Progress in Energy and Combustion Science 60 (2017) 26–67

Contents lists available at ScienceDirect

Progress in Energy and Combustion Science

journal homepage: www.elsevier.com/locate/pecs

Advances and challenges in modeling high-speed turbulent combustion in propulsion systems

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ARTICLE INFO

Article History:
Received 18 November 2015
Accepted 22 December 2016

Keywords:
Turbulent combustion
High-speed flow
Supersonic combustion
Distributed reaction
Computational fluid dynamics

ABSTRACT

Combustion environments in propulsion systems involve the interaction of a variety of physics. In devices such as augmentors, ramjets and scramjets, such environments include the interaction between combustion, high-intensity turbulence, and/or strong flow compressions and expansions, physics which are termed here high-speed combustion. With this motivation in mind, this paper addresses: What are the problems encountered when modeling these interactions, or in other words, what are the problems of turbulent-combustion modeling? Do such interactions need modeling? What are the challenges when going from modeling low-speed- to high-speed-combustion problems? This work addresses these questions by summarizing several modeling studies of gaseous high-speed-combustion problems, and attempts to interpret some predictions in the context of the models' basic assumptions. Interestingly, the challenges to model high-speed combustion are such that a reader not interested in this topic but in the general one of modeling turbulent combustion may find the present paper useful.

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http://dx.doi.org/10.1016/j.pecs.2016.12.003
0360-1285/

1. Introduction

Combustion processes involve highly-nonlinear chemical reactions and many species. These reactions can enhance the compositional gradients and, consequently, alter the micromixing (molecular mixing), which in turn affects the reactions. In a turbulent flow, these processes can be weakly or strongly coupled to the turbulence. In particular, turbulence increases the mixing and consequently enhances the combustion [1]. In turn, the combustion can intensify the turbulence via flow expansion [1]. As a result, the turbulent fluctuations can be very large [2]. The combustion can also dampen the turbulence by increasing the fluid viscosity. Furthermore, pressure and density gradients can reach levels and align in a way to produce or dampen turbulence via baroclinicity. All these phenomena are termed turbulent combustion and it is the main interest of the present work.

In propulsion systems, turbulent combustion has some of the following features. Aero-turbine engines typically inject a hydrocarbon-based liquid fuel into the combustion chamber [3]. The fuel vaporizes and then burns in a way that is difficult to classify as purely premixed or purely nonpremixed, but is rather classified as partially premixed ([3] p. 34). Moreover, in such devices it is common to have fuel and (primary) air streams mixing and reacting with each other in a recirculation zone, from which products of combustion arise and keep burning downstream with air supplied through (secondary and dilution) holes [3,4]. This presence of multiple flow streams occurs in augmentors of turbofan engines as well [4,5]. Augmentors also must function over wide operating regimes, ranging from takeoff to accelerations at high altitude [6]. These wide operating regimes pose a formidable challenge to estimate whether the flame gets stabilized or blown off. Such an estimation is also important in scramjets, where it is particularly difficult because the ambient flow is supersonic and the flame stabilization occurs in some small subsonic regions [7,8]. Since having a flame blown-off in mid-flight is dangerous, the design of ignition systems that re-stabilize it is important, such as plasma-induced systems [9]. In addition, the wide operating regimes over which augmentors and ramjets operate, together with the fact that the acoustic losses tend to be low [10], make them prone to potentially dangerous thermoacoustic combustion instabilities. Another feature of the combustion environment in devices such as aero-turbine engines, augmentors, and scramjets is that, due to high flow speeds and concomitant high levels of turbulent fluctuations, it is likely for the combustion to occur near or in distributed-reaction-like regimes (cf. Section 2). Such regimes are also of practical relevance to other combustion systems, such as industrial lean-premixed gas turbines [11]. Furthermore, high speeds may lead to flow-induced compressions and expansions of the order of the heat-release from combustion. Hence, since all these phenomena are coupled, it is also likely for such fluid-mechanical-induced phenomena to enhance the combustion (cf. Section 2). These processes are vividly exemplified by the interaction of flames and shocks in scramjets (cf. Secs. 4–7). This potential enhancement of the combustion may also be produced by high levels of viscous heating near walls at high speeds (cf. Sections 4.2 and 5.4), unless some strong cooling is applied to the walls, in which case the combustion is quenched. Lastly, physics that are not associated with one device but are with another one, such as a lack of flame/shock interactions in aero-turbine engines or ramjets (at design conditions) but presence of them in scramjets, must be considered in the simulation of the type of hybrid propulsion platforms [7,12,13] that are envisioned to operate over wide regimes of speeds.

The above examples demonstrate that the combustion environment in propulsion systems involves some or all of the following physics (the citations denote representative studies): multiphase phenomena [14,15]; partial-premixing [16]; multiple flow streams; flame extinction, reignition and blowoff [17–19]; ignition [20,21]; flame-wall interactions [22]; thermoacoustic combustion instabilities [23]; distributed-reaction-like combustion [24,25]; and, interactions between combustion and strong flow compressions and expansions [26,27], as well as phenomena not mentioned above such as transcritical and supercritical phenomena in rocket engines, turbulence/radiation interactions [28,29] and thermal nonequilibrium [30]. Among all these phenomena, the concern of the present work is on two sets of physics that perhaps have received less attention: distributed-reaction-like combustion and interactions between combustion and strong flow compressions and expansions. Such physics are called from now on high-speed combustion. What is meant by high-speed combustion is further discussed using various examples in Section 2.

The physics just discussed span a wide range of scales in space-time ranging from those related to molecular interactions to those corresponding to the largest flow structures. Modeling such physics is usually done along the lines of addressing two questions. The first one is: How to model molecular interactions in the framework of continuum mechanics and do so in a computationally affordable way? Once this first question is addressed, one can tackle: How to model in continuum mechanics the interaction between turbulence, chemistry and other phenomena such as droplet evaporation and strong flow compressions and expansions in a computationally affordable way? The concern of the present paper is addressing this second question. Furthermore, this is done in the context of practical engineering applications where it is unlikely that “enough” of the relevant spatio-temporal scales are being resolved with the computational mesh, as further discussed in Section 3. To address this second question various techniques are available. They include Reynolds-Averaged-Navier–Stokes (RANS) techniques [31], large-eddy simulations (LES) [32], detached-eddy simulations [33], scale-adaptive simulations (SAS) [34] (which can be classified as a type of RANS), the partially-averaged-Navier–Stokes model [35], the partially-integrated-transport model [36], and the temporally-and-partially-integrated-transport model, among others. With these techniques, the problem of addressing the second question can be recast into the problem of modeling a series of unclosed terms in the model conservation equations. Section 3 discusses briefly these closure problems and explains which of them are of main interest for the present paper. This is done in the context of the two most popular techniques: RANS and LES. However, regardless of which closure problem is addressed, a central model is that which approximates the interactions between turbulence and chemistry. Such a model is called a turbulent combustion model.

There are many turbulent-combustion models. A partial list includes: flamelet models [1,37–39]; conditional moment closure [40,41]; conditional source estimation [42–44]; transported probability density function (TPDF) [45–48]; linear-eddy model (LEM) [49,50]; one-dimensional-turbulence (ODT) model [51,52]; the eddy-dissipation-concept (EDC) model [53]; the partially-stirred-reactor (PaSR) model [54,55]; the thickened-flame model [56–58]; homogenization-based LES [59]; unsteady flame embedding [60]; and data-driven turbulent combustion models [61,62]. Furthermore, the literature on turbulent-combustion models is vast. It includes books [1,63–65] and general review papers [2,66–71]. It also includes reviews centered around particular topics: LES [72–74]; premixed systems [75]; partially-premixed systems [16]; gas-turbine engines [76,77]; piston engines [78]; and, propulsion devices [79–83], among others. Most of this literature focuses on low-speed flow environments, which is not surprising since these environments are relevant to most combustion devices. Therefore, considering the present interest on high-speed combustion, Sections 5–7 address the following question: What are the challenges when applying a particular model to the problem of high-speed combustion? This question is addressed by analyzing the basic assumptions of the model. In the context of propulsion systems, which is the