The Effect of Perturbations on the Onset of Detonation

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1   Introduction

In deflagration to detonation transition (DDT), the abrupt formation of the detonation generally originates in the turbulent reaction zone of a meta-stable deflagration wave that typically propagates at half the theoretical CJ detonation velocity ($\frac{1}{2}V_{CJ}$) of the given mixture. At the onset of detonation, small perturbations associated with turbulent fluctuations in the reaction zone amplify rapidly to form the detonation. However, due to their irreproducible and random nature, it is rather difficult to study the growth of these perturbations.

Chue *et al.* [1] and Mazaheri *et al.* [2] have previously investigated numerically the effect of perturbations on the onset of detonation by imposing a density (or temperature) variation in the path of the quasi-steady deflagration to create a hot spot. No definitive conclusions were obtained from these numerical studies, and only density (or temperature) perturbations were considered for convenience. However, it is clear that a finite perturbation introduced during the quasi-steady propagation of a deflagration (at the subcritical energy condition) can lead to the onset of detonation. Without any perturbation, the reaction zone decouples from the precursor shock wave, and the deflagration degenerates into an acoustic wave followed by a laminar flame.

It is, therefore, of interest to investigate experimentally the effect of introducing a finite perturbation on a meta-stable deflagration wave prior to the spontaneous onset of detonation. The subsequent amplification of the pressure wave can be monitored, permitting the conditions that lead to its rapid amplification to be determined. From physical considerations, a small perturbation is sufficient to trigger the onset of detonation when conditions are close to critical for the spontaenous onset of detonation to occur whereas away from the critical limit, a larger perturbation is required. The time during which a perturbation grows to a detonation should also depend on the strength of the perturbation as well as the conditions of the mixture itself. An investigation of the conditions that lead to the growth of perturbation should elucidate the mechanism for the onset of detonation.

In the present study, the onset of detonation is triggered by a perturbation introduced during the quasi-steady pre-detonation regime of the deflagration wave. It has been shown that by reflecting a detonation from a perforated plate, a quasi-steady deflagration that propagates at $\frac{1}{2}V_{CJ}$ can be readily generated in a relatively controlled manner downstream of the plate [3]. A perturbation is generated in the path of the quasi-steady deflagration wave by a wire loop placed circumferentially on the inner wall of the tube downstream of the perforated plate. Mixtures of different temperature sensitivity are used to investigate the role of chemistry on the growth of the perturbation.
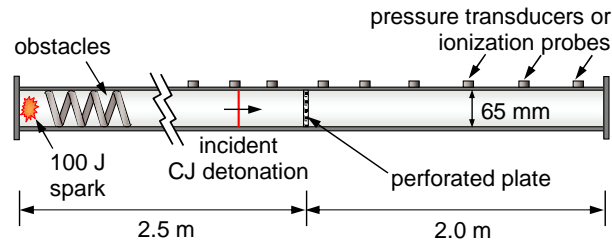
Figure 1: Sketch of experimental apparatus

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 schematic of the experimental apparatus is shown in Fig. 1. A 6 mm thick perforated plate with 5 mm diameter holes was used with 77% blocked area. A 1 mm diameter wire was used as a small obstacle and placed 295 mm downstream of the perforated plate.

Stoichiometric mixtures of acetylene-oxygen and of acetylene-oxygen with 80% argon dilution were tested. The mixtures were prepared beforehand in a separate vessel by the method of partial pressures The gases were allowed to mix in the vessel for at least 24 hours in order to ensure homogeneity. For any given experiment, both upstream and downstream sections of the tube were initially evacuated to approximately 100 Pa. The entire tube was then filled from both ends to the desired initial pressure. The sensitivity of the mixtures was varied by the 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.

3   Results and Discussion

The effect of a perturbation on the onset of detonation can be seen in the wave trajectories shown in Fig. 2a for a stoichiometric acetylene-oxygen mixture at $P_o = 1.8$ kPa. The perforated plate is located at $x = 0$ mm. Upstream, a CJ detonation is measured to propagate at 2180 m/s. Downstream, two cases are shown: the circles represent the reaction front (open circles) and shock (closed circles) trajectories for the unperturbed case while the triangles represent the perturbed case. For the case without any perturbation, a meta-stable deflagration is observed to propagate at a velocity of about 1090 m/s (which corresponds to about $\frac{1}{2}V_{CJ}$) prior to the spontaneous onset of detonation. After a distance of about 1700 mm (or roughly 26 tube diameters), the sudden onset of detonation occurs. A CJ detonation travelling at 2180 m/s is then observed for the remainder of the test section.

When a small 1 mm diameter obstacle is introduced in the path of the meta-stable deflagration wave 295 mm downstream of the perforated plate, the onset of detonation is triggered much sooner. It can be seen from Fig. 2a that after the introduction of the perturbation, the meta-stable deflagration still propagates at a relatively steady velocity of 1090 m/s until the sudden onset of detonation occurs about 14 tube diameters (or 900 mm) downstream of the perforated plate. It should be noted that when the perturbation is placed in the path of the meta-stable deflagration wave, the onset of detonation is not triggered immediately downstream of the obstacle. Instead, the meta-stable deflagration continues to propagate for about 9.5 more tube diameters before onset occurs. Pressure fluctuations induced by the perturbation can be clearly seen in the pressure profile of a meta-stable deflagration (just prior to the
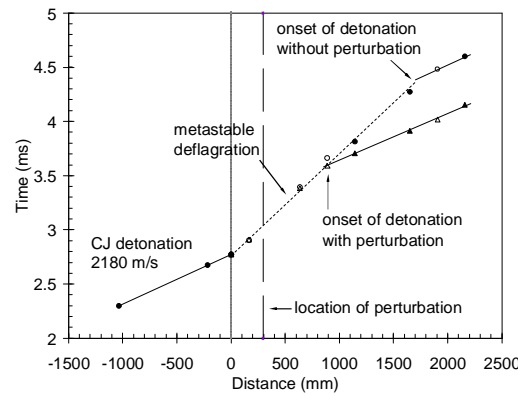
Figure 2: Effect of a perturbation on detonation onset. Perturbation placed at a) 295 mm and b) 588 mm downstream of the perforated plate; stoichiometric acetylene-oxygen at $P_o = 1.8$ kPa.
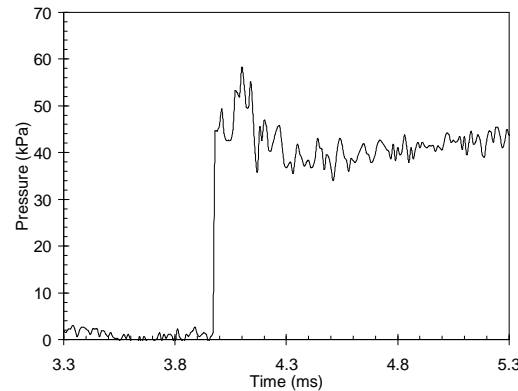

Figure 3: Pressure profile of a perturbed meta-stable deflagration located at $x = 1143$ mm; stoichiometric acetylene-oxygen at $P_o = 1.4$ kPa.

onset of detonation) shown in Fig. 3. A characteristic period of the pressure fluctuations can be identified and corresponds roughly to the time in which an acoustic wave traverses the tube diameter (roughly 0.05 ms). These results suggest that the eventual formation of the detonation is not via a local hot spot that is generated immediately in the wake of the obstacle but rather by a more gradual amplification of the pressure perturbations generated by the obstacle through multiple reflections from the tube wall and from the resonant coupling with the chemical energy release (i.e., the Rayleigh criterion).

Acetylene-oxygen mixtures with 80% argon dilution were also studied in order to investigate the effect of chemistry on the growth of perturbations. Typical streak schlieren photographs of a successful and unsuccessful case of detonation onset are shown in Fig. 4 without any perturbation. For the successful case, a meta-stable deflagration can be seen to propagate for less than 2 tube diameters prior to the sudden onset of detonation, resulting from a localized explosion in the reaction zone. For the unsuccessful case, the meta-stable deflagration can be seen to fail almost immediately, and a shock wave followed by a decoupled reaction front propagating at 800 m/s and 600 m/s (respectively) by the end of the field of view. It is interesting to note that the introduction of the 1 mm perturbation has virtually no effect on the phenomenon. It appears that since highly argon diluted mixtures have reaction rates that are relatively insensitive to temperature fluctuations, small perturbations to the meta-stable deflagration cannot be amplified. Therefore, once the initial plate generated turbulence decays, the meta-stable deflagration decays as well and the onset of detonation is no longer possible.
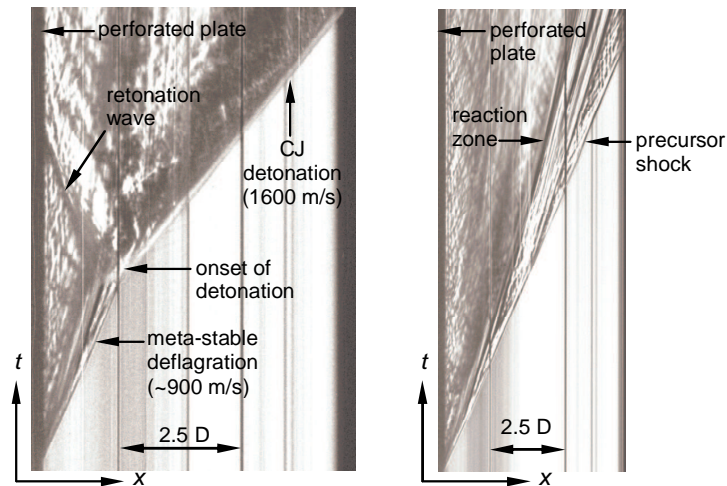
Figure 4: Streak schlieren photographs of a) a successful case and b) an unsuccessful case of detonation onset; stoichiometric acetylene-oxygen with 80% argon dilution at a) $P_o = 35$ kPa and b) $P_o = 25$ kPa.

4   Concluding Remarks

In general, a small perturbation placed in the path of a meta-stable deflagration wave travelling at a velocity of around $\frac{1}{2}V_{CJ}$ promotes the onset of detonation to occur sooner (compared to when no perturbation is present). The onset of detonation occurs via the gradual amplification of the pressure disturbance rather than through a local hot spot. In mixtures with low temperature sensitivity (i.e. mixtures with high argon dilution), the perturbation fails to be amplified as it traverses the reaction zone. The present investigation suggests that the onset of detonation requires the amplification of pressure waves, which in turn depends on the temperature sensitivity of the reaction rates.

References

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