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BOOK REVIEW

Fundamental Aspects of Combustion. By A. Liñan & F. A. Williams. Oxford University Press, 1993, 167 pp. ISBN 019507626 5. £25.

This book, by two of the leading exponents of combustion science, 'is addressed to an audience of mature and scientifically literate readers, in both industry and academia, who have not specialized in combustion'. After a brief introduction to the history of combustion science and its applications, chapter 1 presents the general conservation relations for a chemically reacting medium, with no fewer than 17 dimensionless groups – on the supposed largeness or smallness of many of which much progress has been made in theoretical combustion science in the last 20 years. There is little more than mention of kinetic theory approaches to determine the various species diffusion velocities; for the rest of the book the common reduction to Fick's gradient law is adopted. Common combustion processes are then classified together with the basis for the most important asymptotic schemes; fast chemistry (large Damköhler number), reaction-rate-ratio asymptotics; and large activation energy asymptotics (large Zel'dovich number), with emphasis on the fundamental distinction between premixed and diffusion systems. Next, the Rankine–Hugoniot relations for an exothermically reacting gas are derived, and the ideas of deflagration, detonation, and Chapman–Jouguet points introduced in the (p, V) phase diagram. This last very important material would have benefited from an expanded treatment. Even with a reasonable background in the dynamics of inert gases the reader will have to take much on trust; sometimes enlightenment is provided later, sometimes never.

The laminar flame in a premixed system is the focus of chapter 2. Mikhel'son gave an estimate of the laminar flame velocity as early as 1899 – as the square root of the ratio of thermal diffusivity to reaction time. That estimate implies a simple structure for the fields within the flame, and for large Zel'dovich number β ($\beta = 10$ typically) it is now known that the simple structure splits into an upstream preheat zone, followed by a much thinner reaction–diffusion zone. Analysis of this by matched expansions for large β shows that the Mikhel'son formula is incorrect by a factor β, and that two-term asymptotic expressions give reasonable agreement with the results of numerics and experiment. In the discussion of all this, chapter 2 also gives a good description of the 'cold boundary problem': *sufficiently* far ahead of the nominal flame location, the gas has been slowly heating up for a long time, and will in fact be 'burnt' rather than 'fresh'. The implication is that the laminar flame velocity of a mixture is not a purely chemico–thermal property, but in fact a function of the entire system, with significant dependence on remote geometry.

Chapter 2 also discusses flame stability, identifying four instabilities essentially associated with combustion, and three arising from interaction with unsteady flow. As the authors remark, it was indeed courageous of Darrieus (1938) and Landau (1944) to publish – in the face of laboratory evidence of the existence of stable planar laminar flames – analyses showing the instability of a plane flame sheet to disturbances of all wavenumbers. All real flames are unstable to the Darrieus–Landau mechanism. Gravity cuts off the long-wave instability for downward-propagating waves, and it might be expected that diffusion provides the short-scale cut-off, but that is not the case unless the Lewis number L (ratio of thermal diffusivity to species diffusivity) exceeds unity. For $L \leqslant 1$ radiant heat loss is needed to control the short-scale catastrophic instability. These issues are discussed on a physical basis for the flame sheet model, and the many instabilities interpreted in the plane of (L, heat loss). Given the fundamental importance of all this, an expanded treatment would again be valuable; diffusive–thermal instabilities are said to lead to many interesting observed flame features, including cellular flames, rotating polyhedral flames and spinning deflagrations.

Laminar flame velocity dependence on equivalence ratio is obviously important: the simplest model gives maximum velocity at stoichiometry (equivalence ratio unity), while experiment shows that this can also occur on the fuel-rich or fuel-lean sides. Experiments were difficult until the recent advent of laser Raman spectroscopy. Computation remains difficult for large numbers of species; there is always the cold boundary problem to contend with, and the steady-state equations have singularities at the end-points. To avoid the latter one can integrate the unsteady equations forward in time to a steady state – and then try to control the plethora of instabilities! The best procedure is to use activation energy asymptotics and rate-ratio asymptotics for intermediate reactions ('fast chemistry' for the intermediaries) and then to compute solutions to the simplified equations; this gives a significant reduction in computational complexity, and deeper understanding. Chapter 2 goes into these issues for the hydrogen–halogen reaction, for the hydrogen–bromine reaction, and in general terms for hydrocarbon–air reactions. The latter are very complex; even a common simplified scheme has 31 steps, while more than 200 are often now included in computations. Liñan & Williams show, nevertheless, the effectiveness of a four-step description plus rate-ratio asymptotics, in comparison with experimental data.

Chapter 2 ends with a table of seven deflagration problem areas needing further attention. These are broad and challenging – for example 'stability of planar, curved and stretched flames with model and real kinetics', and 'nonlinear structure and flame extinction at cusps'. Good references, of both recent and older vintages, are provided in this chapter, as indeed throughout.

For diffusion flames, treated in chapter 3, and epitomized by the planar flame in the stagnation-point flow created by counterflowing streams of oxidant and reactant, there is no flame velocity as such, and interest lies in the flame structure, conditions for existence and extinction, and rates of transport and energy release. The authors concentrate on elementary problems as potential input to general kinetic theory formulations of diffusion flame processes – such as, for example, a multi-phase (droplet–oxidant) model for spray combustion. If the fuel–air mixture ratio Z is introduced as a coordinate normal to the flame, then in the fast-chemistry limit one gets a local reaction–diffusion structure in a narrow zone around $Z = Z_c$ (stoichiometry). More complex chemistry gives widely separated zones of fuel and oxidizer consumption, and an overall flame structure with multiple sub-structures. Activation energy asymptotics instead of fast chemistry produces an S-curve for maximum temperature versus Damköhler number, and so can predict ignition and extinction values of the Damköhler number. This theory can be used in counterflow experiments to infer a value for the activation energy E, experimental data giving a convincing validation of the Arrhenius rate law and a consistent determination of E. As a second demonstration of the effective use of asymptotics, the burning of a spherical fuel droplet is considered. A quasi-steady analysis for the fuel–air ratio Z gives droplet and flame radii as functions of time in reasonable agreement with experimental data acquired in a free-fall apparatus. Problems of flame spread – for example through a fuel bed of sticks – are also considered, with physical arguments for the speed of spread as a function of the bed parameters. Many other important applications are mentioned here, as indeed elsewhere in the book.

By way of conclusion, chapter 3 also has seven broad and challenging areas for further study, e.g. flame spread over liquid with buoyancy and surface tension.

Flammability, explosions and detonations come next, in chapter 4. Two points in particular are to be stressed: first the self-accelerating aspects of combustion, and second that here, though not previously in the book, large pressure changes occur except in the initial stages of an explosion. Chain branching, producing an increase in the rate of hydrogen and hydrocarbon combustion as concentrations of the active species H, OH and O increase, leads to exponential increase if, as is often the case, consumption rates of the active species fall below thresholds. More drastic still is the self-acceleration of Arrhenius chemistry which, in the 'induction phase' leads to a logarithmic singularity along some ignition locus $t = t_i(\boldsymbol{x})$ in finite time, a singularity removed only by fuel depletion or heat loss. This is illustrated by a model problem for spatially homogeneous thermal explosion, involving an inverse activation energy $\epsilon \sim 10^{-2}$ and a Frank–Kamenetskii parameter δ (ratio of the heat loss time to ignition time); what is at stake is the critical $\delta = \delta_c(\epsilon)$ for thermal runaway. This critical δ is discussed for plane, cylindrical and spherical geometry. Of particular note is the increase of δ_c with the linear size of the system. Piles of fertilizer exceeding the corresponding size are liable to suffer an explosion, and too large a pile of oily rags will burst into spontaneous deflagration.

In the later stages of thermal runaway, localized hot spots will develop, sensitively related to the initial conditions, ignition fronts will propagate through the medium, and pressure waves will be generated, leading, possibly, to the launching of a detonation in a sufficiently large system.

'Minimum ignition energies' are discussed in this chapter, but are not at all precisely defined – perhaps, on reflection, not surprisingly, because ignition itself is not precisely defined except in the context of an over-simplified mathematical model exhibiting a singularity that one can precisely identify with ignition. This topic needs nonlinear p.d.e.'s for its description, exemplified here by a model for one-dimensional diffusion of temperature with an Arrhenius source term and heat influx in across a boundary. Even with fuel depletion ignored, as here, a complicated structure of space–time regions in which different balances prevail is revealed by activation energy asymptotics.

Strong coupling with gasdynamics is found for the first time in analysis of a detonation wave. Here a strong leading shock is followed by a long 'slow' induction zone, then by a narrow zone of convection–reaction balance and rapid temperature rise. The chemistry is slowly varying except in the final zone, and gasdynamics slowly varying except in the leading shock. Too briefly discussed is the famous ZND (Zel'dovich–von Neumann–Döring) wave of a strong detonation (subsonic flow behind), and the arguments, anticipated in chapter 1, for the realization in practice only of strong detonations or CJ detonations (sonic flow behind). Simple formulae are derived for detonation propagation velocities ($\sim 10^3$ m s^{-1}) and for the length scales associated with different parts of the detonation wave structure.

There is an instability of the ZND wave of a type familiar in conventional fluid dynamics and leading to the generation there of various discrete-frequency feedback loops. There, as here in the ZND wave, the processes are of downstream convection and upstream acoustic propagation, leading to a pulsating instability and a 'galloping detonation'. Spectacular photographic evidence exists for such galloping detonations in the wake of high-speed projectiles fired into reacting media. (Milton van Dyke might wish to include one of these beautiful photographs, showing dozens of spatial cycles of the instability, in a future edition of his book *An Album of Fluid Motion*, Parabolic Press, Stanford, 1982.) Transverse modes are often more unstable, in detonations in tubes, than the planar mode, and produce cellular detonation patterns on the tube walls which are easily visualized. The 'spinning detonations' reported nearly 80 years ago are simply the mode-1 versions.

How the deflagration-to-detonation transition (often mediated or initiated by turbulence – the 'explosion within an explosion', to quote J. W. Meyer & A. K. Oppenheim, 1971, *13th Intl Symp. on Combustion*, pp. 1153–1164, The Combustion Institute) proceeds is a research topic of intense current interest, especially with regard to the effects of turbulence and of lateral confinement. A significant point noted on p. 108 is that a detonation can be effectively confined even by material like thin plastic sheets quite unable to withstand the steady pressure difference associated with a strong detonation; for short times it is inertia which dominates.

Once again, seven areas of work in ignition and explosion and a further seven in detonation are identified for further work, e.g. 'effects of size and shape of hot body or of reactive medium in explosion'; and 'three-dimensional stability of planar detonations'.

Not surprisingly, chapter 5 on turbulent combustion is the most difficult, and also not surprisingly the one that lends itself least well to the very compressed kind of overview attempted in this book. It starts well enough, with a discussion of velocity and length scales to motivate the distributed reaction and wrinkled laminar flame sheet models. The discussion is terse, though balanced, but not helped notationally by the authors' insistence on writing $(2k)^{3/2}/l$ instead of the usual ϵ for the dissipation rate in all the familiar Kolmogorov formulae; ϵ itself is introduced finally on p. 141, but too late! The presentation then follows at an increasingly breathless pace, so that in flame sheet stretching, hole punching through extinction, and fractal description of a flame sheet with holes, one can do little more than register the introduction of these buzz words. For the ratio $y = v_T/v_0$ of turbulent to laminar flame velocity, $y = f(x)$, $x = (2k)^{1/2}/v_0$, the reader is rapidly offered the alternatives $y = 1+x^{4/3}$, $y = 1+x^2$, $y = 2.4x^{0.7}$, $y = 1.4x$ and $y = x/(\ln y)^{1/2}$, with too little discussion to have any idea of the status of any of them, still less to understand why the last of these 'retains the essential physics'.

For turbulent diffusion flames, the postulate that the state variables are unique functions of the mixture fraction Z receives impressive experimental confirmation on p. 134, where our attention is also drawn to the almost linear variation of $T(Z)$, which would come from the reaction sheet model $\partial^2 T/\partial Z^2 = \delta(Z-Z_c)$. But such significant information is diluted by the writing out of the most elementary definitions of probability theory. A point of particular interest to workers in turbulence modelling is that negative turbulent diffusivities are forced by the interaction between modelling assumptions made for the closure of the turbulence and chemical hierarchies, a defect which can apparently be obviated by second-order closure approximations. Later subsections deal with Liouville–Boltzmann formulations for the probability density, with expansion methods, with purely *ad hoc* field models ('age theory', etc.) making no reference to the underlying conservation equations, and with various approaches to direct numerical simulation. The authors emphasize the chaotic sensitivity within individual realizations, but expect weak sensitivity of the statistics on the basis of a generalized appeal to dynamical systems ideas that is not always confirmed in, for example, turbulent shear flows of inert gas. Nine outstanding problems are listed in turbulent combustion, many of a very deep character.

I have written at considerable length here for several reasons. First, publication of a book by two of the great contributors to the field – and, let it be said, two of the great expositors of the field – calls for an extensive review, even though the book itself is short, and leaves out much almost essential detail. Secondly, Professor Williams' own well-known and influential book (*Combustion Theory*, 2nd edn, 1985, Addison-Wesley) has for some time been out of print, and those without a copy readily to hand will have to rely on the book under review rather more than perhaps its authors intended. Thirdly, the field of combustion science is so strongly related to conventional fluid mechanics in so many ways of approach as well as of physics, and offers so many opportunities for creative contributions from fluid dynamicists, that the contents and undoubted virtues of this book should be brought to the attention of readers of *JFM*. Fourthly, I did not find this an easy book to read and digest, rewarding as the effort ultimately was. 'Delicious' was the word used by Paul Clavin, during a lecture, to refer to the book, but I needed several readings before grasping the outlines of some of the arguments. If these notes help or stimulate others to read this book, the effort in writing them will have been worthwhile.

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