Detonation Initiation via Imploding Shock Waves in a Tube

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1 Introduction

Detonation initiation by wave focusing involves propagating an imploding shock or detonation wave into a combustible mixture. The imploding wave geometry forces the shocked gas into an ever-decreasing area that creates additional compression when compared to planar geometries. The implosion process can result in extremely high post-shock pressures and temperatures as the wave radius decreases. These high temperatures and pressures have been shown to promote initiation of detonations and deflagrations [1–4].

In the current experimental study, imploding toroidal shock waves driven by jets of air were used to initiate detonations inside a tube filled with stoichiometric ethylene-oxygen-nitrogen and propane-oxygen-nitrogen mixtures. For each test, the gas-dynamic energy input to the detonation tube was estimated by using the unsteady energy equation. The critical energy input was determined to scale best with the theoretical planar initiation energy, indicating that initiation in the imploding shock tests occurred after the blast wave generated from the implosion had transitioned to a planar wave in the tube.

2 Experimental Work

The experimental shock implosion facility was a variation of the classical shock tunnel concept and consisted of a test-section tube with an annular orifice that protruded into the end of a shock tube as shown in Fig. 1. The test section was a 1.25-m-long main tube with an annular orifice at one end, which was inserted into the driven section of the shock tube.

During an experiment, diaphragms were placed in the shock tube and on the annular orifice of the test section. The test section was then filled to 1.0 bar with a premixed combustible test mixture. Both sections of the shock tube were filled with air at atmospheric pressure and the driver section was pressurized with air until the shock-tube diaphragm ruptured, propagating a shock wave into the driven section. Wave reflection from the end of the driven section created a region of slow-moving test gas with elevated pressure and temperature that ruptured the secondary

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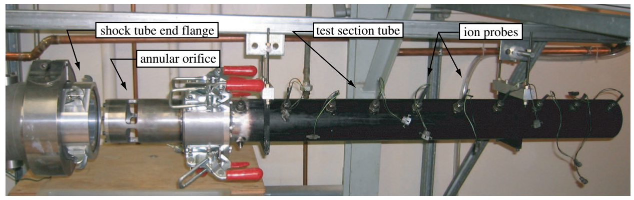
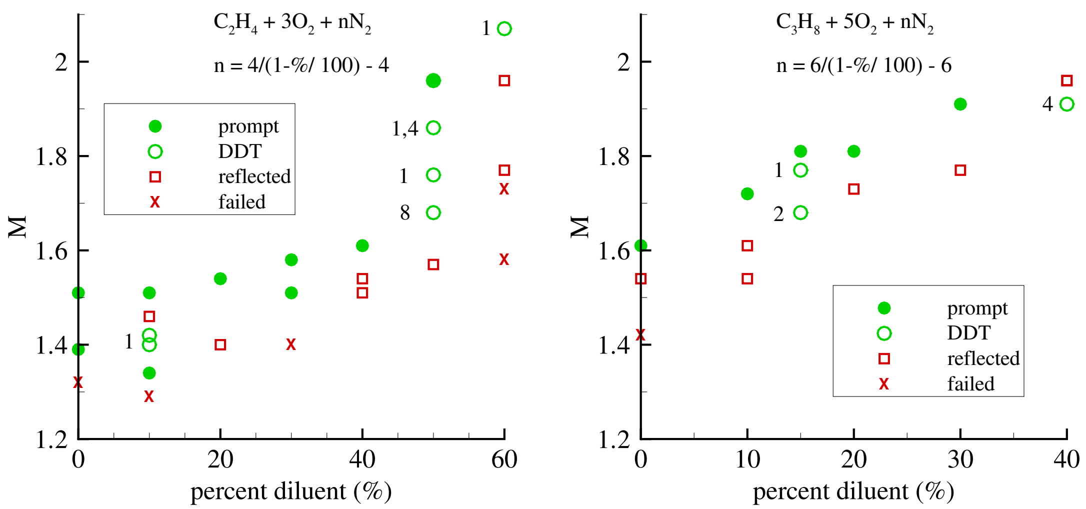


Figure 1: The experimental setup.

diaphragm covering the annular orifice and created an imploding shock wave in the test section. The test section was equipped with four pressure transducers and nine ionization probes in order to detect if initiation occurred.



(a) Ethylene-oxygen-nitrogen data.

(b) Propane-oxygen-nitrogen data.

Figure 2: Initiation result classification for stoichiometric ethylene-oxygen and propane-oxygen test mixtures with varying nitrogen dilutions. M is the incident shock Mach number in the shock tube. Numbers to the left of the DDT data symbols indicate the number of the ionization probe that was closest to the DDT event.

For a given mixture, four different initiation modes were observed to occur depending on the strength of the imploding wave. In order of decreasing implosion strength, those modes were direct initiation, deflagration-to-detonation transition (DDT), initiation after wave reflection from the end wall, and failed initiation. As expected, decreasing mixture sensitivity by increasing the amount of diluent in the mixture required increasing the strength of the implosion for initiation to occur. Summary plots of the incident shock tube Mach number M versus percent diluent are shown in Fig. 2 for stoichiometric ethylene-oxygen and propane-oxygen mixtures with varying nitrogen dilution by volume. Extrapolation of the data predicts that shock tube waves above

$M = 2.8$ would generate sufficient reflected-shock pressures ($P_5 = 40$ bar) to achieve successful initiation in fuel-air dilutions (73% by volume for ethylene and 75% by volume for propane).

3 Energy Input to the Tube

The unsteady energy-balance relation can be used to estimate the energy input to the shock implosion initiator. Setting a stationary control volume around the test-section tube wall and assuming that the flow is adiabatic with no body forces, shear forces, or heat addition, the energy equation is

$$\frac{d}{dt}\int_V \rho\left(e + \frac{|u|^2}{2}\right) dV = h_0\, \rho A u_r \tag{1}$$

where A is the area of the annular orifice, h_0 is the total enthalpy of the inflow (which is conserved), and u_r is the velocity of the gas through the orifice. Note that since the control volume follows the inside of the test-section wall, all flow must enter the control volume through the annular orifice. The flow velcoity u_r is assumed to be radially inward and constant across the orifice.

With the assumption that the flow into the orifice behaves as a perfect gas with a constant heat capacity and isentropically chokes at the orifice, the energy input can be expressed as

$$\int_V \rho\left(e + \frac{|u|^2}{2}\right) dV \approx \left(\frac{\gamma}{\gamma-1}\right)\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(1-\gamma)}} P_0\, c_0\, \left(2\pi R_{tube} w\right) \frac{R_{tube}}{c_1} \tag{2}$$

where $2\pi R_1 w$ has been substituted for the inflow area A. The parameter w is the width of the annular orifice. The equation has been multiplied by a characteristic time t_c, based on the initial speed of sound c_1 in the test section and the tube radius, such that $t_c = R_{tube}/c_1$.

For propane and ethylene mixtures, the value of $\gamma \approx 1.37$ and the energy is approximately

$$\int_V \rho\left(e + \frac{|u|^2}{2}\right) dV \approx 10\, w\, P_0\, R_{tube}^2\, \frac{c_0}{c_1}\ . \tag{3}$$

Figure 3 shows the energy input calculated with Eq. 3 for the data from Fig. 2. Mach numbers in Fig. 2 and the reflected shock relations were used to predict the reservoir conditions P_0 and T_0. The data indicate that it takes roughly twice as much energy input to achieve detonation in the propane mixtures compared to the ethylene mixtures.

Two curves are also plotted on each of the figures, which scale with the planar and spherical initiation energies,

$$E_j^* = m_j \rho_0 D^2 \Delta^j \tag{4}$$

where Δ is the mixture-specific induction zone length and m_j is a scaling constant ($j = 1$ for planar and 3 for spherical geometries) that was chosen such that the two curves coincide at 0% dilution. Over the range shown, the data agree better with the planar critical-energy trend rather than the spherical critical-energy trend for both the ethylene and propane mixtures. This suggests that initiation occurs in a planar geometry after wall reflection has occurred and not from a spherical explosion of the toroidally compressed gas core at the implosion focus.

Note that the characteristic time is approximately constant for all mixtures tested ($t_c = 114 \pm 0.1\ \mu$s). It is primarily used to express the experimentally determined power inflow rates from Eq. 1 as energy values, allowing comparison to other studies. Due to the experimental geometry, it was not possible to vary the actual duration of mass inflow in this study and gas continued to

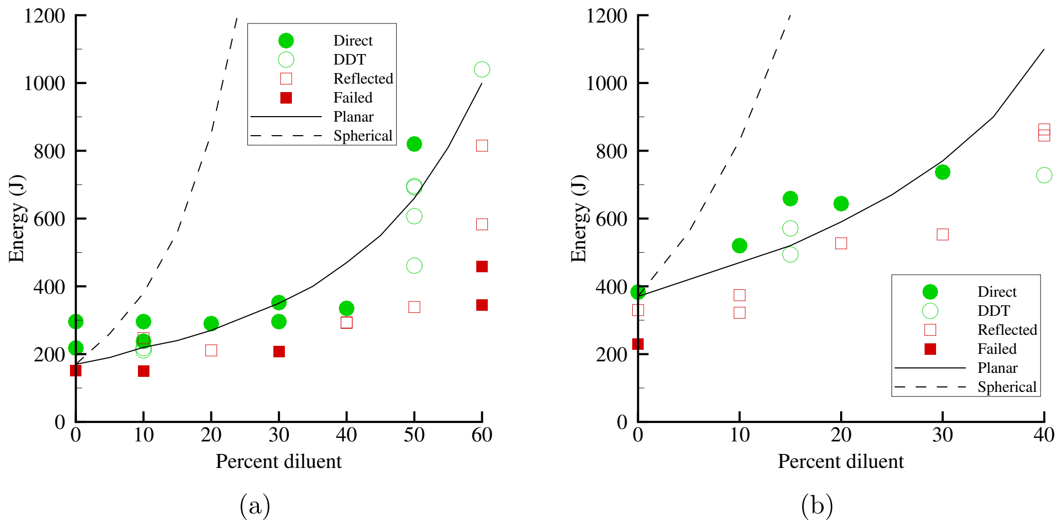


Figure 3: The energy input to the test-section tube for the shock implosion experiment for (a) ethylene-oxygen-nitrogen data with $m_1 = 0.79$ and $m_3 = 8.3{\times}10^8$ and (b) propane-oxygen-nitrogen data with $m_1 = 1.6$ and $m_3 = 1.8{\times}10^9$.

flow from the shock tube into the test section until the pressure in the test section inlet exceed that of the shock tube reservoir due to detonation initiation or wave reflection.

Furthermore, theoretical values of P_0 and T_0 calculated from the experimentally measured Mach number were used in the calculation, while direct measurements of P_0 were 60% of theory (due to mass loss to the test section). The actual T_0 is likely lower as well, but was not measured. Support struts also blocked 13% of the annular orifice, which acted to decrease both the implosion symmetry and the energy inflow. Accounting for these losses in Eq. 3 would significantly decrease the reported energy values.

References

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