Initiation of Detonations and Deflagrations by Shock Reflection and Focusing

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Introduction

Detonation initiation by shock reflection and focusing involves propagating a shock wave into a concave wall. The reflection of the shock from the concave wall will produce a high-energy focus region with temperatures and pressures in excess of those produced by shock reflection from a flat wall. These high temperatures and pressures promote the initiation of detonation and deflagration.

While detonation initiation with focusing reflectors has been studied by several researchers, much of the work (Chan et al. 1990, Medvedev et al. 1999, Bartenev et al. 2000, Gelfand et al. 2000) has been concerned with hydrogen-oxygen-nitrogen mixtures, which are relatively easy to detonate. Less work (Borisov et al. 1990, Dean et al. 2004) is available for hydrocarbon-oxygen-nitrogen mixtures, in spite of the appeal of these fuels for use in current pulse detonation engine technology. Initiation requirements of propane-air mixtures are of particular interest since they have similar detonation properties to heavier hydrocarbon-air mixtures such as JP10- or JetA-air.

In the current study, detonations and deflagrations were initiated by shock reflection from a parabolic end wall in a tube filled with stoichiometric fuel-oxygen mixtures diluted with nitrogen. Hydrogen, ethylene, and propane were used as fuels. The results determine the critical shock strength necessary to initiate detonations and deflagrations in hydrocarbon mixtures. Mixtures using hydrogen fuel are a baseline and relate these experiments to other studies. The data also provide a comparison to several other types of wave focusing schemes (toroidal imploding detonations and shock waves) used to initiate detonations (Jackson et al. 2003, Jackson and Shepherd 2004).

Experimental Details

Experiments were conducted in a shock tube consisting of three sections: a driver section, a driven section, and a test section. The driver section had a 16.5 cm inner diameter (ID) and was 6.2 m long; the driven section had a 15.2 cm ID and was 11.3 m long. The 2.44 m long test section tube was located at the end of the driven section and had a 7.6 cm ID. An axisymmetric, parabolic reflector was located at the end of the test section. Four different parabolic reflectors were used with four ratios of reflector depth to reflector radius (Fig. 1). The depth-to-radius ratios tested were 0 (flat wall), 0.5 (shallow), 1.25 (intermediate), and 2 (deep). Pressure transducers and ionization probes located in the test section provided pressure histories and detected the presence of combustion, allowing waves to be classified as nonreactive shock waves, detonations, or deflagrations.

A tube with the same ID as the test section protruded 1.94 m into the end of the driven section in a cookie-cutter-style setup which ensured that the shock wave was transferred from the larger-diameter shock tube to the smaller-diameter test section with minimal disruption. The cookie-cutter tube also prolonged the test time of the experiment by extending the duration required for waves reflected from the driven section end flange to enter the test section.

A 12.7 μm thick Mylar diaphragm located between the cookie-cutter and the test section separated the test section gas from the shock tube gas. Compressed air was used in the driver section of the shock tube; nitrogen was used in the driven section. As previously mentioned, the test section gas consisted of stoichiometric fuel-oxygen mixtures diluted with nitrogen. Hydrogen, ethylene, and propane were used as fuels. For each reflector and fuel combination, the incident shock strength and amount of diluent were varied to determine the critical values necessary to initiate detonations and deflagrations at the reflector. The initial pressure of the test section mixture was set such that the pressure behind the reflected wave was approximately 1 bar. This involved varying the initial pressure of the test section mixture from 0.13 bar to 0.73 bar depending on the incident shock strength.

Results

Four combustion modes were observed during the experiments: detonation initiation inside the reflector, deflagration-to-detonation transition (DDT), deflagration initiation outside the reflector, and no combustion. Additionally, for low-nitrogen dilutions, the direct initiation of detonations and deflagrations near the Mylar diaphragm was observed to occur before the incident shock wave reached the reflector. It was concluded that locally high pressures resulting from the interaction of the incident shock wave with the Mylar diaphragm were responsible for the premature initiation.

Selected experimental data for ethylene mixtures (Figs. 2 and 3) show the modes of combustion observed in the test section as a function of incident shock Mach number and percent diluent. Each plot is for a specific fuel and reflector combination. Ethylene mixtures were tested with all four reflectors and it was observed that the conditions under which a given mode of combustion occurs are very similar for two separate pairs of reflectors: the two deepest reflectors and the two shallowest reflectors. Hence, only the shallow reflector and the intermediate reflector were used with the propane and hydrogen mixtures.

Discussion and Conclusions

The results indicate that, as the mixture dilution was increased, the critical Mach number value required for detonation initiation also increased. The highest incident shock Mach number achieved in these experiments was 2.4. Up to this value, detonation initiation inside the reflector was obtained with the intermediate reflector for every mixture tested except for the case of the propane-air (76% nitrogen dilution by volume) mixture. For the shallow reflector, prompt initiation was obtained for hydrogen cases only.

The trend observed was that, for each mixture, there was a minimum Mach number below which no combustion would occur. Mach numbers above the minimum would initiate deflagrations while larger Mach numbers would promote the onset of DDT. Finally, increasing the Mach number even higher would initiate a detonation inside the reflector. Typically, DDT was more prevalent with the flat and shallow reflectors. With the deeper reflectors, the combustion mode was more likely to transition directly from deflagration outside the reflector to detonation inside the reflector.

Additionally, in several situations, combustion was initiated before the incident shock wave reached the reflector. For 20% nitrogen dilution in ethylene mixtures (Fig. 2 and 3), direct initiation of detonation was observed. For 20% nitrogen dilution in hydrogen mixtures, direct deflagration was observed. As previously mentioned, in these cases, the direct initiation was attributed to wave reflections from the Mylar diaphragms.

The two deeper reflectors were found to be more effective at the initiation of detonations and deflagrations via wave focusing. The results obtained for ethylene mixture indicate no difference between the performance of the intermediate and deep reflectors for detonation initiation. However, reflector depth did affect the minimum Mach number required for deflagration initiation with these two reflectors. Since prompt detonation initiation was not observed during the shallow and flat reflector tests, nothing can be discerned about the effectiveness of these reflectors at promptly initiating detonation.

Comparing the three fuels tested, hydrogen mixtures required the lowest Mach numbers for initiation, and propane mixtures required the highest. For example, in hydrogen mixtures, detonation initiation inside the reflector occurred with both reflectors tested, while, in the hydrocarbon fuels, this mode of combustion occurred only for the deeper reflectors. Significantly higher Mach numbers were required to cause combustion in propane mixtures than in two other fuel mixtures. During the experiments, the highest incident Mach number used was 2.4, which was not high enough to initiate detonations inside intermediate reflectors for propane-air mixtures. However, applying the trend from the ethylene data to the propane data suggests that an incident shock wave Mach number of approximately 3.5 would be required to initiate propane-air with the intermediate reflector.

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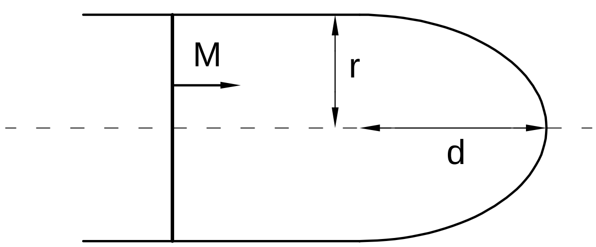

Figure 1: Schematic of a reflector, M is the incident Mach number, r is the radius of the test section tube, and d is the reflector depth. Reflector is axisymmetric.

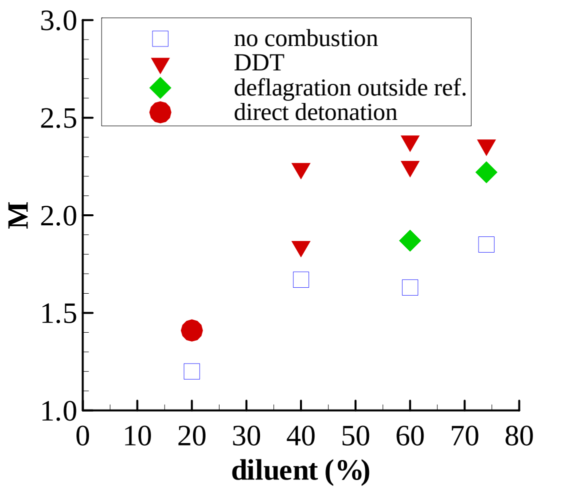

Figure 2: Ethylene-oxygen mixtures diluted with nitrogen tested with the shallow reflector.

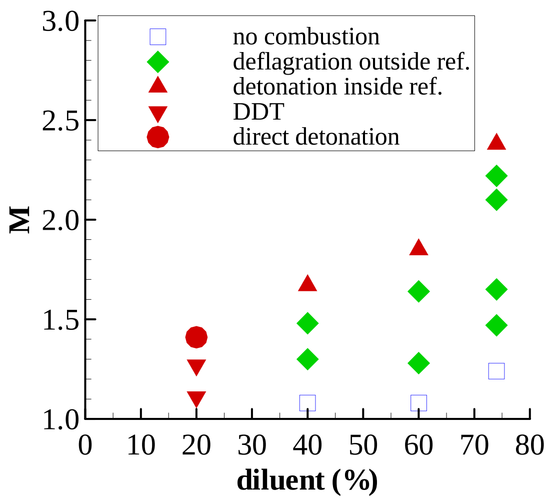

Figure 3: Ethylene-oxygen mixtures diluted with nitrogen tested with the intermediate reflector.