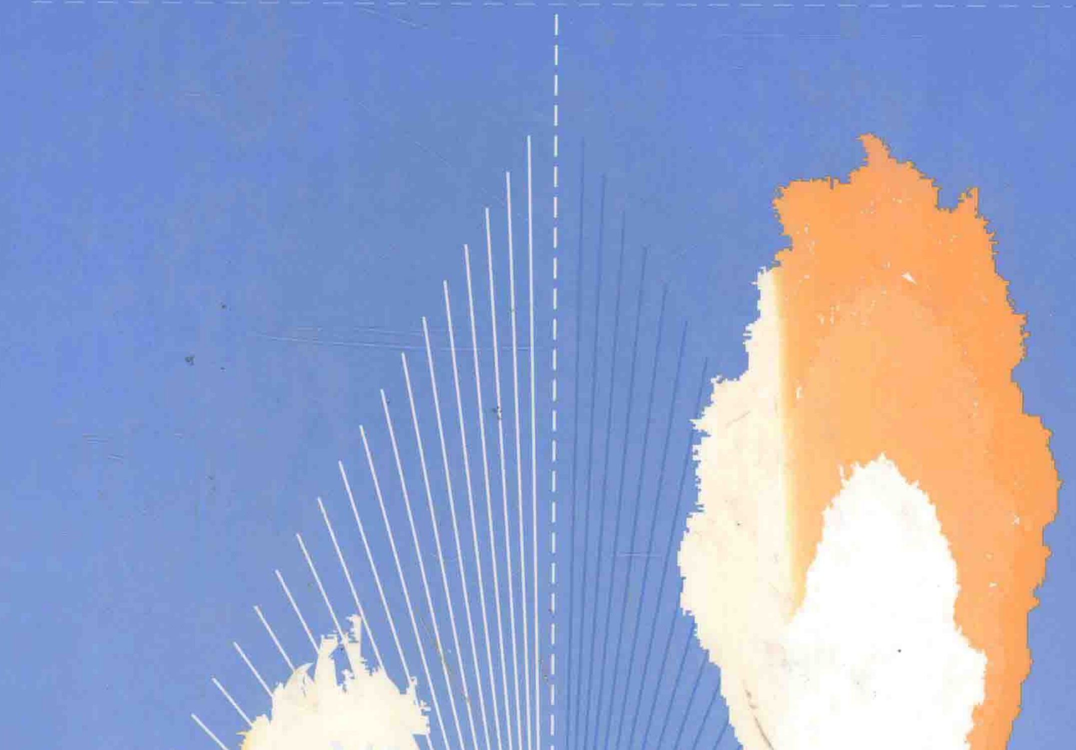
An Introduction to Combustion

Concepts and Applications



Stephen R. Turns

AN INTRODUCTION TO COMBUSTION
Concepts and Applications

Stephen R. Turns

Propulsion Engineering Research Center
and
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AN INTRODUCTION TO COMBUSTION
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Stephen R. Turns received degrees in mechanical engineering from The Pennsylvania State University (B.S., 1970), Wayne State University (M.S., 1974), and the University of Wisconsin at Madison (Ph.D., 1979). He was a research engineer at General Motors Research Laboratories from 1970 to 1975. He joined the Penn State faculty in 1979 and is currently Professor of Mechanical Engineering. Dr. Turns teaches a wide variety of courses in the thermal sciences and has received several awards for teaching excellence at Penn State. He is an active combustion researcher, publishing widely, and is an active member of The Combustion Institute, the American Society of Mechanical Engineers, and the Society of Automotive Engineers.

This Book Is Dedicated to
My Wife, Joan, and Our Sons,
Matthew and Michael

By contrast, the first fires flickering at a cave mouth are our own discovery, our own triumph, our grasp upon invisible chemical power. Fire contained, in that place of brutal darkness and leaping shadows, the crucible and the chemical retort, steam and industry. It contained the entire human future.

LOREN EISELEY
THE UNEXPECTED UNIVERSE

PREFACE

High interest in combustion and combustion applications exists among many engineering students. Although undergraduate, senior-level courses in combustion and combustion-related areas are offered at many institutions, finding an appropriate textbook for such courses is difficult, at best. The need for an introductory text on combustion, specifically structured for an undergraduate readership, has served as the motivation for writing this book. The offering of an introductory course at Penn State and the development of an introductory textbook were conceived jointly, and this book is the result of those developments.

Although the primary audience is intended to be senior-level students in mechanical and related engineering majors, others may find the text useful as a bridge between the basic undergraduate thermal sciences and advanced treatments of combustion. Many examples and problems are presented to aid in understanding and to relate to practical applications. Thus, is it hoped that both first-year graduate students and practicing engineers can benefit from the material presented here.

In its organization, the text provides flexibility. The 15 chapters provide much more material than can be covered in a single-semester course; this overkill makes it easy for an instructor to tailor a course to a particular theme or set of topics, while allowing the theme to evolve or change from one course offering to another. For example, a one-semester course providing a general overview could cover Chapters 1–6, 15, 8, 9, and 14; while a course with some emphasis on spark-ignition engines could cover Chapters 1–6, 8, 11, 12, 15, and 9.

Located in Chapters 1–3 are topics considered essential for an undergraduate course. Chapter 1 defines combustion and the types of flames, and introduces the effects and control of combustion-generated air pollution, which is treated in greater detail in Chapter 15.

The thermochemistry needed for a study of combustion is presented in Chapter 2. This chapter emphasizes the importance of chemical equilibrium to combustion. Software provided with this book provides students with a simple means of calculating complex equilibria for combustion gases; this software can be put to good use in many interesting and pedogogically helpful projects. Chapter 3 introduces mass transfer. The approach taken here, and throughout the book, is to simplify theoretical developments by treating all mass transfer within the context of simple binary systems. Except for a brief mention in Chapter 7, the treatment of multi-component diffusion is left to more advanced texts. Such an approach allows students with no previous exposure to mass transfer to gain an appreciation of the subject without getting bogged down in its inherent complexities. Chapter 3 uses both the classical Stefan problem and simple droplet evaporation to illustrate mass transfer theory.

Onward to the subject of chemistry, Chapters 4 and 5 deal with chemical kinetics by presenting basic concepts (Chapter 4) and discussing chemical mechanisms of importance to combustion and combustion-generated air pollution (Chapter 5). In addition to showing the unavoidable complexity of hydrocarbon combustion chemistry, simple single- and multi-step kinetics are presented that can be used to incorporate chemical kinetic effects in simple analyses or models, recognizing, of course, the pitfalls of simplified kinetics.

The interrelation of chemical kinetics and thermodynamic modeling is the subject of Chapter 6. Here, models of constant-pressure and constant-volume reactors, and well-stirred and plug-flow reactors, are developed. These simple models allow a student to clearly grasp how chemical kinetics fits into the bigger picture. This chapter also offers many opportunities for projects involving reactor analysis and/or design. Both the usefulness and uniqueness of this chapter make it a lot of fun.

Having completed our study of thermochemistry, molecular transport, and chemical kinetics, Chapter 7 is devoted to the development of the simplified conservation equations for reacting systems used in subsequent chapters. The conserved-scalar concept is introduced here. This chapter is intended to provide a background from which more rigorous developments can be followed. For an undergraduate course, this chapter is clearly optional, and is probably best skipped; however, for an introductory graduate-level course, the chapter may be quite useful.

Elementary treatments of flames are presented in Chapters 8–13. Laminar premixed flames are discussed in Chapter 8, and laminar nonpremixed flames in Chapters 9 and 10; while turbulent flames are dealt with in Chapter 12 (premixed) and Chapter 13 (nonpremixed). Topics treated include flame propagation, ignition and quenching, and flame stabilization. Simplified analyses are presented wherever possible, and practical applications emphasized. In all cases, rigorous mathematical development is eschewed in favor of developing the most basic understanding. This approach has the shortcoming of not being able to deal with some phenomena at all, and others, incompletely at best. Usually in these areas, warnings are given and references cited to help the reader who seeks a more complete understanding. Because of the wealth of material in these chapters, one can conveniently choose to cover only laminar flames (Chapters 8, 9, and 10) or to focus only on premixed flames (Chapters 8, 11, and 12) or nonpremixed flames (Chapters 9, 10, and 13). Particular emphases on specific applications might suggest which topics to cover.

Linking droplet vaporization theory to practical devices is the subject of the second half of Chapter 10, where a model of a one-dimensional vaporization-controlled combustor is developed. The primary purposes of this section are to reinforce previous concepts of equilibrium and evaporation, help develop students' powers of analysis, and to provide ideas and concepts that can be used in applications-oriented projects. Design projects can easily be fitted into the framework of Chapter 10. Depending on course objectives, this section of Chapter 10 can be treated as optional.

In Chapter 14, burning of solids is introduced, using carbon combustion as the archetypical system. Again, simplified analyses are presented to illuminate heterogeneous combustion concepts and to introduce the ideas of diffusionally and kinetically controlled combustion. This chapter also acquaints the student with coal combustion and its applications.

Omitting a treatment of combustion-generated pollutants would be unthinkable in a modern book on combustion. Chapter 15 focuses on this topic. This chapter introduces the reader to the quantification of emissions as well as discussing the mechanisms of pollutant formation and their control. This chapter emphasizes applications and should be of particular interest to the intended readers of this book. The placement of this chapter does not suggest its relative importance. Depending on course objectives, the material here could be covered following Chapters 1–6.

Now, in summary, this book attempts to present an introduction to combustion at a level easily comprehended by students nearing the completion of an undergraduate study in mechanical engineering and related fields. Through the use of examples and homework problems, students can develop confidence in their understanding and go on to apply this to various projects and "real world" problems. It is hoped that this text will fit the needs of instructors, and others, desiring simplified and appropriately structured materials for an introductory study of the fascinating field of combustion.

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University Park, PA

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Stephen R. Turns

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