Stabilized Delayed Initiation of Detonations by Projectiles

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Abstract

New experimental observations of delayed initiation of detonation by projectiles confirm that this unpredicted phenomenon is stable and repeatable. Other researchers have observed non-detonative bow shocks transition to detonations in isolated instances [1, 2]. Normally, initiation is expected to occur at the nose of the projectile, with failure or stabilization of the detonation in the far field. Re-initiation of a failing detonation has not been considered theoretically except as a transient event. The new experimental evidence was obtained in the modified T5 hypervelocity shock tunnel facility at GALCIT. Photographic images were made using laser shadowgraphy and intensified CCD imaging of natural fluorescence. Clear examples of the delayed initiation phenomenon were observed in $2H_2$+O_2+$3.76N_2$ and C_2H_4+$3O_2$+$4.3N_2$ mixtures.

Apparatus

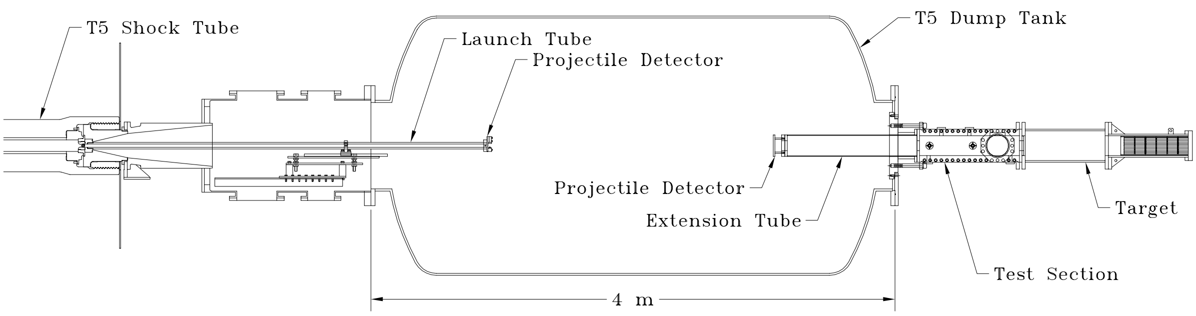


Figure 1: T5 dump tank showing launch tube, test section, extension tube, and target section

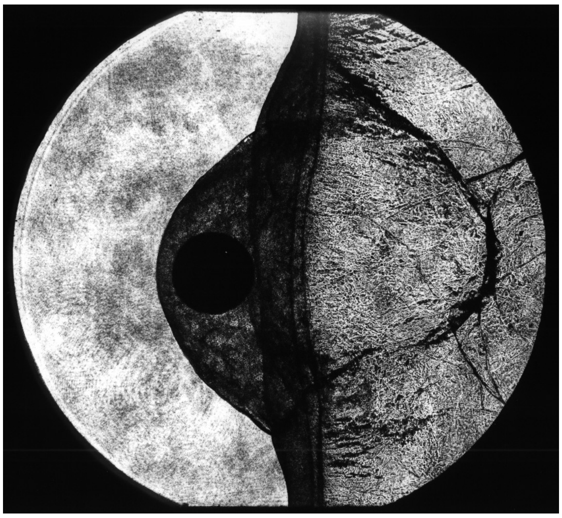
The conversion of T5 to a gas gun mode and the general experimental procedure have been described elsewhere [3, 4]. Changes to the apparatus for the present experiments included addition of an extension tube and use of an intensified CCD (ICCD) camera [5]. Figure 1 shows the T5 dump tank with the launch tube, test section, extension tube, and target section. The extension tube was added to increase the distance from the entrance to the photographic station. It was 1 m long and had an inside diameter of 152 mm. The test section had a 152-mm square inside cross section.

Results

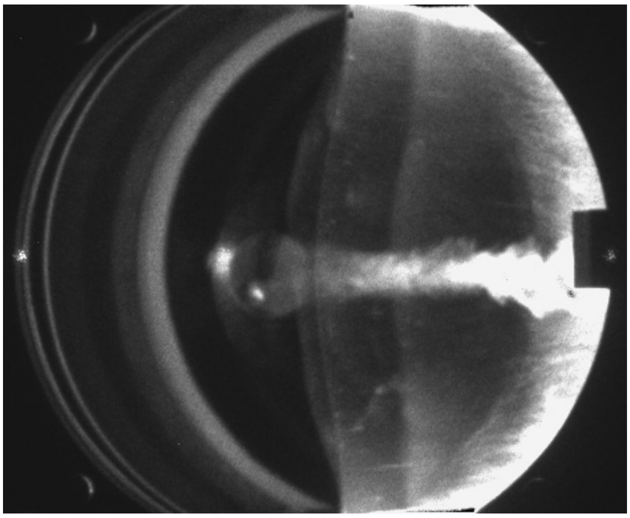
Table 1: Summary of test conditions

T5 Shot	Speed (m/s)	D_{CJ} (m/s)	Ma	λ_{CJ} (mm)	Mixture	Pressure (bar)
1820	2300	1985	5.62	4.9	$2H_2$+O_2+$3.76N_2$	2.000
1832	2400	2012	7.05	6.8	C_2H_4+$3O_2$+$4.3N_2$	0.350

Table 1 summarizes the conditions of the tests discussed below. The cell sizes, λ_{CJ}, were estimated from data obtained from literature sources and experiments in the GALCIT Detonation Tube. Chapman-Jouguet speeds, D_{CJ}, were computed using the thermochemical equilibrium STANJAN code [6].



(a) Shadowgraph



(b) Intensified CCD

Figure 2: Shot 1820: $2H_2+O_2+3.76N_2$ at 2.000 bar

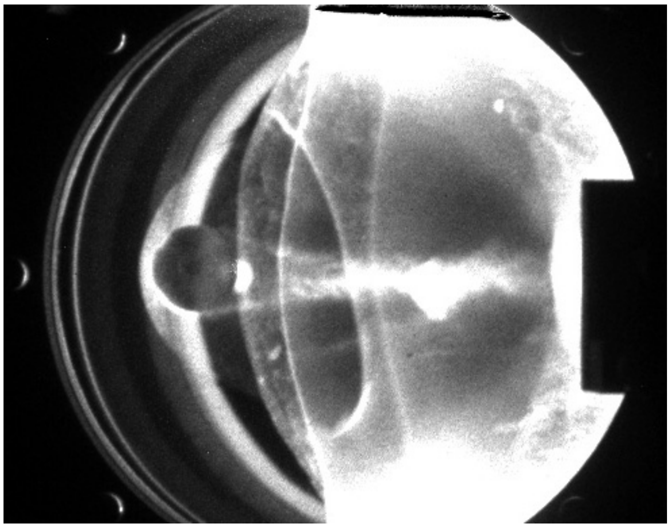


Figure 3: Shot 1832 ICCD: $C_2H_4+3O_2+4.3N_2$ at 0.350 bar, 2400 m/s

Figures 2 and 3 are photographic images from delayed-initiation events. The shadowgraph in Fig. 2(a) shows a non-detonative bow shock with decoupling reaction zone, followed immediately behind the projectile by a curved detonation wave. The detonation is overdriven at the intersection with the bow shock, decays toward the CJ state, and forms a Mach reflection with the top and bottom walls. The reflected shock waves are also visible behind the detonation. The ICCD images in Figs. 2(b) and 3 were taken at a different viewing angle than the shadowgraph. They both show the faint bow shock followed by the brighter detonation. The intersections of the detonation with the front and back windows of the test section are visible as slightly curved vertical lines. The image in Fig. 3 is brighter mainly because the hydrocarbon combustion products fluoresce in the visible range, whereas hydrogen combustion products primarily fluoresce in the ultraviolet. The ICCD camera was UV sensitive, but the BK7 test section windows blocked most of the UV radiation. Especially visible in Fig. 3 is the intersection of the bow shock and the detonation on the far side of the projectile.

Discussion

Most theoretical treatments of detonation initiation and stabilization by projectiles have focused on prompt initiation, in which the bow wave decays from the overdriven state at the nose to the CJ state, which persists out to the boundary. In this case, the wave angle decreases monotonically to the CJ wave angle ($\beta_{CJ} = \sin^{-1}[D_{CJ}/U]$). This scenario has been observed within the present study [3, 4, 5] as well as by other researchers [1, 2]. Normally, failure occurs as a result of bow-wave curvature in the vicinity of the CJ point, which leads to streamline curvature and quenching of the reaction zone. Once the reaction zone is decoupled from the bow wave, the separation between the two grows as the bow wave decays to the Mach angle.

In a stable delayed-initiation case, the bow wave takes the appearance of a decoupling shock and reaction zone. In fact, the bow wave decays beyond the CJ point without stabilizing. At some point, generally immediately behind the projectile, a detonation wave is stabilized and decays to, or nearly to the CJ state. In our experiments, the CJ state is approached but not reached before the wave curves forward in a Mach reflection at the wall. Similar configurations have been reported by Chernyi et al. [2] and by Endo et al. [1], who referred to it as a "secondary-shock supported oblique detonation wave".

Similar phenomena have been observed that are inherently unsteady, i.e., an overdriven detonation overtakes the projectile and momentarily appears superimposed on the failing bow wave. However, the repeated occurrence of the described configuration suggests that it is not accidental, and wall pressure records indicate that the detonation waves were roughly steady and propagating at the same speed as the projectile. Even so, the stability of the delayed-initiation configuration is apparently marginal, because experiments at very similar conditions resulted in promptly initiated stabilized detonations.

The factors determining whether initiation is prompt or delayed are as yet unknown. Considering the delayed detonation initiation as a secondary explosion in the partial shock-induced combustion products, it resembles the type of unsteady re-initiation described by Lee [7] in blast-initiation experiments. The unsteadiness is a key difference, however, since in the stable initiation process, some mechanism must be responsible for stabilizing the detonation in the observed position. This may be related to the radial expansion of the streamlines, or it may be a result of chemical kinetic effects.

Conclusions

The present experimental results show delayed initiation to be ubiquitous. Detonation initiation by projectiles is difficult to model and predict considering even the simplest scenarios. The delayed-initiation phenomenon is an example of the rich and complex dynamics that can occur, making analysis and prediction especially challenging. As global models for initiation in general are pursued, an understanding of the conditions leading to delayed initiation represent a particularly interesting goal.

References

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