Initiation of Detonation by Conical Projectiles

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1 Introduction

The use of oblique detonation and shock-induced combustion is of interest for hypersonic airbreathing engines such as scramjets. The use of aeroballistic testing, in which a projectile is fired into a stationary combustible gas, to investigate shock-induced combustion and oblique detonations has advantages over wind tunnel testing in that the full range of Mach number and Reynolds number can be achieved without the issues of undesirable preconditioning of the test mixture or contamination of the test conditions that occur in hypersonic tunnels (shock tunnels, expansion tubes, etc.). While there has been extensive investigation of shock-induced combustion and detonation by blunt projectiles beginning with the early studies of Ruegg and Dorsey [1] and Behrens et al. [2], studies using wedge or conical projectiles that are of greater relevance to the flow fields that would occur in engines are relatively limited (see the work of Toong [3], Behrens et al. [4] and Kasahara et al. [5]). The study of Kasahara et al., for example, emphasized relatively blunt projectiles, so that shock-induced combustion could be observed at relatively low initial pressures ($p \leq 0.5$ atm). This study extends these investigations to shallow cone angles ($\theta = 30°$). The combustible mixture used in this study is stoichiometric acetylene/oxygen diluted with argon at 80% at an initial pressure ranging from 0.67 to 1.3 atm. Of particular interest is the boundary between shock-induced combustion occurring decoupled from the conical shock and oblique detonation and the dynamics (stability) of shock-induced combustion.

2 Theory

2.1 Initiation of Detonation

The critical conditions required for a projectile to be able to initiate a detonation wave in gaseous mixture is predicted by a simple theory developed independently by Vasiljev [6] and Lee [7]. The theory makes use of the hypersonic blast wave analogy, which states that a projectile traveling through a gas deposits energy in the gas that drives a cylindrical shock wave outward; this energy deposition per unit length is simply the drag on the projectile:

$$D = \frac{1}{2}\rho V_{\mathrm{proj}}^2 A C_D = \frac{1}{2}\gamma p M_{\mathrm{proj}}^2 A C_D \tag{1}$$

This energy per unit length can be equated to the critical energy required to initiate a cylindrical detonation (Lee [7]):

$$E_c = 10\gamma p M_{CJ}^2 \lambda^2 \tag{2}$$

where λ is the detonation cell size. The resulting expression gives the relation between the projectile size and the detonation cell size required to initiate a detonation:

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$$\frac{D_{\text{proj}}}{\lambda} = \sqrt{\frac{80}{\pi C_D}} \left(\frac{M_{CJ}}{M_{\text{proj}}} \right) \tag{3}$$

This theory has been shown by Higgins and Bruckner [8] to be accurate in predicting the initiation of detonation in a hydrogen/oxygen/argon mixture by spherical projectiles ($C_D = 1$) ranging from 5 mm to 25 mm in diameter and traveling at the CJ detonation speed of the mixture. For this study, conical projectiles were considered, which have values of drag coefficient that can be approximated by a simple correlation from Linnell and Bailey [9]:

$$\frac{C_D}{\sin^2 \theta_c} = \frac{(10 + 32\beta \sin \theta_c)}{1 + 16\beta \sin \theta_c} \tag{4}$$

where θ_c is the cone half angle and $\beta = \sqrt{M_\infty^2 - 1}$. For this study, cone half angles of 30, 45, and 60° were used, corresponding to drag coefficients of $C_D \approx 0.5$, 1.0, and 1.5, respectively. For the cell size λ of acetylene/oxygen/argon mixtures, the data of Desbordes et al. [10] was fit with a power law of the form $\lambda = 1.2625p^{-1.228}$. The predictions of this model are compared to experimental results in Section 4.

2.2 Chemical Kinetics

In order to observe either shock-induced combustion or oblique detonation, the length scale of the chemical energy release zone (induction length) must be comparable to the length scale of the flow field (characterized by the nose cone length). Given a conical projectile velocity, the associated inert conical shock angle was calculated using a Taylor-Maccoll algorithm, providing the flow temperature and velocity behind the shock and at the cone surface. The temperature at these two locations was the input parameter to an adiabatic, zero-dimensional reactor at constant volume. The detailed reaction mechanism of Varatharajan and Williams [11] was implemented in the reactor to model the acetylene oxidation. Once the induction time was obtained, the velocity at the two locations (downstream of the conical shock and at the cone surface) was used to calculate the induction length. The effect in using the temperature and velocity at the two different locations for the induction length calculation was determined to be negligible compared to the effect of changing the projectile velocity and the cone angle. The parameters for which the induction length equals the scale of the flow field (i.e., nose cone length) determines the kinetic limit. This limit is compared to experimental results in Section 4.

3 Apparatus

The projectiles were launched from a single stage, combustion driven gas gun using hydrogen and oxygen as propellant. This launcher is capable of velocities of 2.5 km/s; the details of its design and operation are given in [12]. After passing through an evacuated section to absorb the muzzle blast from the launcher, the projectiles were injected through a Mylar diaphragm into a combustible mixture contained in cylindrical test section (16.5 cm in diameter, 92 cm long) equipped with windows permitting flow visualization. The results were monitored using self-luminous high-speed photography (HSFC-Pro image-intensified camera). There were two motivations for choosing a stoichiometric acetylene/oxygen mixture diluted with argon at 80% as the investigated mixture. Firstly, as the pictures were taken using self-luminous photography, light emission from the combustion products was necessary, which is the case with acetylene/oxygen combustion. Secondly, considering the limitation of the launcher capability, the mixture CJ velocity of the mixture had to be less than 1 800 m/s. 80% of Argon dilution provides a CJ velocity between 1 700 m/s and 1 730 m/s, depending on the initial pressure. The projectiles were 1.27 cm in diameter with cone angles varying from $\theta_c = 30° - 60°$. The projectiles were made from 7075 aluminum alloy and were hollowed from the back in order to reduce mass and for a better seal against the launch tube via internal pressurization.

4 Results

Results in which both projectile-initiated detonation and failure to initiate were observed for different test conditions. Figure 1 presents a typical case of a projectile initiating a detonation wave. The cone half angle was 60° and the velocity was 1 987 m/s. The transition from an overdriven normal detonation wave in front of the projectile to a CJ conical detonation in the farfield can be seen. The detonation wave angle depends on the mixture CJ velocity and the projectile velocity in the same manner as a nonreacting shock wave angle depends on the sound speed and the velocity of the body that produces the shock wave. Therefore, the angle of the detonation wave can be calculated using the following relation: $\sin\theta_{\mathrm{CJ}} = V_{\mathrm{CJ}}/V_{\mathrm{proj}}$. Figure 2 shows this relation with experimental results. It can be observed that most of the experimental results follow the trend of the theoretical relation. Whereas the discrepancy can be as much as 10°, in all cases a luminous front at constant angle was seen propagating away from the projectile. When compared to the Mach angle for a nonreacting shock ($\theta \approx 8°$), it can be concluded that a detonation wave was definitely initiated in all the cases displayed in Figure 2.

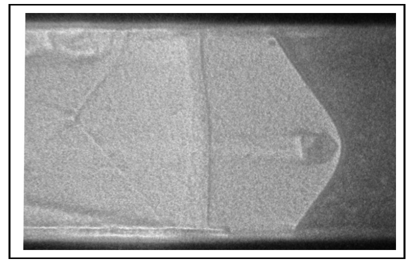

Figure 1: Conical projectile launched into C_2H_2+2.5O_2+14Ar mixture

As mentioned in Section 2, two requirements need to be fulfilled in order to directly initiate a detonation wave with a conical projectile: the energy deposited by the projectile has to be equal or greater than the energy required to initiate a cylindrical detonation and the chemical length scale has to be equal or greater than the length scale of the projectile. These two limits depend on the projectile velocity, the cone half angle and the initial pressure of the mixture. Figure 3 presents the two limits as a relation between the initial pressure and the cone half angle for two projectile velocities. Above the energetic limit, the energy deposited by the projectile is sufficient to initiate a detonation and on the right of the kinetic limit, the induction length behind the inert conical shock wave is smaller than the projectile size. The projectile with a half angle of 30° deposits sufficient energy to initiate detonation but does not have sufficiently fast kinetics, and the experiment showed that no detonation was initiated. For all the other projectiles, they are in the detonable and fast kinetic region and they all initiated a

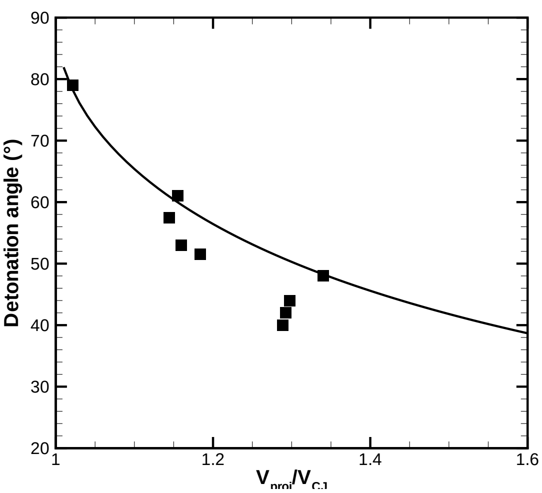

Figure 2: Detonation angle as a function of the ratio of the projectile velocity and the CJ velocity

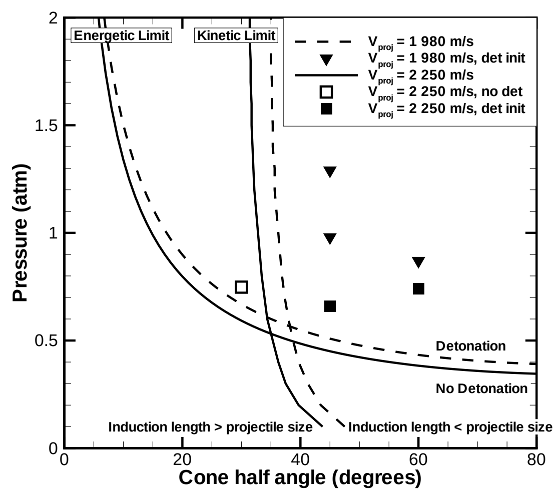

Figure 3: Energetic and kinetic requirements to initiate a detonation by a conical projectile

detonation. It can be seen that with the current results, the energetic and the kinetic limits appear sufficient to define the conditions required to initiate a detonation by a hypersonic conical projectile.

5 Conclusions

Conical projectiles were launched at hypervelocities into a stoichiometric acetylene/oxygen mixture with 80% argon dilution. Self-luminous pictures of the projectiles initiating a detonation wave were taken. Varying the projectile velocity from 1 980 m/s to 2 250 m/s, the cone half angle from 30° to 60° and the mixture initial pressure from 0.67 to 1.3 atm, initiation of a detonation was observed in some cases. An energetic and a kinetic limit were proposed to predict the conditions required to observe detonation initiation. These two limits were consistent with the experimental results.

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