J. Fluid Mech. (2015), vol. 766, pp. 656–658. © Cambridge University Press 2015
doi:10.1017/jfm.2015.67

BOOK REVIEW

Unsteady Combustor Physics. By T. C. Lieuwen. Cambridge University Press, 2012. 426 pages. ISBN-13:978-1107015999, ISBN-10:0174246978.

At a system level, the flow through the combustion chamber of a rocket or aircraft engine is usually considered to be steady. Nevertheless, some of the most crucial features and persistent problems in rocket and aircraft engines arise because the flow is unsteady. On the one hand, flames must be turbulent, and therefore unsteady, in order to achieve sufficient heat release per unit volume for propulsion applications. On the other hand, unsteady flow causes (i) hot spots and cold spots in flames, which lead to excessive NOx and unburnt hydrocarbon emissions, (ii) higher heat transfer to the walls, which then need careful thermal management, (iii) flame flash-back and blow-off, which gravely disrupt the performance of the engine, and (iv) thermoacoustic oscillations, which cause severe vibrations and can lead to catastrophic failure. The problems caused by unsteady combustor physics have been known since the 1930s and there has been continual motivation from industry to solve or at least mitigate them. Progress has been steady but many problems remain. There is no realistic alternative to combustion as an energy-conversion process in aerospace because such high energy densities are required. Therefore research in this area will continue to be important for several decades to come, providing the motivation for this book.

Existing textbooks relevant to unsteady combustor physics tend to be devoted to acoustics, combustion, and hydrodynamics as single disciplines. For example, thermoacoustic oscillations are often treated from the point of view of acoustics, with the unsteady heat release treated as a simple time-delayed function of the acoustic velocity or pressure. While this captures the main physical mechanism that drives many thermoacoustic oscillations, a more detailed analysis requires modelling of the flame's hydrodynamic response to acoustic forcing, which depends strongly on its hydrodynamic stability, and modelling of the heat release caused by combustion at the strained and possibly broken flame. Combustion itself is a well-studied discipline and several excellent books are already devoted to it. However, the most important mechanisms in unsteady combustor physics do not require the level of detail that is found in these textbooks. In many cases, single-step chemical reactions are sufficient, as long as they are combined with the influences of hydrodynamic stability and acoustics.

In response to these requirements, this book combines hydrodynamics, acoustics, and combustion to provide a detailed description of the most important physical processes at play in a combustor.

The book starts with a general introduction to the basic equations of fluid mechanics and a brief introduction to perturbation methods as applied to combustor physics, including the decomposition into acoustic, entropy, and vortical disturbances. This is an informative way to categorize the unsteady components of the flow inside a combustor because the couplings between each type of disturbance can be modelled readily, for example at boundaries, nonlinearities, and mean flow inhomogeneities. There is also a brief introduction to linear stability analysis and nonlinear dynamics, both of which are used extensively in the study of combustor physics. After these introductory comments, the book is divided into three parts.

https://doi.org/10.1017/jfm.2015.67 Published online by Cambridge University Press

The first part deals with the stability of incompressible flow, particularly with regard to instabilities that are relevant to combustors. The most important of these are the Kelvin–Helmholtz instability in single shear layers and the von Kármán instability in wakes. This necessitates a discussion of temporal and spatio-temporal instability analysis and the phenomena of local absolute and convective instability. The structures that develop in a globally unstable shear flow are described with clear diagrams and several images from experiments. This part contains a description of backward-facing step and cavity flows, which are canonical geometries encountered in combustors. This is an impressive summary of the elements of hydrodynamic stability that are most relevant to combustors and sets the scene for later chapters on the dynamics of similar flows that also contain flames.

The first part continues by dealing with acoustics. The book does not assume any prior knowledge of acoustics so this is a stand-alone graduate-level introduction to the subject. It includes mean-flow effects, acoustic damping processes, and the influence of unsteady heat release, which is central to thermoacoustic instability. At every stage, this introduction to acoustics is placed within the context of gas turbine engines. This leads to a description of the physics behind thermoacoustic instability and the derivation of a useful toy model of this instability. Crucially, nonlinear dynamics is included, which is particularly important in thermoacoustics because limit cycle behaviour is often substantially different from linear behaviour around steady solutions. This reflects the progression of combustor physics over the decades, from steady flow analysis, to linear stability analysis around steady flows, to fully nonlinear analysis within the framework of dynamical systems theory. A mention of weakly nonlinear analysis would have been useful here because it can reveal the aspects of a thermoacoustic system (for example heat release nonlinearities or acoustic nonlinearities) that determine whether bifurcations are subcritical or supercritical.

The second part considers the flames inside combustors and how they interact with the flow around them. It starts with an overview of the aspects of combustion that are most relevant to combustor physics. This includes the jump in fluid properties across a premixed flame, the influence of the flame thickness, the influence that a flame has on vorticity, flame roll-up induced by hydrodynamic oscillations and the change in heat release due to flame stretch. Detailed chemistry is not required here and is excluded, which adds to the clarity of the presentation. This part continues by considering autoignition and forced ignition (e.g. by a spark) in a premixed combustor. This inevitably requires some description of the chemical species and reactions involved in a flame. This is perhaps the lightest section of the book and provides just a basic introduction to the field. This is reasonable because many other textbooks and review articles are devoted to this subject. The second part finishes by describing the structure and behaviour of premixed and non-premixed flames. The heat release rate from premixed flames depends not only on quasi-steady properties such as pressure, temperature, and stoichiometry, but also on unsteady processes such as fluid mechanical shear and instantaneous flame curvature. The level of detail is sufficient to explain these dependencies physically, without overwhelming the reader with detail. The heat release rate from non-premixed flames is less interesting in the context of this book and depends only on the rate of species diffusion.

The third part combines the first and second parts of the book in order to describe some of the large-scale features seen in unsteady combustors, such as the mechanisms of flame stabilization, flame holding, flashback, and blow-off. In combustor design, it is important to encourage the first two phenomena while discouraging the second two. These are all non-oscillating features of the flow and could be considered as

https://doi.org/10.1017/jfm.2015.67 Published online by Cambridge University Press

steady bifurcations to a new steady solution. More subtly, however, flashback and blow-off can be induced by thermoacoustic oscillations and, in turn, can be sources of unsteady heat release that cause thermoacoustic oscillations. In this context, they become particularly important for the study of unsteady combustors. The response of premixed flames to external (e.g. acoustic) forcing is then examined. This builds on the second part of the book, in which it was shown that the heat release rate of a premixed flame depends strongly on the kinematics of the flame. A linear expression for the flame sheet dynamics is derived, which gives good physical insight into, for example, wrinkle propagation. However, nonlinear flame front dynamics are also considered. These impact strongly on the unsteady heat release and the nonlinear behaviour of thermoacoustic systems. Forced non-premixed flames are also considered but their behaviour is rather simpler. This part ends with an overview of all the factors that affect the heat release response of the flame, with particular application to thermoacoustic instability. All the mechanisms through which the heat release is affected by velocity perturbations or equivalence ratio perturbations are clearly described with the aid of diagrams. This shows why certain flame shapes are more susceptible to fluctuating heat release. The book builds up gradually to this section, which is arguably the most important part of the book.

In summary, this book provides an excellent and readable overview of unsteady combustor physics, with extensive references. I highly recommend it as a starting point for graduate students, particularly in the area of thermoacoustics.

Matthew Juniper

https://doi.org/10.1017/jfm.2015.67 Published online by Cambridge University Press