Preface

The field of turbulent combustion has undergone significant progress since the first original paradigms for modeling turbulent combustion flows emerged more than 60 years ago. In the seventies, the emergence of computational fluid dynamics (CFD) and access to more advanced non-intrusive laser-based techniques for combustion measurements have enabled further development in the field. More recently, rapid progress in the modeling and simulation of turbulent flows has occurred. This progress may be attributed to different factors. First, we have access to more advanced computational and experimental resources. Advanced computational resources enable the computations of more realistic combustion flows with better description of the flow and chemical reactions. The higher access to computational resources also enabled the emergence of new paradigms in turbulent combustion simulation that address direct computations of unresolved physics. Turbulent combustion has long been considered a paradigm for multiscale problems and has long been identified as one of the important problems to solve, hence the increasing interest from the computational and applied mathematics communities.

Advanced experimental resources enabled measurements that serve as standards for validation. We cite here the great synergy created by the Turbulent Nonpremixed Flames (TNF) workshop and its counterpart, Turbulent Premixed Flames workshop. More experimental data is being made available online for validation, where in the past they can be gleamed only through plots from archival journals and reports.

A second impetus is the increasing requirements to design both efficient and clean combustion technologies. These technologies no longer represent operation at prescribed modes (e.g. premixed, non-premixed) or regimes (e.g. the flamelet regime). Computer simulation of turbulent combustion flows can potentially reduce the turn-around time for the expensive design cycle.

To cover all the progress in the field of turbulent combustion may be beyond the scope of a single volume; and chances are, revisions on such a volume may have to be started once it is published. However, some of the basic foundations that every researcher in the field relies on remain timeless and are covered by some recent textbooks and monographs. We cite here, for example, *Turbulent Combustion* by Peters [1]; *Theoretical and Numerical Combustion* by Poinsot and Veynante [2]; *Computational Models for Turbulent Reacting* Flows by Fox [3]; and *An Introduction to Turbulent Reacting Flows* by Cant and Mastorakos [4]. There are also books that have reviewed on a regular basis progress in the field. They include in particular the series *Turbulent Reacting Flows* edited by Libby and Williams. [5] [6] Extensive reviews in aspects of turbulent combustion models are also available in a number of journals and proceedings, including *Progress in Energy and Combustion Science*, *Proceedings of the Combustion Institute*, and *Annual Reviews of Fluid Mechanics*.

Having recognized the progress that has been achieved recently in the turbulent combustion field, we have adopted a two-pronged approach in this book. First, we have attempted to present to the reader the current state-of-the-art in advanced models in turbulent combustion. Here, we have attempted to avoid duplication of topics that are already covered in the aforementioned textbooks. Instead, we have emphasized more recent progress and have identified the current needs and trends associated with the state-of-the-art models in turbulent combustion.

Perhaps an important distinction between the present volume and the now classic Libby and Williams series is a greater emphasis on the topic of computation of turbulent combustion flows. This emphasis represents the second scope of the present volume.

The primary audience for this book is graduate students in engineering, applied and computational mathematics, and researchers in both academia and industry. It is assumed that readers have a good knowledge of the state-of-the-art models in turbulent reacting flows. Therefore, the book can serve as a graduate text or desk reference.

The book is divided into four major parts and includes 19 chapters. The first introductory part includes two chapters. The first chapter attempts to reassert the role of combustion science in the current energy debate and identifies the current challenges and requirements to advance the field forward. The second chapter summarizes the governing equations for turbulent reacting flows and motivates the various approaches needed to address the closure problem.

In Part II, the state-of-the-art and current trends of advanced turbulent combustion models are presented. The discussion addresses the flamelet approach (Chapter 3), models for premixed combustion (Chapter 4), the conditional moment closure model (Chapter 5), transported probability density function function meth-

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[1] Peters, N.: Turbulent Combustion, Cambridge University Press, Cambridge, UK (2000)

[2] Poinsot, T., Veynante, D.: Theoretical and Numerical Combustion, 2nd Ed., R.T. Edwards, Philadelphia, USA (2005)

[3] Fox, R.O.: Computational Models for Turbulent Reacting Flows, Cambridge University Press, Cambridge, UK (2003)

[4] Cant, R.S., Mastorakos, E.: An Introduction to Turbulent Reacting Flows, Imperial College Press, London, UK (2008)

[5] Libby, P.A., Williams, F.A. (Eds): Turbulent Reacting Flows, Springer-Verlag, Berlin Heidelberg, Germany (1980)

[6] Libby, P.A., Williams, F.A. (Eds): Turbulent Reacting Flows, Academic Press, London, UK (1994)

ods (Chapter 6), and the multiple mapping conditioning approach (Chapter 7). These chapters introduce aspects of the model formulations, illustrate the models through examples and identify challenges and trends in advancing these modeling approaches.

Part III addresses multiscale approaches in turbulent combustion. Chapter 8 motivates requirements for multiscale scale models in combustion and summarizes current approaches. Chapter 9 addresses methods and strategies for the integration and acceleration of chemistry in reacting flow computations. Chapters 10, 11 and 12 present the linear-eddy, the one-dimensional turbulence and the unsteady flame-embedding approaches as multiscale strategies based on hybrid solutions combining coarse-grained and fine-grained approaches. The following two chapters illustrate multiscale strategies through mesh-adaptivity based on the adaptive mesh refinement approach (Chapter 13) and the wavelet approach (Chapter 14).

The final part of the book, Part IV, presents what is termed 'cross-cutting science'. It samples important disciplines that are relevant to advancing the field of turbulent combustion. The first discipline is associated with the topic of validation and verification. Chapter 15 reasserts the role of experiment in advancing turbulent combustion models. The second discipline is associated with requirements to manage large-scale computations associated with turbulent combustion. This discipline is represented by two chapters. Chapter 16 reviews recent progress and trends in uncertainty quantification. Chapter 17 discusses a computational framework, based on the common component architecture, as a strategy to efficiently develop computational tools for advancing science. Examples are presented in this chapter for combustion flows. The third discipline is multiscale science. An important role of multiscale mathematics is the construction of frameworks to couple models designed for disparate scales. Chapter 18 illustrates the development and implementation of such frameworks for combustion using the heterogeneous multiscale method. The fourth discipline is associated with the choices of the governing equations for turbulent reacting flows. The Navier-Stokes equations in their instantaneous or filtered forms are the most popular forms of representing turbulent combustion flows. Chapter 19 discusses progress on an alternative representation of the governing equations based on the lattice-Boltzmann method. The method may serve as an alternative to the continuum-based Navier-Stokes equations where potentially closer coupling with atomistic scales is needed.

This book is a collaborative effort that has involved researchers/experts from different disciplines. This is a reflection of how complex the theme of turbulent combustion has become. It could not have been completed without the expert opinion, the patience and the diligence of the 31 contributors.

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