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Reaction zones in highly unstable detonations

J.M. Austin[a], F. Pintgen[b], J.E. Shepherd[b,*]

[a] *Department of Aerospace Engineering, University of Illinois, Urbana-Champaign, Urbana, IL, USA*
[b] *Graduate Aeronautical Laboratories, California Institute of Technology, Pasadena, CA, USA*

Abstract

Experimental images of detonation fronts are made for several fuel-oxidizer mixtures, including hydrocarbon–air systems. Schlieren and planar laser induced fluorescence techniques are used to image both the shock configurations and the OH reaction front structure in a single experiment. The experiments are carried out in a narrow rectangular channel. The degree of instability of detonation fronts in different mixtures is evaluated by comparing calculated mixture parameters with the longitudinal neutral stability curve. The images reveal that the structure of the front increases dramatically in complexity as the mixture parameters move away from the neutral stability curve into the unstable region. Of the mixtures studied, nitrogen-diluted hydrocarbon mixtures are predicted to be the most unstable, and these show the greatest degree of wrinkling in the shock and OH fronts, with distortion occurring over a wide range of spatial scales. In the most unstable cases, separation of the shock and OH front occurs, and localized explosions in these regions are observed in a high-speed schlieren movie. This is in dramatic contrast to the weakly unstable waves that have smooth reaction fronts and quasi-steady reaction zones with no evidence of localized explosions. A key feature of highly unstable waves is very fine scale wrinkling of the OH and shock fronts, which is absent in the low-activation energy cases. This may be due to the superposition of cellular structures with a wide range of cell sizes. In contrast to soot foils, images of the OH front have a more stochastic appearance, and organized cellular structure is not as apparent.

Keywords: Detonation; Unstable; Planar laser induced fluorescence; Cellular structure

1. Introduction

Gaseous detonations propagating close to the Chapman-Jouguet (CJ) velocity all have unstable fronts, and there is a large body of work [1–5] documenting the common features of oscillations in the main shock strength, weak shocks moving transversely to the main front, and the quasi-periodic or cellular nature of the disturbances. These features are particularly prominent in mixtures with large amounts of monatomic gas dilution, which make them appealing for numerical or experimental study. In our laboratory, we have recently carried out studies [6–9] using planar laser induced fluorescence (PLIF) to directly visualize a chemical species (OH) within the reaction zone. We have identified distinctive features of the OH reaction fronts in mixtures with regular cellular systems and shown that they are characterized by smooth OH fronts, with “keystones” of high or low OH concentration located between the transverse waves, and a single characteristic spacing for the transverse waves.

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[*] Corresponding author. Fax: +1 626 449 2677.
E-mail address: jeshep@galcit.caltech.edu (J.E. Shepherd).

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From the very earliest investigations of detonation front structure, it has been clear that there is a bewildering range of behaviors depending on the chemical makeup of the mixture being studied [10–13]. These studies have shown that the dynamic response of detonation fronts is dependent on the regularity of the cellular structure. For example, for a given detonation length scale and facility dimension, a mixture with irregular structure may successfully transition through an area change, while a mixture with regular structure may fail. In contrast to the sedate instability and regular fronts of mixtures diluted with large amounts of argon, hydrocarbon-air mixtures, which are of greater practical interest, exhibit very unstable and irregular fronts. A key issue is how these instabilities may affect the fundamental combustion mechanism behind the front.

The present paper extends our previous work in two ways: (1) use of a narrow channel to reduce the integrating effect of the schlieren images and to simplify the interpretation of the corresponding PLIF images, (2) examination of mixtures over a wide range of stability parameters corresponding to reduced activation energy between 5 and 13. This included mixtures considered by previous researchers to have a highly irregular cellular structure. In selecting these mixtures, we have used as a figure of merit for instability the distance from the neutral curve for longitudinal instability in reduced activation energy-Mach number coordinates.

2. Detonation front instability

Traditionally, the degree of detonation front instability has been classified by the regularity of the cellular structure as determined from soot foils by visual inspection [14,15] and image analyses [16]. As an alternative, we use the distance from the longitudinal neutral stability boundary in reduced activation energy versus Mach number coordinates as a figure of merit to quantify the degree of instability. For the mixtures considered in this study, the activation energy is the dominant parameter. This choice is motivated by experimental observations [17] and the key role of the activation energy in determining the growth rate of small disturbances in one- [18,19] and two-dimensional [20] treatments of detonation front linear stability.

In the context of a single-step irreversible reaction rate, detonation waves are stable if the activation energy E_a is less than a critical value, which depends on the ratio of specific heats γ, chemical energy content Q/RT_1 of the mixture, and overdrive factor $f = (U/U_{CJ})^2$. Eckett [21] showed that the one-dimensional neutral stability curve for $f = 1$ is independent of γ if expressed in terms of the reduced activation energy $\theta = E_a/RT_{vN}$ where T_{vN} is the temperature at the von Neumann state and the CJ Mach number, M_{CJ}. In Fig. 1, we show the neutral stability curve of Lee and Stewart [18] in these coordinates together with the parameters for the mixtures considered in the present study. The CJ Mach number for each mixture is calculated [22] using realistic thermochemical properties, and the reduced activation energy is computed using a detailed chemical reaction mechanism as described in [23].

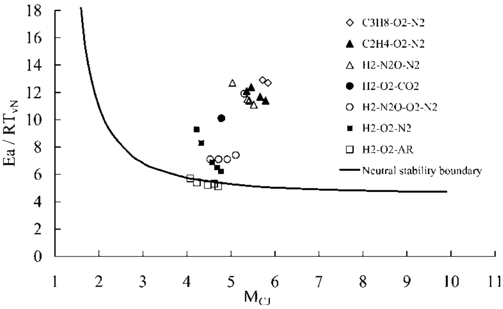

Fig. 1. Categorization of detonation front structure from stability considerations. Parameters [9] for mixtures considered in this study (symbols) are compared to the neutral stability boundary from Lee and Stewart [18].

The mixtures shown in Fig. 1 all have similar M_{CJ} and reduced activation energies ranging from values of $\theta \sim 5$ for highly Ar-diluted mixtures up to $\theta \sim 13$ for the hydrocarbon-air mixtures. As shown in previous soot foil studies, the mixtures closest to the neutral curve show the greatest cellular regularity, and those farthest from the neutral stability curve show the least regularity.

3. Experimental setup

A detonation tube in the form of a narrow channel was built for this study [9]. This design has the advantage of simplifying the flow field by reducing or entirely eliminating the transverse waves propagating in the direction of the smaller dimension. Previous work by other researchers has shown that this arrangement results in some differences in the detonation structure from that observed in a rectangular or circular channel. In particular, Strehlow and Crooker [24] report that the track angle and the calculated transverse wave strength are increased. On the other hand, it is much more straightforward to interpret the schlieren images in a narrow channel than in a square cross section tube. In addition, chemiluminescence is reduced, so that the PLIF imaging technique could be used in hydrocarbon detonations. Parameters for representative mixtures considered in this study are given in Table 1 and shown in Fig. 1.