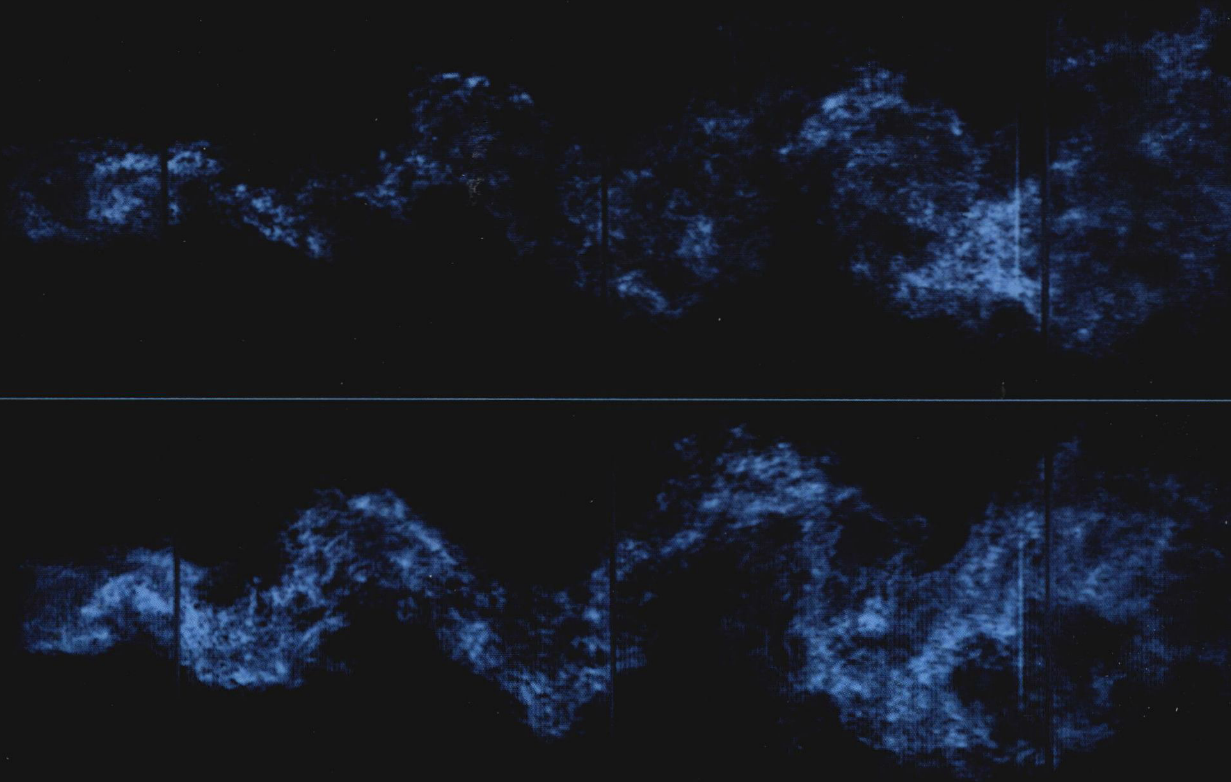
UNSTEADY COMBUSTOR PHYSICS



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UNSTEADY COMBUSTOR PHYSICS

Clean, sustainable energy systems are a preeminent issue of our time. Most projections indicate that combustion-based energy conversion systems will continue to be the predominant approach for the majority of our energy usage. Unsteady combustor issues pose one of the key challenges associated with the development of clean, high-efficiency combustion systems such as those used for power generation, heating, or propulsion applications. This comprehensive textbook is unique in that it is the first systematic treatment of this subject. This text places particular emphasis on the system dynamics that occur at the intersection of the combustion, fluid mechanics, and acoustic disciplines, synthesizing these fields into a systematic presentation of the intrinsically unsteady processes in combustors.

Tim C. Lieuwen is Professor in the School of Aerospace Engineering at Georgia Institute of Technology. Dr. Lieuwen's research interests are generally in the area of energy, environment, and propulsion, particularly in chemically reacting fluid mechanics and acoustics. He has edited 2 books, written 7 book chapters and more than 200 papers, and holds 3 patents. Dr. Lieuwen is editor-in-chief of the AIAA Progress in Astronautics and Aeronautics series and has served as associate editor of the *Journal of Propulsion and Power*, *Combustion Science and Technology*, and the *Proceedings of the Combustion Institute*. He is a Fellow of the ASME and is the recipient of various awards, including the AIAA Lawrence Sperry Award, the ASME Westinghouse Silver Medal, ASME best paper awards, Sigma Xi Young Faculty Award, and the NSF CAREER award. Dr. Lieuwen resides in Atlanta with his wife and four daughters.

Introduction

This book is about unsteady combusting flows, with a particular emphasis on the system dynamics that occur at the intersection of the combustion, fluid mechanics, and acoustic disciplines – that is, on *combustor* physics. In other words, this is not a combustion book – rather, it treats the interactions of flames with unsteady flow processes that control the behavior of combustor systems. Whereas numerous topics in reactive flow dynamics are "unsteady" (e.g., internal combustion engines, detonations, flame flickering in buoyancy dominated flows, and thermoacoustic instabilities), this text focuses specifically on unsteady combustor issues in high Reynolds number, gas phase, subsonic flows. This book is written for individuals with a background in fluid mechanics and combustion (it does not presuppose a background in acoustics) and is organized to synthesize these fields into a coherent understanding of the intrinsically unsteady processes in combustors.

Unsteady combustor processes define many of the most important considerations associated with modern combustor design. These unsteady processes include transient, time harmonic, and statistically stationary, stochastic processes. For example, ignition, flame blowoff, and flashback are transient combustor issues that often define the range of fuel/air ratios or velocities over which a combustor can operate. As we discuss in this book, these transient processes involve the coupling of chemical kinetics, mass and energy transport, flame propagation in high shear flow regions, hydrodynamic flow stability, and interaction of flame-induced dilatation on the flow field – much more than a simple balance of flame speed and flow velocity.

Similarly, combustion instabilities are a time-harmonic unsteady combustor issue in which the unsteady heat release excites natural acoustic modes of the combustion chamber. These instabilities cause such severe vibrations in the system that they can impose additional constraints on where combustor systems can be operated. The acoustic oscillations associated with these instabilities are controlled by the entire combustor system; that is, they involve the natural acoustics of the coupled plenum, fuel delivery system, combustor, and turbine transition section. Moreover, these acoustic oscillations often excite natural hydrodynamic instabilities of the flow, which then wrinkle the flame front and cause modulation of the heat release rate. As such, combustion instability problems involve the coupling of acoustics, flame dynamics, and hydrodynamic flow stability.

Turbulent combustion itself is an intrinsically unsteady problem involving stochastic fluctuations that are both stationary (such as turbulent velocity fluctuations) and nonstationary (such as turbulent flame brush development in attached flames). Problems such as turbulent combustion noise generation require an understanding of the broadband fluctuations in heat release induced by the turbulent flow, as well as the conversion of these fluctuations into propagating sound waves. Moreover, the turbulent combustion problem is a good example for a wider motivation of this book – many time-averaged characteristics of combustor systems cannot be understood without an understanding of their unsteady features. For example, the turbulent flame speed, related to the time-averaged consumption rate of fuel, can be one to two orders of magnitude larger than the laminar flame speed, precisely because of the effect of unsteadiness on the time-averaged burning rate. In turn, crucial issues such as flame spreading angle and flame length, which then directly feed into basic design considerations such as locations of high combustor wall heat transfer or combustor length requirements, are directly controlled by unsteadiness.

Even in nonreacting flows, intrinsically unsteady flow dynamics control many time-averaged flow features. For example, it became clear a few decades ago that turbulent mixing layers did not simply consist of broadband turbulent fluctuations, but were, rather, dominated by quasi-periodic structures. Understanding the dynamics of these large-scale structures has played a key role in our understanding of the time-averaged features of shear layers, such as growth rates, two-fluid mixing rates, or exothermicity effects. Additionally, this understanding has been indispensable in understanding intrinsically unsteady problems, such as how shear layers respond to external forcing.

Similarly, many of the flow fields in combustor geometries are controlled by hydrodynamic flow instabilities and unsteady large-scale structures that, in turn, are also profoundly influenced by combustion-induced heat release. It is well known that the instantaneous and time-averaged flame shapes and recirculating flow fields in many combustor geometries often bear little resemblance to each other, with the instantaneous flow field exhibiting substantially more flow structures and asymmetry. Flows with high levels of swirl are a good example of this, as shown by the comparison of time-averaged (a) and instantaneous (b–d) streamlines in Figure I–1. Understanding such features as recirculation zone lengths and flow topology, and how these features are influenced by exothermicity or operational conditions, necessarily requires a knowledge of the dynamic flow features. To summarize, continued progress in predicting steady-state combustor processes will come from a fuller understanding of their time dynamics.

Modern computations and diagnostics have revolutionized our understanding of the spatiotemporal dynamics of flames since publication of Markstein's *Nonsteady Flame Propagation* [1]. Indeed, massive improvements in computational power and techniques for experimental characterization of the spatial features of reacting flows have led to a paradigm shift over the past two decades in understanding turbulent flame processes. For example, well-stirred reactors once served as a widely accepted physical model used to describe certain types of flames, using insight based on line-of-sight flame imaging, such as shown in the top three images

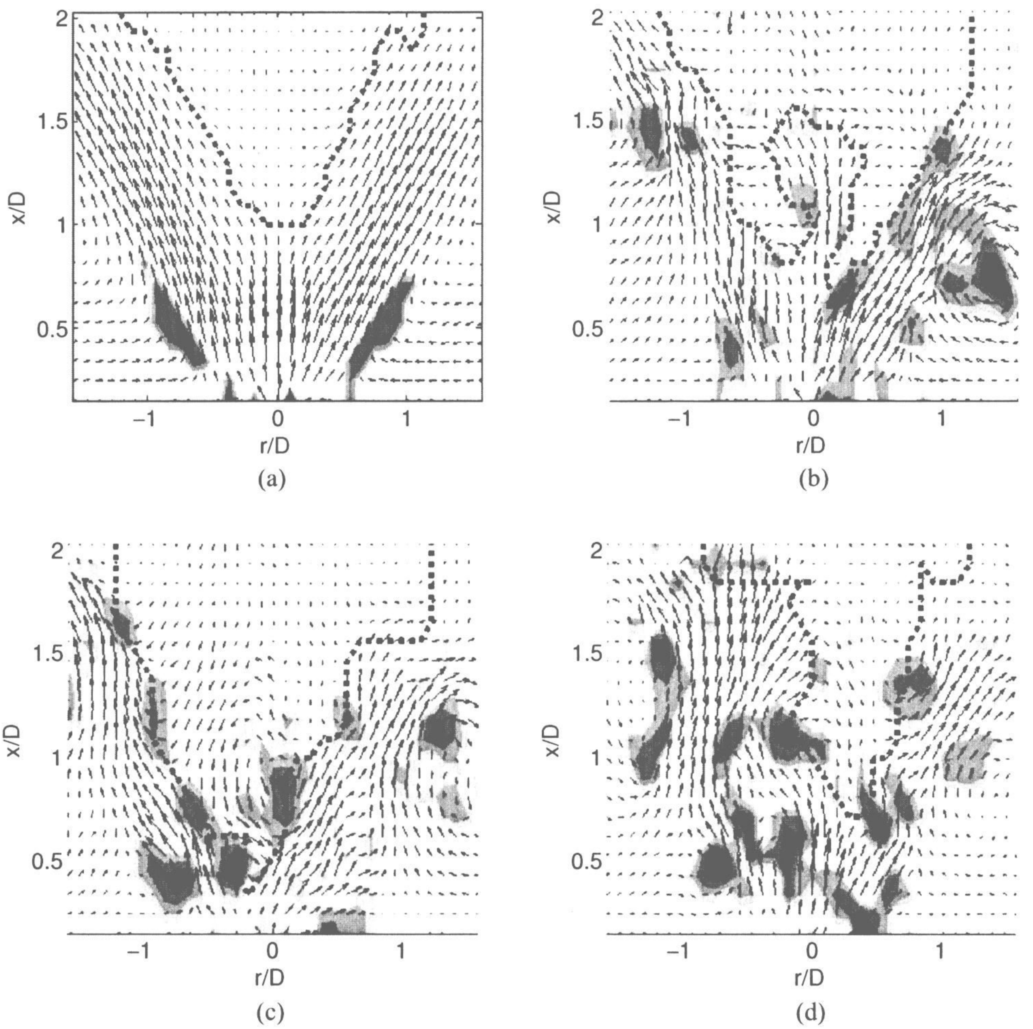

Figure I–1. (a) Time-averaged and (b–d) instantaneous flow field in a swirling combustor flow. Dashed line denotes iso-contour of zero axial velocity and shaded regions denote vorticity values. Image courtesy of M. Aguilar, M. Malanoski, and J. O'Connor.

taken from a swirling flow in Figure I–2. These descriptions suggest that the combustion zone is essentially a homogeneous, distributed reaction zone due to the vigorous stirring in the vortex breakdown region. Well-stirred reactor models formed an important conceptual picture of the flow for subsequent modeling work, such as to model blowoff limits or pollutant formation rates. However, modern diagnostics, as illustrated by the planar cuts through the same flame that are shown in the bottom series of images in Figure I–2, show a completely different picture. These images show a thin, but highly corrugated, flame sheet. This flame sheet is not distributed but a thin region that is so wrinkled in all three spatial dimensions that a line-of-sight image suggests a homogeneous reaction volume.

Such comparisons of the instantaneous versus time-averaged flow field and flame, or the line-of-sight versus planar images, suggest that many exciting advances still lie in front of this community. These observations – that a better understanding of temporal combustor dynamics will lead to improved understanding of both its

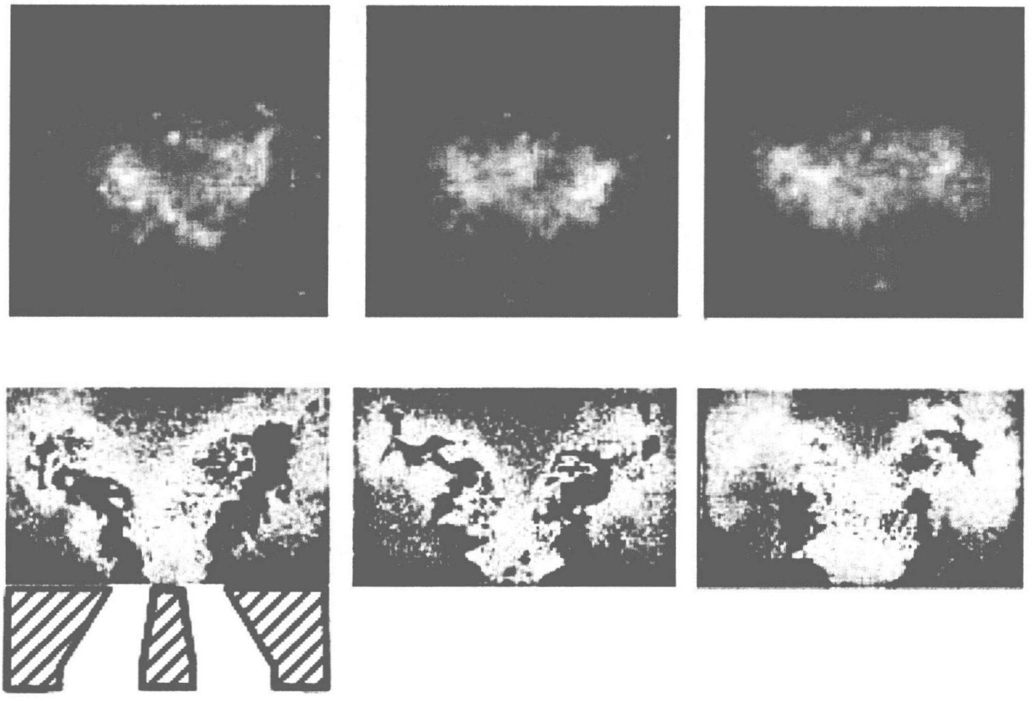

Figure I–2. Line-of-sight (top) and planar (bottom) OH-PLIF (planar, laser-induced fluorescence) images of turbulent, swirling flame [2]. Images courtesy of B. Bellows.

time-averaged and unsteady features – serve as a key motivator for this book. I hope that it will provide a useful resource for the next generation of scientists and engineers working in the field, grappling with some of the most challenging combustion and combustor problems yet faced by workers in this difficult yet rewarding field.

REFERENCES

[1] Markstein G.H., *Nonsteady Flame Propagation*. 1964: Pergamon.
[2] Bellows B.D., Bobba M.K., Seitzman J.M., and Lieuwen T., Nonlinear flame transfer function characteristics in a swirl-stabilized combustor. *Journal of Engineering for Gas Turbines and Power*, 2007. 129(4), pp. 954–961.

Overview of the Book

This section previews the structure and content of this book and provides suggestions for how readers of different backgrounds can use it most profitably. The bulk of Chapter 1 is dedicated to reviewing the basic equations to be used in this text. The remainder of the book is divided into three main sections: Chapters 2–6, 7–9, and 10–12. The first section, Chapters 2–6, discusses flow disturbances in combustors. Chapter 2 details how different types of disturbances arise and propagate in inhomogeneous, reacting combustor environments. By introducing the decomposition of flow disturbances into acoustic, vortical, and entropy disturbances, this chapter sets the stage for Chapters 3–6, which delve into the dynamics of disturbances in inhomogeneous environments in more detail. Specifically, Chapters 3 and 4 focus on the evolution of vortical disturbances in combustor environments. Chapter 3 provides a general overview of hydrodynamic stability theory and details some general features controlling the conditions under which flows are unstable. Chapter 4 then details specific canonical flow configurations that are particularly relevant to combustor environments, such as shear layers, wakes, and swirling jets. This chapter also discusses effects of flow inhomogeneity and acoustic forcing effects on flow instabilities.

Chapters 5 and 6 treat acoustic wave propagation in combustor environments. Chapter 5 provides a general introduction to acoustic wave propagation, boundary conditions, and natural acoustic modes. Chapter 6 then provides additional treatment of the effects of heat release, mean flow, and complex geometries on sound waves. This chapter also includes an extensive discussion of thermoacoustic instabilities.

The second section of the book, Chapters 7–9, incorporates reacting flow phenomena and kinetics. Chapter 7 details how flames influence the bulk flow field but does not treat internal flame processes explicitly. Rather, it focuses on the influence of the flame on pressure, entropy, vorticity, and velocity fields. Chapter 8 then treats auto- and forced ignition. Chapter 9 covers flames, first reviewing premixed and non-premixed fundamentals, then moving on to more complex topics such as flame stretch, flame extinction, and edge flames.

The third section of the book, Chapters 10–12, treats transient (in addition to the ignition processes discussed in Chapter 8) and time-harmonic combustor phenomena. Chapter 10 focuses on the transient, unsteady combustor issues of blowoff, flashback, and flame stabilization in general. Chapters 11 and 12 then focus on forced flame dynamics and discuss the interactions of these nominal flame dynamics with narrowband and broadband (turbulent) acoustic and vortical forcing.

The basic narrative is intended to be accessible to the new reader who has taken an introductory graduate course in fluid mechanics and has had an undergraduate exposure to combustion. Expanded discussions of various topics are also included in the "Asides." Although the book has been organized to be read through in the order the material is presented, there are several topical groupings of materials that readers using this text for reference will find useful. Readers particularly interested in hydrodynamic stability or large-scale structures in combustor flows can start with Chapter 2 to understand, first, the more general context of disturbance propagation modes. They can then proceed immediately to Chapters 3 and 4. Similarly, readers interested in acoustic phenomena can start with Chapter 2 and then proceed directly to Chapters 5 and 6. Those interested in thermoacoustics will also want to read Chapters 11 and 12 on forced flame response. Finally, those interested in flame stabilization, blowoff, and flashback phenomena can work through the material in Chapters 7, 9, and 10. In addition, readers specifically interested in expanded topics outside the scope of this text, such as supersonic and/or two-phase combustor physics, will find several of these topical groupings, such as hydrodynamic stability, thermoacoustics, or flame stabilization, to be useful introductions to foundational issues controlling dynamics of other flows.

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