have been substantial and most useful, and I thank them sincerely for their collegiality and generosity.

It was by chance that I became a student of Professor Forman A. Williams in the spring of 1970. His influence on my intellectual and professional development has been profound. I am immensely thankful for his mentorship.

I reserve my most heartfelt appreciation for my wife, Helen Kwan-mei, for having transcribed the first drafts of this text, for constantly encouraging me to bring it to fruition, and for her patience and love over the years.

Chung K. Law
Princeton, New Jersery
January 2006

Contents

Introduction

This book is about combustion science and technology and, as such, covers not only the basic laws and phenomena related to the physics and chemistry of combustion, but also the implications of the fundamental understanding gained therein to the principles behind the practical combustion phenomena affecting our daily lives. It presents the diverse knowledge required of combustion scientists and engineers, the challenges they face, and the satisfaction they derive in providing the proper linkage between the fundamental and the practical.

In Section 0.1 we identify the major areas of practical combustion phenomena, illustrated by some specific problems of interest. In Section 0.2 we discuss the scientific disciplines comprising the study of combustion, and in Section 0.3 we present the classifications of fundamental combustion phenomena. An overview of the text is given in Section 0.4.

0.1. MAJOR AREAS OF COMBUSTION APPLICATION

It is fair to say that the ability to use fire is an important factor in ushering the dawn of civilization. Today our dependence on the service of fire is almost total, from heating and lighting our homes to powering the various modes of transportation vehicles. Useful as it is, fire can also be menacing and sometimes deadly. Wildland and urban fires cause tremendous loss of property and lives every year; the noxious pollutants from automotive and industrial power plants poison the very environment in which we live; and the use of chemical weapons continues to be an agent of destruction with ever greater efficiency. Combustion is certainly one branch of science that affects almost every aspect of human activities.

Practical combustion problems can be roughly divided into the following five major categories, in each of which we cite some examples of current interest.

Energy and Combustion Devices: Despite the large variety of alternate energy sources available, such as nuclear, solar, wind, hydroelectric, geothermal, and OTEC