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REVIEW

Turbulent Reacting Flames. Edited by P. A. Libby and F. A. Williams. Academic Press, 1994. 647 pp. ISBN 0 12 447945 6. £100.

This book is a tutorial review of developments in the theory of turbulent combustion during the last decade. It is essential reading for all researchers interested in a quantitative understanding of the nature of flame. The first four chapters, in which Libby, Williams, Bray and Peters feature prominently as authors, provide the essential background with the presentation of the governing equations and how they might be treated. The central problem is the combination of Kolmogorov's energy cascade with large numbers of chemical reactions involving chain initiation, branching, and termination. Early in the most fundamental first chapter by Libby and Williams we are disabused of any idea that current computing power will allow direct numerical simulation at realistic Reynolds numbers. Nevertheless, in restricted regimes this approach is valuable for scrutiny of some of the modelling assumptions currently made to achieve closure and of the solubility of the equations.

Constant-density non-reacting flow modelling assumptions can become invalid for the large density variations in combustion. In the familiar $k-\epsilon$ model the first-moment Favre-averaged equations are closed by replacing the Reynolds stresses and fluxes by a turbulent coefficient and first-moment gradients. Second-order closure avoids this and retains the anisotropy of these equations. Importantly, the mean pressure gradient terms give rise to counter-gradient diffusion and turbulence generation, which are absent in constant-density flows. There are closure problems also with the dissipation terms in these equations, as well as with the turbulent energy dissipation (ϵ) equation. These are further discussed by Bray and Libby in chapter 3.

In non-premixed flames, where the concept of a conserved scalar is used, important closure problems arise in the second-moment equations. There is a full discussion of this in chapter 5 by Chen and Kollman, who point out that, were it not for the large variations in density, the conserved scalar mixing in combustion would be analogous to the two-stream mixing of water jets. Their chapter also considers conditional moment methods, and is one of the few chapters with detailed comparisons with experimental flame measurements.

Despite all these problems, some reassurance is provided by Jones in chapter 6, which deals with turbulence modelling and numerical solution methods. He argues that the re-writing of turbulence closures derived for constant-density flows in terms of Favre-averaged quantities is often sufficient for a reasonably accurate representation of turbulent transport in many variable-density combusting configurations.

With regard to the treatment of the chemical source term, the early Ray–Moss premixed flame model assumes reaction to be rapid within thin surfaces and the p.d.f. of the reaction progress variable to be dominated by delta functions for reactants and products. The mean rate of creation of product is then related to the mean scalar dissipation of the progress variable. If the questionable assumption is made that this dissipation can be modelled in the same way as the scalar dissipation in constant-density non-reacting flows the well-known eddy-break-up expression of Mason and Spalding is obtained and mixing rates dominate over chemical rates. Such expressions, though widely used in engineering codes, cannot be generally valid and more detailed chemistry can be incorporated through flamelet models. Currently, these provide one of the most popular and practically rewarding approaches. In them, a turbulent flame is an ensemble of thin laminar locally one-dimensional structures, molecularly dominated, that are embedded within the turbulent flow field. This can conveniently uncouple, then recouple, chemical kinetics and aerodynamics. The different varieties of flamelet modelling, particularly for premixed combustion, and including the important influence of flame stretch rate, are reviewed in chapter 2 by Bray and Peters.

Detailed chemical kinetics feature in the fourth chapter, by Seshadri and Williams, with emphasis on the derivation of reduced chemical systems that are amenable to incorporation in analyses of turbulent reacting flows. Such systems rest upon appropriate selection of the kinetic mechanism, steady state, and partial equilibrium assumptions and mathematical truncation. Reduced systems are particularly relevant to direct p.d.f. methods. In principle, with such methods, the chemical source terms are handled without approximation. Nevertheless, as Dopazo's comprehensive review of such methods in chapter 7 makes clear, in practice reduced step mechanisms are necessary. Additional problems that arise in p.d.f. methods involve the modelling of p.d.f. fluxes due to fluctuating pressure gradient and molecular transport processes.

In chapter 8 on spectral and random vortex (Lagrangian) methods, Givi argues that closure always suppresses most of the interesting dynamical information, since it has been modelled *a priori*, and argues for model-free simulations, albeit over a limited range. These include studies of the influence of turbulence on chemistry at low Reynolds numbers in direct numerical simulations. In contrast, large-eddy simulations involve a degree of modelling of the subgrid scale.

In chapter 9, Bray, Champion and Libby point to the advantages for experimental studies of opposed jet turbulent flames in stagnating turbulence. The final chapter 10 by Bray, Libby and Williams deals with the rather neglected area of high-speed turbulent combustion, in which shock waves may be present, but are not essential for combustion. The starting point is the treatment of compressible turbulence without reaction. In sufficiently strong detonation waves, cellular structure is suppressed and a detonation wave can be stabilized in a supersonic flow of a combustible mixture. Here reduced mechanisms for hydrogen combustion and autoignition phenomena are important.

This important book should be on the library shelves of every institute with an interest in combustion. It rightly claims to provide an entry to the recent literature. This reviewer, however, is a little uneasy at the not uncommon tendency in multi-authored 'updating' reviews to omit references to, and discussions of, past seminal papers. Burke and Schumann are mentioned, but not their classical paper of 1929 which, contrary to the intention of its authors, had an enormous influence in encouraging combustion models without chemistry. We meet the Markstein number, but no reference to the work of this formidable researcher. The Zeldovich number appears in different contexts in different forms, but there is no reference to his seminal papers with Frank-Kamenetskii in 1938, discussion of which could have helped the reader to a better understanding of it. Logical explanation and comprehension of a subject is enhanced by at least an outline explanation of its historical evolution.

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