Detonation initiation by hypervelocity projectiles

J. Bélanger[*], M. Kaneshige, J. E. Shepherd
California Institute of Technology
Pasadena, CA 91125 USA

Abstract: We report experimental studies on the initiation of detonations by hypervelocity projectiles in hydrogen-oxygen-nitrogen mixtures. The experimental facility T5 at Caltech was modified to launch 25-mm diameter projectiles at speeds around 3000 m/s. Flow visualization and pressure measurements are reported for several mixture conditions. A clear transition between shock-induced combustion and detonation is observed. Transition to detonation is observed with an overtaking wave occurring in the shocked but unreacted gas.

Key words: Detonation, Projectile, Hypervelocity

1. Introduction

Experiments on detonations initiated by hypervelocity projectiles ($U > U_{\mathrm{CJ}}$) have been carried out in the T5 shock tunnel. Our goal is to understand the conditions needed to produce stabilized detonation waves. Effects of initial pressure have been explored in this preliminary study. There are two principal configurations (Fig. 1) that we anticipate observing for hypervelocity projectile

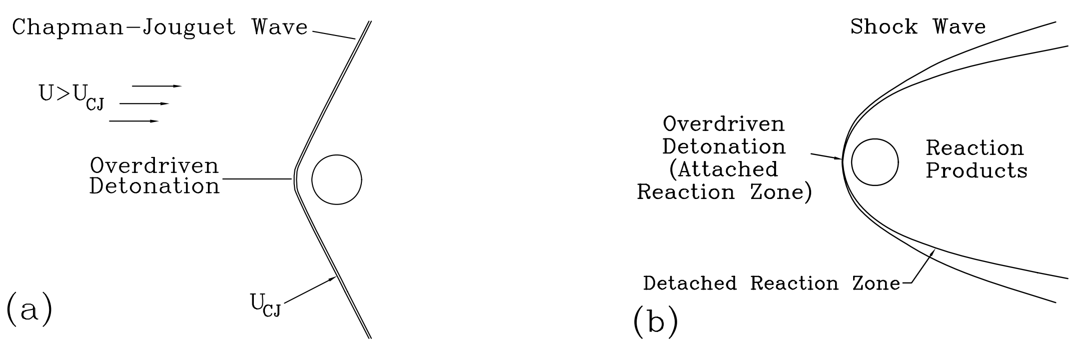

Figure 1. Hypothetical wave configurations: (a) attached reaction zone, (b) detached reaction zone.

flight in detonable mixtures. To date, only the second configuration (Fig. 1b),

[*]University of Minnesota, Minneapolis-St. Paul, MN USA.

shock-initiated combustion of a limited extent, has been observed.

Key factors in the initiation and stabilization of a detonation wave on a projectile are the ratio of the detonation cell size to projectile diameter and the ratio of the projectile speed to the mixture Chapman-Jouguet (CJ) speed (Shepherd 1994). For the mixture used in these experiments, CJ velocities and estimated cell sizes (30 times the ZND reaction zone length) are given in Table 1 for a range of wave speeds.

In previous experiments using projectiles (for example, Lehr 1971), stabilized detonation waves have not been observed because the projectiles were either too slow or too small. In the present tests, we used a very sensitive mixture (stoichiometric hydrogen-oxygen) diluted with a small amount of nitrogen to reduce the Chapman-Jouguet wave speed (2400 m/s) to significantly less than the projectile velocity. The estimated detonation cell width of this mixture for an initial pressure of 1 bar is approximately 2 mm, a factor of 10 less than the projectile diameter.

Table 1. Detonation parameters for $2H_2 + O_2 + N_2$

P_0(bar)	1.0	0.50	0.25	0.10
U_{CJ}(m/s)	2400	2370	2340	2300
U (m/s)	λ (mm)	λ (mm)	λ (mm)	λ (mm)
2400	1.9	3.3	6.4	16
2500	1.3	2.4	4.7	11
2600	0.94	1.8	3.5	8.8
2700	0.71	1.4	2.7	6.7
2800	0.55	1.1	2.2	5.3
2900	0.44	0.87	1.7	4.2
3000	0.35	0.70	1.4	3.3

2. Facility

T5 has been modified by the addition of a launch tube, extending from the nozzle throat, and a test section/target section assembly, which is mounted on the downstream door of the dump tank. A schematic of the apparatus is shown in Fig. 2.

The high-enthalpy gas generated by T5 accelerates a 25-mm diameter nylon sphere (about 10 grams) through the 3-m long launch tube. Passing through the T5 dump tank, the sphere breaks a timing wire, ruptures a mylar diaphragm, and enters a test section mounted on the downstream door of the dump tank. This test section has a 150-mm square inside cross-section and is 760 mm long.

It is equipped with three evenly spaced pressure transducers, two optical ports (for projectile timing by laser triggers), and optical windows for flow visualization centered 550 mm from the entrance. The projectile impacts an assembly of aluminum honeycomb and plates in the target section. Using a shock speed of 5000 m/s and helium gas in the shock tube section of T5, the projectile muzzle velocity is approximately 3000 m/s.

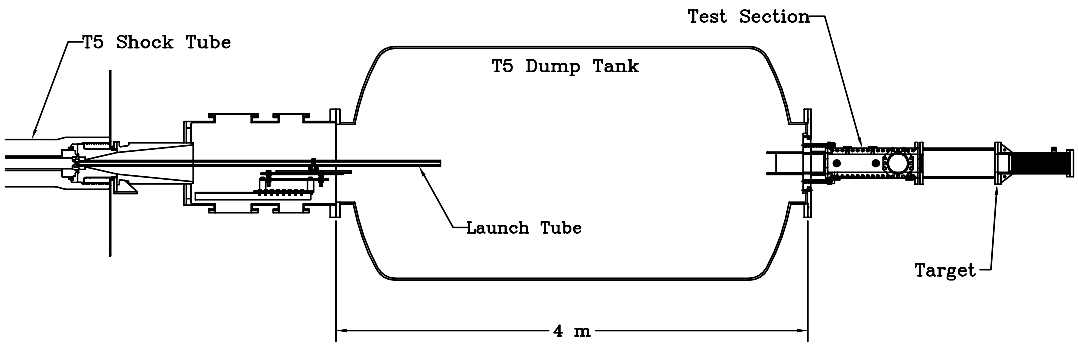

Figure 2. Schematic of T5 with gas gun modification and detonation test section.

3. Results

A summary of results from several experiments is given in Table 2.

Table 2. Summary of selected T5 detonation experiments.

T5 Shot	Projectile Velocity (m/s)	Wave Speed 1 (m/s)	Wave Speed 2 (m/s)	Mixture	Initial Pressure (bar)
861	2940	2860	2860	N_2	0.25
862	2820	3060	3020	$2H_2+O_2+N_2$	1.00
863	2930	3060	3110	$2H_2+O_2+N_2$	1.00
865	2690	2380	3200	$2H_2+O_2+N_2$	0.10
1007	2740	2780	2710	N_2	0.25
1009	2420	3460	2980	$2H_2+O_2+N_2$	0.50
1010	2560	3460	2860	$2H_2+O_2+N_2$	0.50
1011	2640	3250	3060	$2H_2+O_2+N_2$	0.25
1012	2790	2580	3200	$2H_2+O_2+N_2$	0.25

Differential interferograms and pressure transducer traces from five experiments are shown in Figs. 3 through 6. The optical windows are 165 mm in diameter, which allows a clear view of portions of the top and bottom walls. The projectile is 25 mm in diameter and is shown moving from right to left.

The images were made with a differential interferometer using a Q-switched Nd:YAG laser. In Figs. 4a and b, the round shadows at the top of the window are caused by chips in the optical glass windows. Small pieces of debris from the diaphragms are occasionally visible in the flow as conical shocks, sometimes in front of the projectile (Fig. 4a) and somtimes in the wake (Fig. 3a).

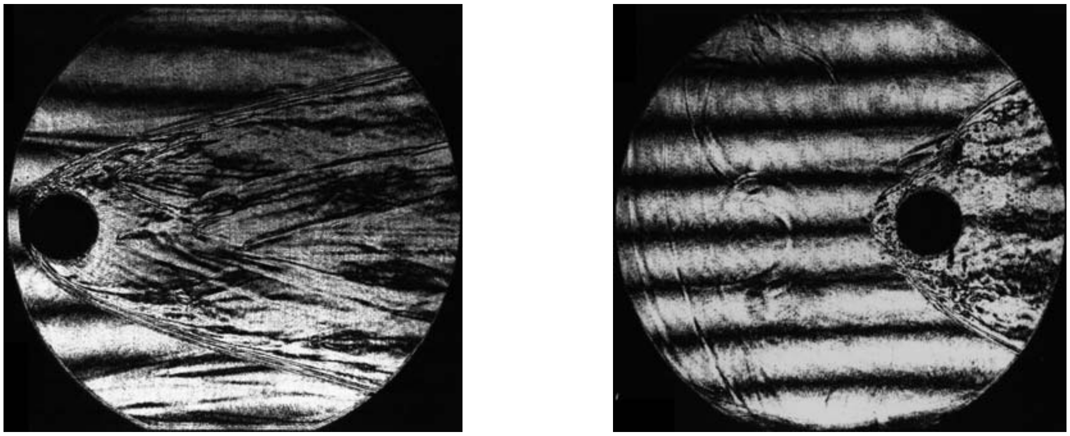

Figure 3. (a) T5 Shot 861 (b) T5 Shot 865

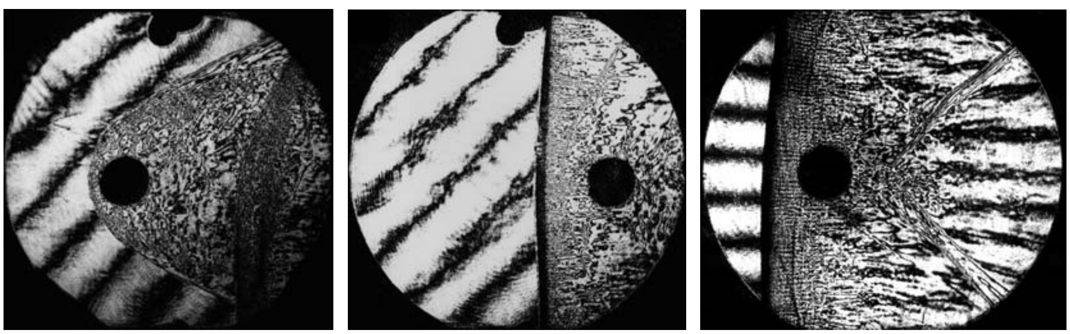

Figure 4. (a) T5 Shot 1012 (b) T5 Shot 1010 (c) T5 Shot 863

The pressures were recorded with PCB 113A24 transducers sampled at 1 MHz. The plots show the data normalized by the initial pressures. In Fig. 6, the clipping visible in T5 shot 1010 was caused by a fault in the data acquisition system. The dashed lines show the path of the projectile, as determined from the laser triggers and photographs.

As a reference case, a non-reacting experiment was performed (Figs. 3a and 5). The pressure signals and wave shapes compare favorably with the known results for hypersonic shock waves on spheres. Experiments involving reacting mixtures with increasing initial pressures (and consequently decreasing cell sizes) are shown in Figs. 3b through 4c and 5 through 6.

Although only four initial pressures were examined, it is apparent from the data that a critical transition occurs near 0.25 bar. At 0.10 bar, the bow wave is similar to the non-reactive shock, although the photograph and pressure data show the effects of combustion. Figure 4a, at 0.25 bar, shows a bow wave similar to that at 0.10 bar, but more interesting phenomena are also visible. The reaction zone detaches from the shock wave at about 1.5 diameters behind the front of the sphere. Similar detachments have been observed in previous studies (Lehr 1971). This indicates that the initial reaction process is being quenched due to the expansion behind the curved bow shock wave.

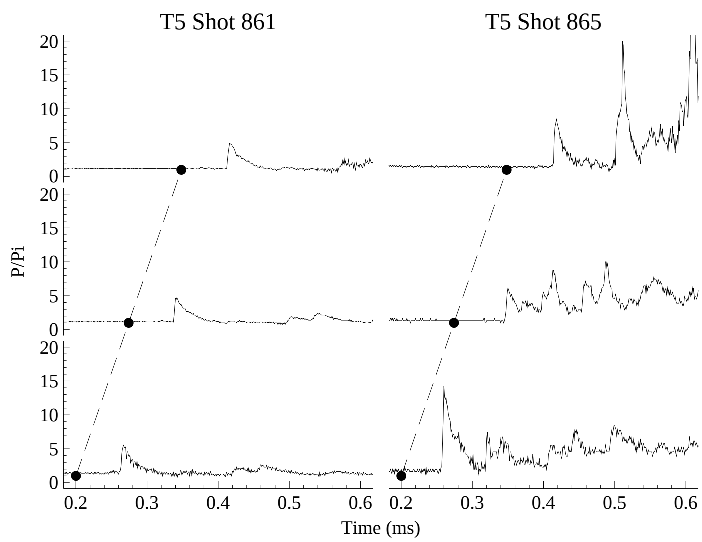

Figure 5. Pressure transducer plots for T5 shots 861 and 865.

More significantly, a second wave is seen to be overtaking the projectile from behind. This wave appears to be a detonation propagating in shocked but unreacted gas. The origin of this wave is not certain, but may be a result of processes occurring when the projectile enters the test section. The pressure data and the photograph together indicate that this was a Deflagration to Detonation Transition (DDT) event.

Figures 4b and c show clear detonation events, with cellular structure visible behind the leading waves. Sooted foil records confirmed the photographic observations. The nearly normal angle of the waves was unexpected. As shown in Fig. 1, the overdriven leading wave is expected in steady flow to decay to a CJ wave away from the body and the steady flow wave angle is predicted to be about 63 degrees. Laser trigger data show that the projectile velocities were constant ($\pm$ 50 m/s) during the flight, while the pressure data indicate that the apparent leading wave velocities were not constant. These variations are evident in the data in Table 2. An acceleration of the leading wave in T5 shot 1012 is consistent with the second shock wave overtaking the first. A deceleration of the leading waves in T5 shots 1010 and 863 suggest that the waves were overdriven but weakened as they propagated. We conclude that the waves observed in shots 863 and 1010 are transient configurations.

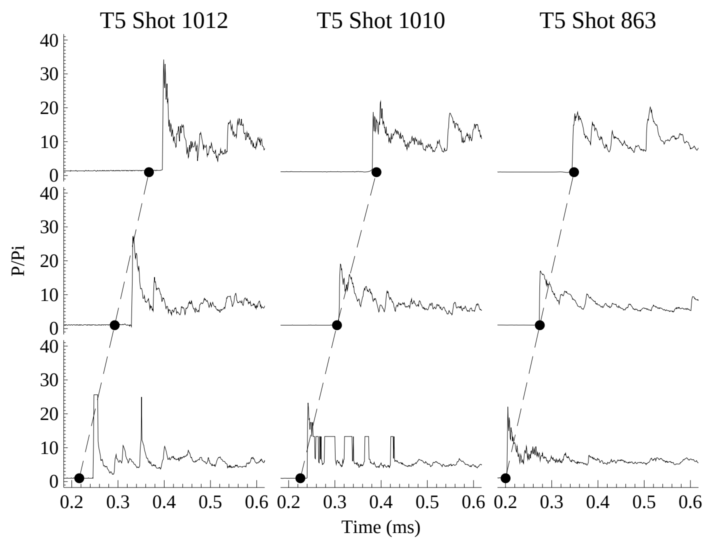

Figure 6. Pressure transducer plots for T5 shots 1012, 1010, and 863.

4. Conclusion

These results demonstrate new aspects of hypersonic projectile behavior in detonable gases. There are clearly very significant implications for combustion processes in ram accelerators and other hypersonic propulsion schemes. Further exploration in this ongoing program will examine the effect of body size, velocity, and the unsteadiness of the waves.

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