

Meta-stable Deflagration Waves

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1 Introduction

Experiments on deflagration to detonation transition (DDT) in a smooth tube indicate that a deflagration wave does not accelerate continuously to the final detonation velocity. Instead, the maximum deflagration velocity that is reached just prior to the abrupt onset of detonation corresponds to about half the CJ detonation velocity of the mixture ($\frac{1}{2}V_{CJ}$). The duration of this quasi-steady $\frac{1}{2}V_{CJ}$ state can be of the order of a few tube diameters but, under certain conditions, can also persist for tens of tube diameters before detonation onset occurs. This $\frac{1}{2}V_{CJ}$ state is meta-stable, and the onset of detonation corresponds to the “explosive growth” of instabilities, manifested by the spontaneous appearance of cellular structure when the detonation is formed.

This meta-stable state is also observed in the direct initiation of spherical detonations in the critical energy regime where the initiation blast decays to about $\frac{1}{2}V_{CJ}$ prior to the onset of detonation [1]. The low velocity phase of a galloping detonation is also found to be similar to this meta-stable state. At the end of the low velocity phase, rapid amplification of the precursor shock leads to the formation of an overdriven detonation to start the next galloping cycle [2]. Even when the transverse waves of a self-sustained detonation are dampened out by acoustic absorbing walls, the detonation fails and becomes a $\frac{1}{2}V_{CJ}$ meta-stable deflagration wave [3]. Therefore, it appears that the $\frac{1}{2}V_{CJ}$ meta-stable deflagration state is a common feature in the phenomenon that leads to the abrupt formation of a detonation.

Although this meta-stable regime has been observed in previous investigations of DDT, it has not been singled out for a more thorough study. In the present paper, results of an experimental study of this meta-stable deflagration regime are reported. A detonation is reflected from a perforated plate in order to bypass the irreproducible flame acceleration phase and to establish a meta-stable deflagration wave downstream. Since each individual hole is choked, the combustion products flow through the holes at the speed of sound (or about $\frac{1}{2}V_{CJ}$). Therefore, the interface (between the transmitted combustion products and the unburned mixture) where ignition of a deflagration occurs is also initially at the $\frac{1}{2}V_{CJ}$ meta-stable state. A meta-stable deflagration can thus be generated in a reproducible manner for varying initial conditions.

2 Experimental Details

A 4.5 m long steel detonation tube with an inner diameter of 65 mm was used in the present investigation. The detonation tube was divided into two sections with a perforated plate: the upstream section is 2.5 m long and the downstream test section is 2.0 m long. A high energy spark (~ 100 J) was used to directly initiate a CJ detonation in the upstream section. A 275 mm long window section was used for streak

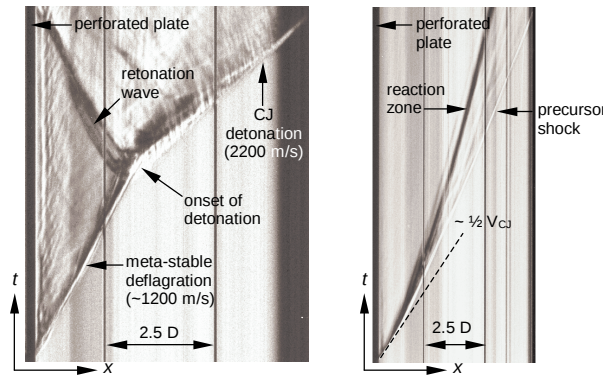


Figure 1: Streak schlieren photographs of a) meta-stable deflagration wave leading to the onset of detonation (stoichiometric acetylene-oxygen at $P_o = 4.0$ kPa) and b) unsuccessful detonation onset (stoichiometric acetylene-oxygen at $P_o = 0.6$ kPa).

Schlieren photography. Two 6 mm thick perforated plates with different hole diameters ($d = 5$ and 8 mm) but with the same blockage (77%) were used. A third perforated plate with $d = 8$ mm and less blockage of 60% was also used.

Stoichiometric mixtures of acetylene-oxygen and of acetylene-oxygen with 80% argon dilution were tested. The sensitivity of the mixtures was varied by the initial pressure. The mixtures were prepared beforehand in a separate vessel by the method of partial pressures. For any given experiment, both upstream and downstream sections of the tube were initially evacuated. The entire tube was then filled from both ends to the desired initial pressure.

Ionization probes were used to measure the time of arrival of the reaction front. PCB pressure transducers were used to measure the time of arrival of the shock front and the pressure rise behind the shock. A rotating drum streak camera with a constant film speed of about 80 m/s was also used in conjunction with a double pass Schlieren optical system in order to obtain flow visualization downstream of the perforated plate.

3 Results and Discussion

A typical streak schlieren photograph of a meta-stable deflagration wave leading to the successful onset of detonation is shown in Fig. 1a. It can be seen that the meta-stable deflagration consists of a precursor shock wave and a reaction zone that propagate together away from the perforated plate at a velocity of about 1200 m/s (which roughly corresponds to the $\frac{1}{2}V_{CJ}$ value). After a distance of about 2.5 tube diameters, the sudden onset of detonation occurs from the spontaneous formation of localized explosions in the reaction zone. The characteristic retonation wave can be seen to propagate back upstream, and a CJ detonation continues to propagate downstream for the remainder of the field of view. In Fig. 1b, a streak schlieren photograph of an unsuccessful case of detonation onset is shown for comparison. Immediately downstream of the perforated plate, the meta-stable deflagration wave begins to propagate away from the plate at about $\frac{1}{2}V_{CJ}$. Within a tube diameter, however, the reaction front begins to recede rapidly from the precursor shock wave. The reaction front and the precursor shock decay to velocities of 600 and 800 m/s, respectively, by the end of the field of view (of about 7 tube diameters). It should be noted that the onset of detonation is never observed when the meta-stable deflagration velocity of $\frac{1}{2}V_{CJ}$ cannot be maintained and the deflagration decays.

The effect of the perforated plate is shown in Fig. 2. It is interesting to note that in all three cases, a meta-stable deflagration wave travels at a velocity around $\frac{1}{2}V_{CJ}$ prior to the onset of detonation regardless of the characteristics of the perforated plate. By changing the hole diameter from 5 to

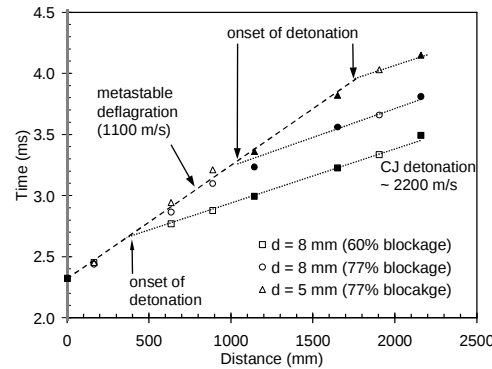


Figure 2: Effect of perforated plate characteristics on meta-stable deflagration waves.

8 mm (and fixing the percentage of the blocked area to the flow), the turbulence scales generated by the perforated plate in the downstream flow is varied. Furthermore, decreasing the percentage of the blocked area from 77% to 60% (but keeping the hole diameter fixed at 8 mm) results in a faster downstream interface velocity and higher turbulent intensities downstream. Nevertheless, the same $\frac{1}{2}V_{CJ}$ velocity is observed in all cases, which suggests that meta-stable deflagrations are neither affected by the turbulence generated by the perforated plate nor driven from behind by the interface (that separates the transmitted detonation products and the downstream product gases). In general, turbulent deflagration velocities are strongly dependent on turbulent transport rates and are therefore very sensitive to initial and boundary conditions. However, the present results indicate that the meta-stable state of $\frac{1}{2}V_{CJ}$ is relatively insensitive to variations in initial and boundary conditions, which suggests that the propagation of meta-stable deflagration waves are not controlled by turbulent transport but rather by the energetics of the mixture-similar to a CJ detonation. Theoretical considerations by Chue *et al.* suggested that these quasi-steady deflagration waves are CJ deflagrations [4], which is the maximum theoretical deflagration velocity and is only dependent on the amount of chemical energy released by the mixture.

The characteristics of the perforated plate do, however, have an effect on the distance from the plate to the location of the onset of detonation. While the “onset distance” varies slightly from shot to shot, it can be seen from Fig. 2 that, in general, a larger hole diameter and less blockage promote shorter distances to onset. It is also interesting to note that the duration of the meta-stable state can be rather long. From Fig. 2, the meta-stable deflagration is observed to propagate up to 28 tube diameters (or about 1800 mm) before the onset of detonation occurs. It appears that the meta-stable state of $\frac{1}{2}V_{CJ}$ must be maintained for a sufficiently long duration in order for the proper conditions for the onset of detonation to be achieved. Although the initial plate generated turbulence decays, the sustained propagation of a meta-stable deflagration in acetylene-oxygen is possible due to the reaction rates that are sufficiently sensitive to temperature fluctuations [5]. Therefore, chemical instabilities can be sustained for long durations, and the “run-up” to onset is essentially an incubation period during which the gradual amplification of pressure waves leads to the resonant coupling between pressure fluctuations and the chemical energy release and the eventual onset of detonation. It should be noted that the onset of detonation can also be effected by a localized explosion that amplifies into a fully-developed detonation.

The effect of high argon dilution was also tested in the present study. A typical streak schlieren photograph of a successful case of onset is shown in Fig. 3a for stoichiometric acetylene-oxygen with 80% argon dilution at $P_o = 30$ kPa. A meta-stable deflagration can be seen to propagate at $\frac{1}{2}V_{CJ}$ for a short distance (about 1.5 tube diameters) prior to the sudden onset of detonation. The onset of detonation is effected by a localized explosion in the reaction zone; the characteristic detonation wave can be seen to propagate upstream while a CJ detonation continues to propagate downstream. This is in stark contrast to the unsuccessful case where onset is not observed (shown in Fig. 3b). Downstream of the perforated plate, the reaction zone quickly recedes from the precursor shock wave, and the meta-stable

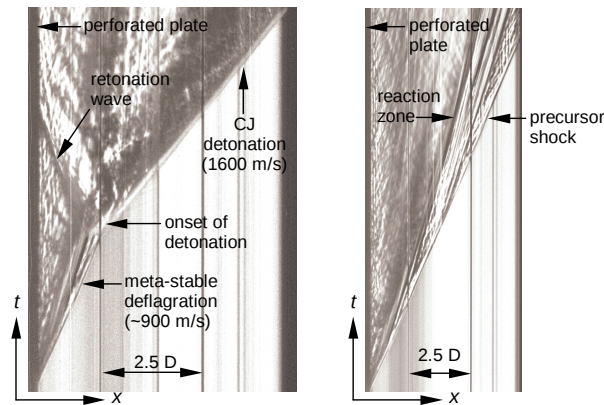


Figure 3: a) Successful and b) unsuccessful onset of detonation in stoichiometric acetylene-oxygen with 80% argon dilution.

state cannot be maintained. Essentially, meta-stable deflagration waves are not observed to propagate for long distances (greater than 4 tube diameters) in heavily argon diluted mixtures. “Stable” mixtures (i.e. with high argon dilution) are relatively insensitive to temperature perturbations [6]. As a result, the onset of detonation must occur near the perforated plate due to a localized explosion prior to the decay of the initial plate generated turbulence.

4 Concluding Remarks

The onset of detonation is preceded by a meta-stable deflagration wave that propagates at a relatively constant velocity of $\frac{1}{2}V_{CJ}$. The $\frac{1}{2}V_{CJ}$ meta-stable state is independent of turbulence parameters from the perforated plate and is controlled by the energetics of the mixture like a CJ detonation. The initial high turbulent intensities generated by the perforated plate are maintained through chemical instabilities that sustain and amplify transverse waves in the reaction zone. Therefore, unstable mixtures (with irregular cell patterns) are capable of supporting the propagation of meta-stable deflagration waves for long durations. In stable mixtures (with regular cell patterns), meta-stable deflagrations can only propagate when the initial turbulence generated by the perforated plate has not yet decayed. The final onset of detonation is manifested through the coupling of the amplified transverse pressure waves in the distributed reaction zone with the chemical energy release.

References

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