Visualization of Reaction Zones in Highly Unstable Detonations

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Introduction

Gaseous detonations all have unstable fronts and there is a large body of work [1, 2, 3, 4, 5] documenting the common features of oscillations in the main shock strength, weak shocks moving transversely to the main front, and associated shear layers. However, there is a bewildering variety of behavior depending on the chemical ingredients in the mixture being studied. Undiluted hydrocarbon-oxygen mixtures exhibit wildly unstable and irregular fronts while mixtures diluted with large amounts of argon have a very sedate instability and regular fronts. A key issue is how these instabilities may affect the fundamental combustion mechanism behind the front. In particular, do the highly irregular fronts involve a distributed or turbulent combustion mechanism in contrast to the laminar, shock-induced chain-branching/thermal explosion that is observed in very regular fronts?

Our contribution has been to build on the past work and add diagnostics (PLIF) that enable the direct visualization of chemical species within the reaction zone. In our previous studies, we examined highly-diluted mixtures with very regular but three-dimensional structure. The present study extends our previous work in two ways: 1) use of a narrow channel in order to improve the correspondence between schlieren and PLIF images; 2) examine very unstable mixtures.

Experimental Setup

Two facilities were used in this study: a large-scale facility consisting of a 280 mm diameter tube with a 152 mm square test section that has been described elsewhere [6, 7], and a high aspect ratio (18x152 mm) rectangular channel. The channel is 4.2 m long with 150 mm diameter windows. An initiator capable of producing a planar detonation wave from the merging of several wavefronts [8] was used. The initiator was filled with acetylene-oxygen gas which was ignited using a spark plug. Pressure transducers monitored the linearity of the detonation front at the exit plane of the initiator. In addition, four piezoelectric pressure transducers were mounted along the channel to measure detonation pressure and time-of-arrival. From these data, velocity deficits relative to the CJ velocity could be obtained. Ruby laser schlieren [6]

and planar laser-induced fluorescence of the OH radical [9, 10] were used to obtain separate images of the shock and reaction zone structure. The two images were then superimposed by postprocessing [9]. The time between images was approximately 800 ns.

Experimental Results

The Influence of Channel Geometry

Soot foils from each facility may be used to illustrate the influence of confinement geometry on the structure of the front. We observe that the cell size is increased in the narrow channel [11]. The geometry of the cellular structure has also changed. In the 280 mm diameter facility, transverse waves propagate around the circumference of the tube and cells appear as parallelograms (with constant track angle). In the narrow channel, the tracks show some curvature and the track angle varies through the cell. There is also some evidence of weak "slapping" waves.

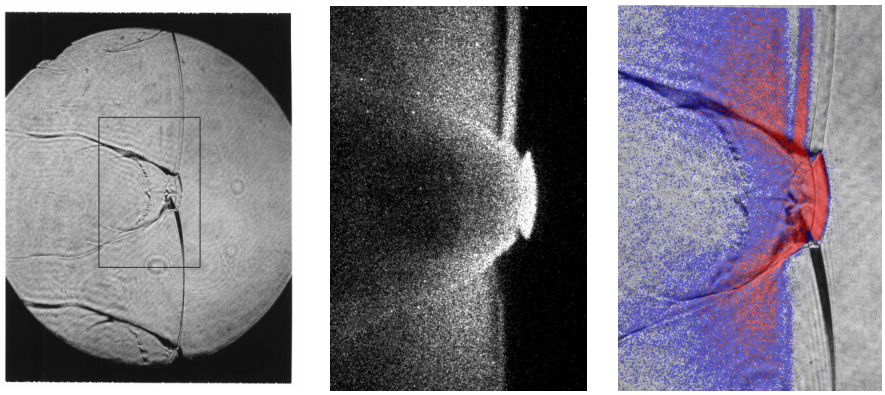
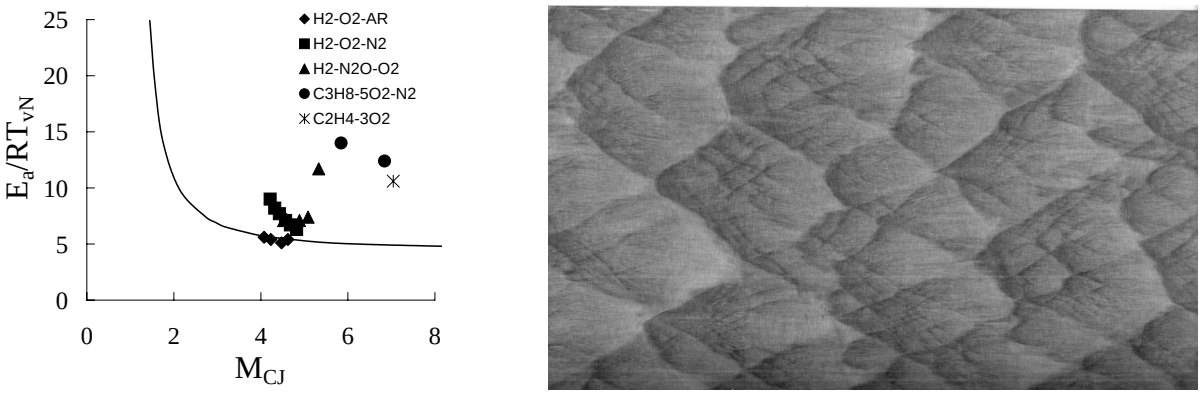


Figure 1: Schlieren and OH fluorescence images in stoichiometric H_2-O_2 mixture diluted with 85% Ar. The square shows the location of the PLIF image, which has a 65x30 mm field of view.

Sample images of a detonation front in H_2-O_2-85%Ar at 20 kPa initial pressure in the narrow channel are shown in Fig. 1. The schlieren visualization of the triple point structure is very similar to that reported by [1] and the correspondence between the gas dynamic features and the OH front can be seen quite clearly.

Cellular Substructure

The main purpose of this study is to examine the propagation mechanism of detonations in mixtures with varying stability characteristics. One simple way to measure stability is to compute effective activation energy and energy release (CJ Mach number), the parameters



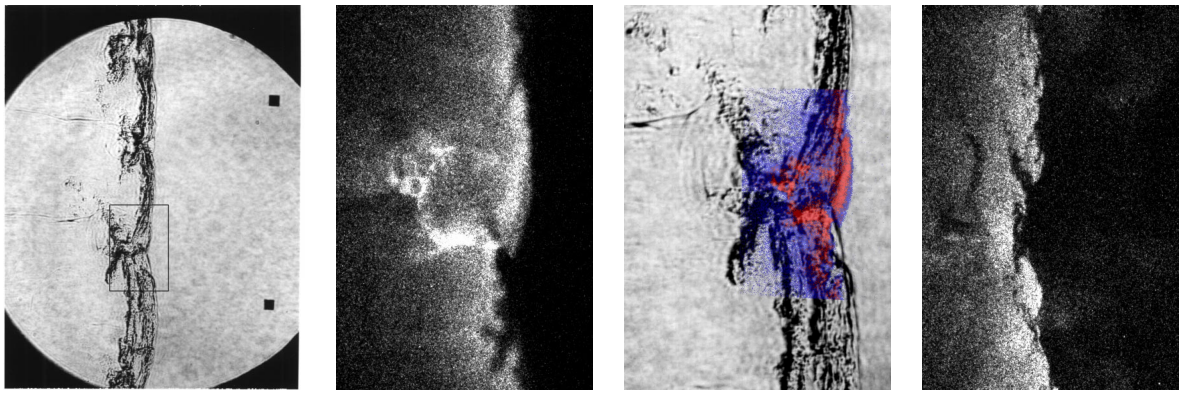
(a) (b)

Figure 2: (a) Stability of mixtures considered in this study relative to the 1D neutral stability curve. (b) Soot foil in stoichiometric C_3H_8-O_2-60% N_2 from the 18x152 mm facility.

which are key quantities that emerge from stability analysis of single-step reaction mechanisms. A one-dimensional neutral stability curve [12], taken from [13], is shown in Fig. 2 (a), together with the parameters for the mixtures considered in this study.

In some mixtures far from the stability boundary, cellular substructure has been observed on soot foils [14]. Substructure (structure that appears at multiple scales that are smaller than the main cell size) is evident on the soot foil shown in Fig. 2 (b). Manzhalei [15] proposed a minimum activation energy criterion of $E_a/RT_{vN} \geq 6.5$ for substructure to occur. The criterion is satisfied by the hydrocarbon mixtures while some N_2-diluted H_2 mixtures exceed this activation energy by up to 30% and do not have substructure. The nature and role of substructure in detonation propagation is still poorly understood.

Sample images of a detonation in an N_2-diluted C_3H_8-O_2 mixture in the narrow channel are shown in Fig. 3 (a)-(c). Also shown is an OH fluorescence image of a H_2-N_2O mixture from the 280 mm facility. In both fluorescence images, small-scale wrinkling of the front is apparent. A key question is whether this structure results from an instability that is similar in nature to the large-scale cellular instability but occurs at a smaller scale behind the overdriven Mach stem, i.e. substructure, or whether this is due to a change in combustion regime [16]. Work is in progress to address this issue. In addition, in the C_3H_8 mixture, the collision at the apex of a main cell has been captured, and the formation of a new Mach stem appears to result from an explosive interaction, contrasting significantly with what is observed in more stable mixtures.



(a) (b) (c) (d)

Figure 3: (a)-(c) Schlieren and OH fluorescence images in stoichiometric C_3H_8-O_2 mixture diluted with 60% N_2 in the narrow channel. (d) OH fluorescence image in H_2-N_2O with 50% N_2 in the 280 mm facility. OH fluorescence images are 30 mm high.

High-speed schlieren movies have also been obtained of these events and will be presented.

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