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Mohamad Aslani & Jonathan D. Regele

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Numerical simulation of finite disturbances interacting with laminar premixed flames

Mohamad Aslani and Jonathan D. Regele *

Department of Aerospace Engineering, Iowa State University, Ames, USA

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Compression waves can be generated during combustion processes and subsequently interact with flames to augment their behaviour. The study of these interactions thus far has been limited to shock and expansion waves only. In this study, the interaction of finite compression waves with a perturbed laminar flame is investigated using numerical simulations of the compressible Navier–Stokes equations with single-step chemical kinetics. The interaction is characterised using three independent parameters: the compression wavelength, the pressure ratio of the disturbance, and the perturbation amplitude of the flame interface. The results reveal a wide range of behaviours in terms of flame length and heat release rate that could occur during such an interaction. The results are compared to the classical reactive Richtmyer–Meshkov instability and the role of baroclinic torque and vorticity generation are shown to be primary drivers of the flow instability.

KEYWORDS: finite disturbances; laminar premixed combustion; perturbed flame; Richtmyer–Meshkov; wavelet collocation method

1. Introduction

Shock waves drive flow features far more dynamically than standard combustion instabilities [1]. For instance, the primary mechanism of instability in supersonic combustion devices, such as pulsed detonation engines or wave rotor combustors, is the interaction of (reflected) shock waves with the burning medium, already wrinkled by the Darrieus–Landau (DL) instability [2–6]. Since the deformed flame front is a source of density gradients, its interaction with a pressure gradient region due to a shock wave produces baroclinic torque ($\nabla p \times \nabla \rho/\rho^2$). This form of instability, as an example of shock-induced Rayleigh–Taylor instability, was predicted by Richtmyer [7] and demonstrated experimentally by Meshkov [8] and thus referred to as Richtmyer–Meshkov instability (RMI). The induced RMI can trigger inflectional multi-mode instabilities like Kelvin–Helmholtz (KH) and thus turbulence and mixing is enhanced in the resulting fluid flow [9–12].

Shock-wave interaction with a curved flame was initially investigated experimentally by Markstein [13] in a shock tube. As shown in this primary study, flow features are mainly driven by baroclinic vorticity, and thus this interaction is commonly referred to as reactive RMI. In an attempt to understand the role of shock waves and hot spot generation in deflagration-to-detonation transition, the authors in [14–17] analysed reactive RMI by performing two-dimensional numerical simulations using one-step kinetics of shock waves impacting premixed flames. They showed that fewer small scale structures (perturbations) exist in a reactive RMI versus the regular non-reactive RMI, as reported also by more recent

*Corresponding author. Email: jregele@lanl.gov

studies in [18–20]. An analytical study by Massa and Jha [21] provided a linear analysis of this interaction, which showed that the absence of high wave number disturbances (small features in the flow) is due to the scaling between convective and reactive processes which only appears after the development of the mushroom shape.

In practical situations, flames may interact with expansion waves as well. Kilchyk *et al.* [22] performed simulations of expansion waves interacting with flames and showed that the interaction of an expansion wave with a flame increases the burning rate by increasing the flame (interface) length. Nevertheless, gas dynamical effects such as pressure and temperature gradients, which drop across an expansion fan, adversely affect reaction rates. As the flame length behaves nonlinearly, the overall burning rate is a competition between these two flame dynamics.

In more realistic situations, finite disturbances consist of both compressive and expansive phases. While the literature provides adequate information about how compressive (shock) and expansive waves interact with the flames, little is known about the combination of these two waves in a common compression wave. The study of such interactions is important in understanding the generation of instabilities that lead to turbulence and further mixing of reacting fluids.

The objective of this study is to understand the behaviour of a perturbed laminar flame front when it interacts with a finite amplitude disturbance composed of a shock wave followed immediately by an expansion wave. A finite amplitude wave arrangement is studied in this work, which tallies with a (weak) blast wave, to create compression waves that combine both the compressive and expansive aspects in a single waveform. This is an initial assessment of the nonlinear transition in flow quantities that might occur in combustion settings where compressible effects are known to exist. The parameters that control the amplitude and duration of the disturbance are the leading shock pressure ratio and the trailing expansion wavelength (compression-wave duration), respectively. The wavelength is normalised by the flame thickness, which is a characteristic length scale for this problem. Another key parameter is the perturbation amplitude of the flame front normalised similarly with the flame thickness. As is common in other studies of shock–flame interaction [1,16,23,24] as well as flame acceleration and deflagration-to-detonation transition (DDT) [1,25], single-step kinetics are used to model the reaction. The single-step chemistry model reduces the overall complexity of the problem and minimises complexities associated with multi-step chemistry.

Mazaheri *et al.* [26] and Mahmoudi *et al.* [27,28] showed that high-resolution simulations are required to study diffusion and hydrodynamic instabilities. The existence of localised structures like shock waves and reaction fronts requires a numerical tool to resolve the structure of the flow adaptively. In this paper, high-resolution simulations of finite amplitude disturbance interactions with flames are performed using the parallel adpative wavelet collocation method (PAWCM) [29].

The paper is organised as follows: in Section 2, the governing equations are described followed by the proposed model for finite amplitude disturbances and the initial and boundary conditions. In Section 3, the numerical framework is detailed. Finally, the results are presented and discussed in Section 4.

2. Problem statement

2.1. *Governing equations*

The physical model in this study is based on the two-dimensional, unsteady, compressible, reactive Navier–Stokes equations. Combustion is modelled using single-step (i.e.