The onset of detonation in mixtures with regular and irregular detonation cellular structures

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1 Introduction

In recent years, there is ample evidence to show that the detonation structure for mixtures with large amounts of argon dilution differs significantly from that of undiluted mixtures. Most of the common fuel-oxygen or fuel-air mixtures have turbulent detonation structures with highly irregular transverse wave patterns. The prominent feature of high argon dilution is to yield piecewise laminar detonation structures with highly regular triple point trajectories, as demonstrated experimentally [1–5] and numerically [6, 7]. More importantly, mixtures with regular and irregular detonation cellular structures have been found to behave much differently near the critical conditions that separate failure from successful detonation propagation. For example, in thin smooth tubes, the velocity deficit and critical failure diameter were found to be larger for regular mixtures [8]. Similarly, Radulescu and Lee [3] used porous wall tubes to damp the detonation transverse waves and found that the failure limit in regular and irregular mixtures is d/λ=11 (or equivalently 11 cell sizes per tube diameter) and d/λ=4, respectively. Moreover, for most irregular detonation mixtures, the critical tube diameter in diffraction experiments was found to follow the empirical correlation dc=13/λ [9]. However, for mixtures with highly regular cellular structures, critical tube diameters as large as 40 cell sizes (λ) were measured [4, 8, 10]. Lee [11] proposed that the distinct failure limits of regular and irregular mixtures are the result of different detonation failure mechanisms. He argued that irregular detonations fail from the inability to generate local hot spots while regular detonations fail by the excess curvature imposed on the leading front.

In the present work, the reflection of a fully established detonation from a perforated plate and the reinitiation of detonation downstream are investigated in smooth tubes with mixtures having regular and irregular detonation cellular structures. The aim of this study is hence to determine the critical conditions for the onset of detonation in both types of mixtures and inquire into the influence of the detonation cellular regularity on the mechanisms that lead to the onset of detonation.

2 Experimental details

Experiments were carried out in a 2.5 m long detonation tube with a rectangular cross-section of 64 x 38 mm (see Fig. 1). A perforated plate was installed inside the tube, either upstream or inside of a glass-walled test section. Three different perforated plate geometries (i.e. hole sizes of 2, 4.8 and 7.5

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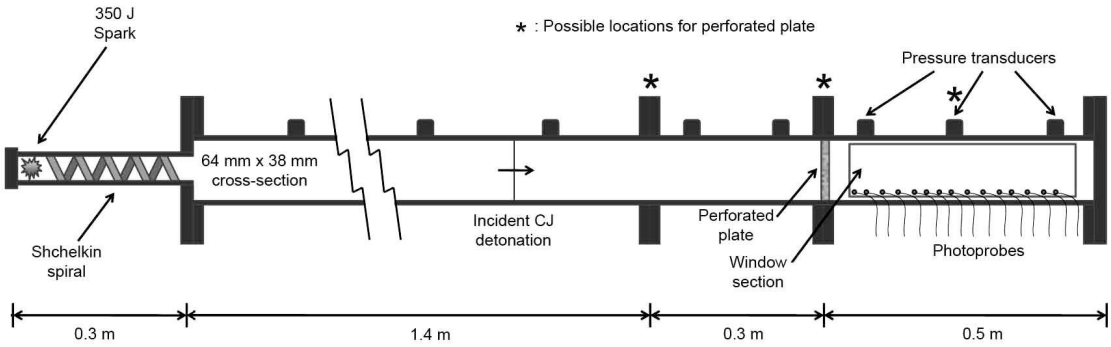

Figure 1: Schematic of the detonation tube.

mm in diameter) were tested in the present investigation. All perforated plates had blockage ratios (BR) of 70% and hole spacing to hole diameter ratios of 0.5.

Two different mixtures were investigated: C_3H_8 + $5O_2$ (irregular detonation structure) and C_2H_2 + $2.5O_2$ + 70%Ar (regular detonation structure), and were prepared by the method of partial pressures in separate vessels. The range of initial pressures investigated was from 2 kPa to 20 kPa at atmospheric temperature. Ignition of the mixture was obtained by means of a powerful spark, generated by the discharge of a 4.5 μF capacitor charged at 12.5 kV. The flow fields upstream and downstream of the perforated plate were monitored with single-frame schlieren photography, using a conventional double-mirror Z-type schlieren system. Simultaneously with schlieren photography, the combustion wave trajectories were recorded with a circuit consisting of 15 photoprobes seated on the glass wall. Also, the pressure characteristics were recorded with PCB pressure transducers installed along the tube.

3 Results and discussion

3.1 Highly argon diluted acetylene-oxygen mixtures

For the highly argon diluted mixture, Fig. 2a) shows typical wave trajectories of Chapman-Jouguet (CJ) detonations transmitting through the 4.8 mm hole perforated plate. Upstream of the plate, the detonation propagates at about 1750 m/s, which corresponds to the CJ detonation velocity. Upon reflection from the plate, the detonation products are transmitted downstream. The flow through the holes of the plate is chocked and thus the flow velocity is about the sound speed of the combustion products ($\approx$1000 m/s), which is of the order of half the CJ detonation velocity. Fig. 2b) shows the transmission process through the perforated plate. When the detonation products jet through the holes, they drive small spherical shocklets downstream. These small curved shocklets eventually coalesce to form a corrugated shock front. The network of turbulent jets and pressure waves yield a complex turbulent flow field where the transmitted detonation products mix with and ignite the unburned mixture. Hence, a turbulent reaction front continues to propagate downstream. It is found that there exists a well defined critical value of the initial pressure in which this turbulent reaction front will evolve back into a detonation, as shown in Fig. 3b). There is a distinct critical initial pressure for each plate geometry and it is about 16.5 kPa, 11.0 kPa and 9.0 kPa for the 2 mm, 4.8 mm and 7.5 mm hole perforated plates, respectively. Thus, it appears that large scale turbulent eddies facilitate the re-initiation of the detonation downstream of the perforated plate by promoting more rapid mixing of the unburned mixture with the transmitted hot combustion products.

For this mixture, transition to detonation occurs always at a relatively close distance from the plate

downstream, when the turbulent intensities generated by the plate have not yet decayed. Systematically in all experiments, there is either formation of detonation close to the plate or the turbulent reaction zone decays and the onset of detonation is not observed. This implies that the initial turbulent intensities generated by the perforated plate cannot be maintained by the chemical reactions for long distances. In the numerical work of Ng et al. [6] and Radulescu et al. [7], the regular detonation cell pattern for high argon diluted mixtures was found to be the result of the reaction rates being insensitive to temperature fluctuations. Hence, in such mixtures, the chemical instabilities are weak and may not be able to maintain or amplify the turbulent fluctuations generated by the plate. Consequently, when the detonation is not reinitiatied downstream of the plate (subcritical initial pressures), the turbulent fluctuations die out and the turbulent reaction front decays into a deflagration, with the progressive decoupling of the leading shock from the reaction zone, as shown in Fig. 3a). On the basis of these results, it appears that mixtures with large amounts of argon dilution cannot self-generate the critical conditions that are required for detonation transition. External sources of turbulence are required in order to maintain and amplify the turbulent intensities in the reaction front. One can thus speculate that Deflagration-to-Detonation-Transition (DDT) will never be observed in smooth tubes for mixtures with highly regular detonation cell patterns.

3.2 Propane-oxygen mixtures

Fig. 4a) shows typical wave trajectories of detonation re-initiation downstream of the perforated plate in propane-oxygen mixtures. Subsequent to the reflection of the detonation upstream, the turbulent reaction front propagates downstream at about 1350 m/s (compared to the CJ detonation velocity of 2220 m/s), which again is of the order of the sound speed of the combustion products. The phenomenon for the propane-oxygen mixture is in contrast to that for the high argon diluted mixture in that the duration of the pre-detonation phase can be much longer and that the onset of detonation fluctuates significantly from one experiment to the other. At around the critical initial pressure, the onset of detonation is found to take place at distances from the plate downstream between 12.5 cm to as much as 25 cm. As shown in Fig. 5a), the propane-oxygen mixture seems to be able to sustain the propagation of the high speed turbulent reaction front without the decoupling of the leading shock from the reaction zone. The local fluctuations of the shock front (e.g. 1st frame), the presence of pockets of unreacted gases behind (e.g. 2nd frame) and the formation of vortex-like structures within the reaction zone (e.g. 3rd frame) all demonstrate that the turbulent fluctuations generated by the plate are maintained even after a relatively long travel. For the propane-oxygen mixture, the critical conditions leading to detonation transition seem not to be directly generated by the perforated plate but rather to be developed within the reaction zone. For mixtures which exhibit irregular detonation cell patterns, the reaction rates are highly sensitive to temperature fluctuations [6]. Thus, small perturbations in the reaction zone will amplify and lead to large pressure fluctuations. The turbulent fluctuations generated by the perforated plate can hence be maintained and amplified through the chemical instabilities. The growth of the chemical instabilities will eventually lead to the transition into detonation, as displayed in Fig. 5b).

4 Conclusions

For the high argon diluted acetylene-oxygen mixture, which has a very regular cell pattern and a piece-wise laminar structure, the onset of detonation is found to only occur in the vicinity of the perforated plate where the initial turbulent intensities have not yet decayed. If the detonation is not reinitiated immediately downstream of the plate, the pertubations generated by the plate die out and the reaction front decays into a deflagration with the complete decoupling of the leading shock from the reaction zone. On the basis of these results, it appears that high argon diluted mixtures cannot self-generate the critical

conditions that are required for detonation transition. Only the mixtures with irregular detonation cell patterns are found to be able to maintain the turbulent intensities generated by the perforated plate and induce the turbulent flow fields required for detonation transition. The contrast between the two types of mixtures seems to be related to the fact that for irregular mixtures, chemical instabilities dominate the propagation mechanism whereas they are not prevalent for regular mixtures.

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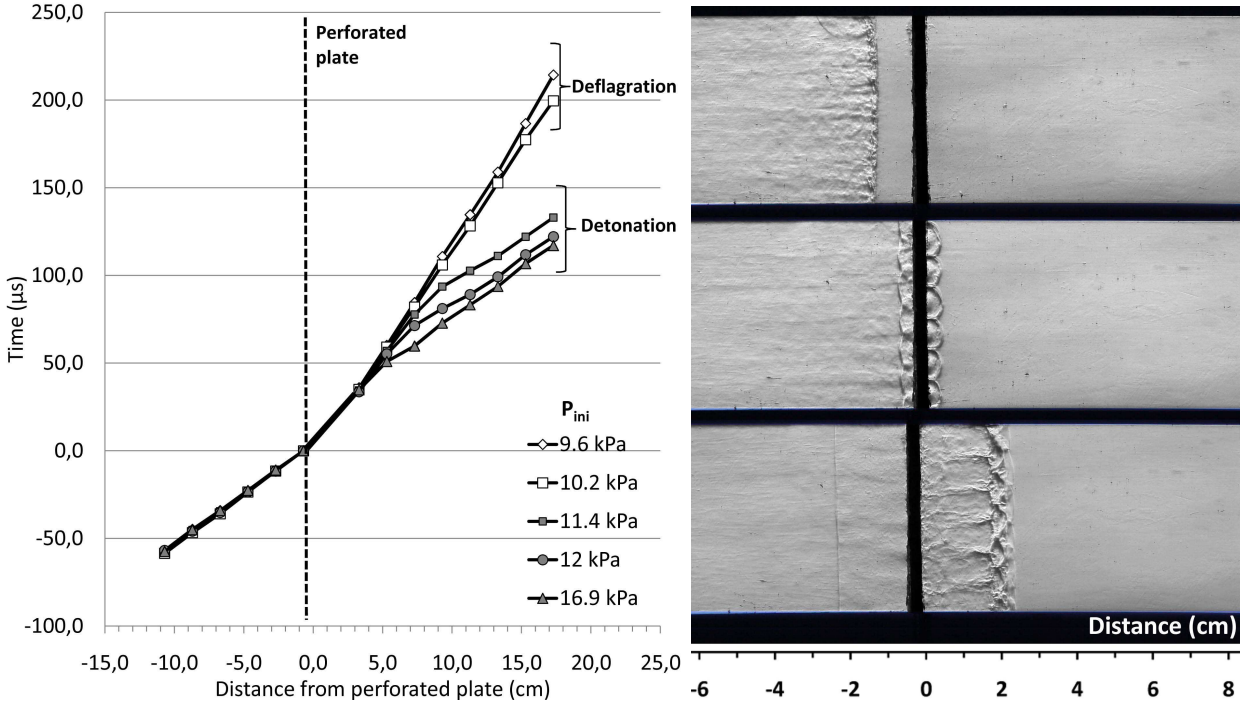
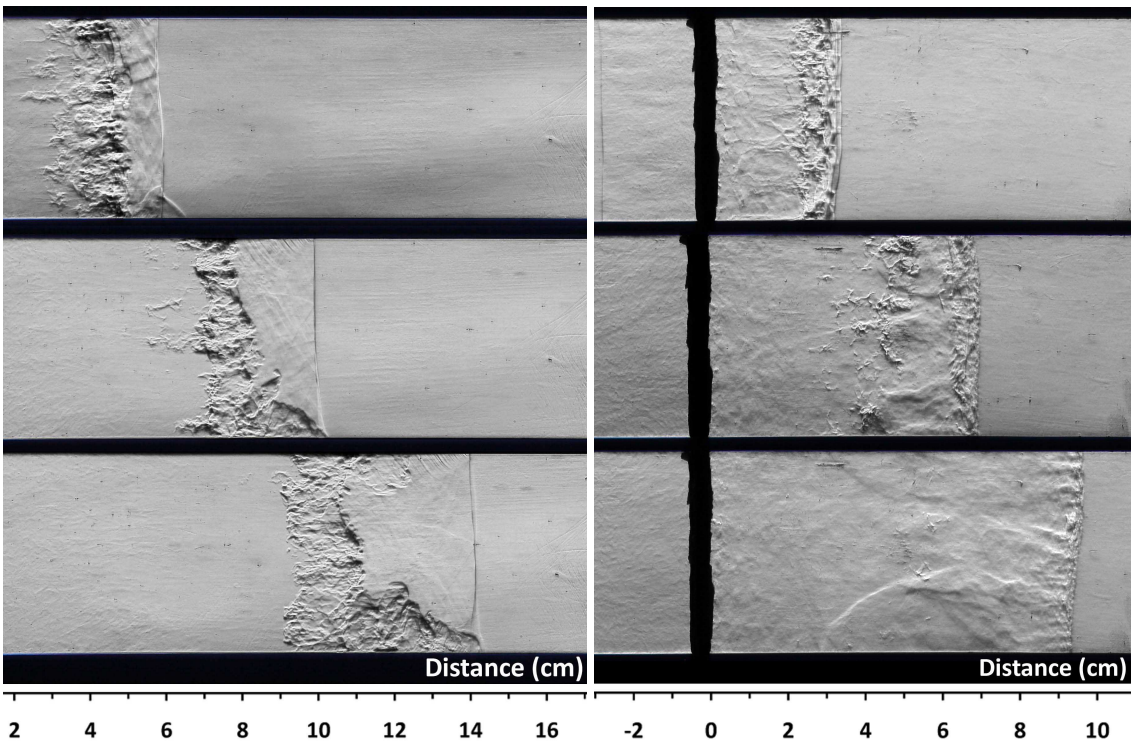


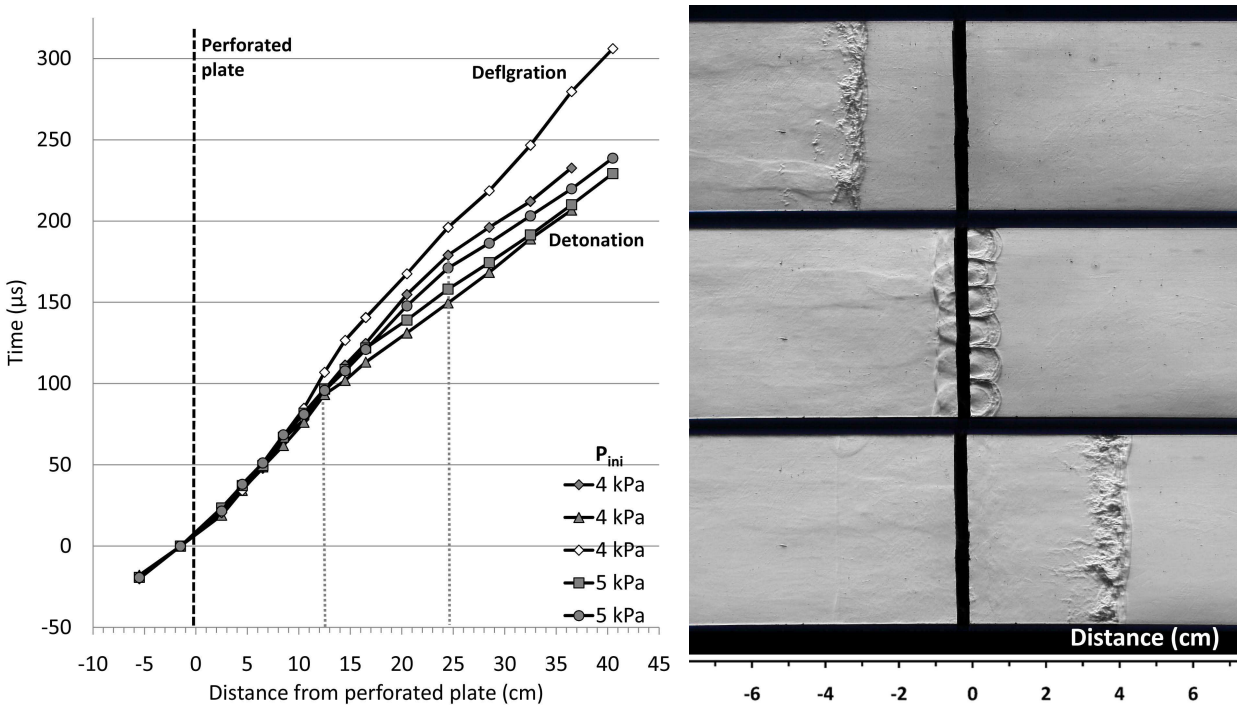
(a) (b)

Figure 2: a) Wave trajectories and b) schlieren photographs of the transmission of detonations through the perforated plate. (C_2H_2 + 2.5O_2 mixture, Hole diameter=4.8 mm)



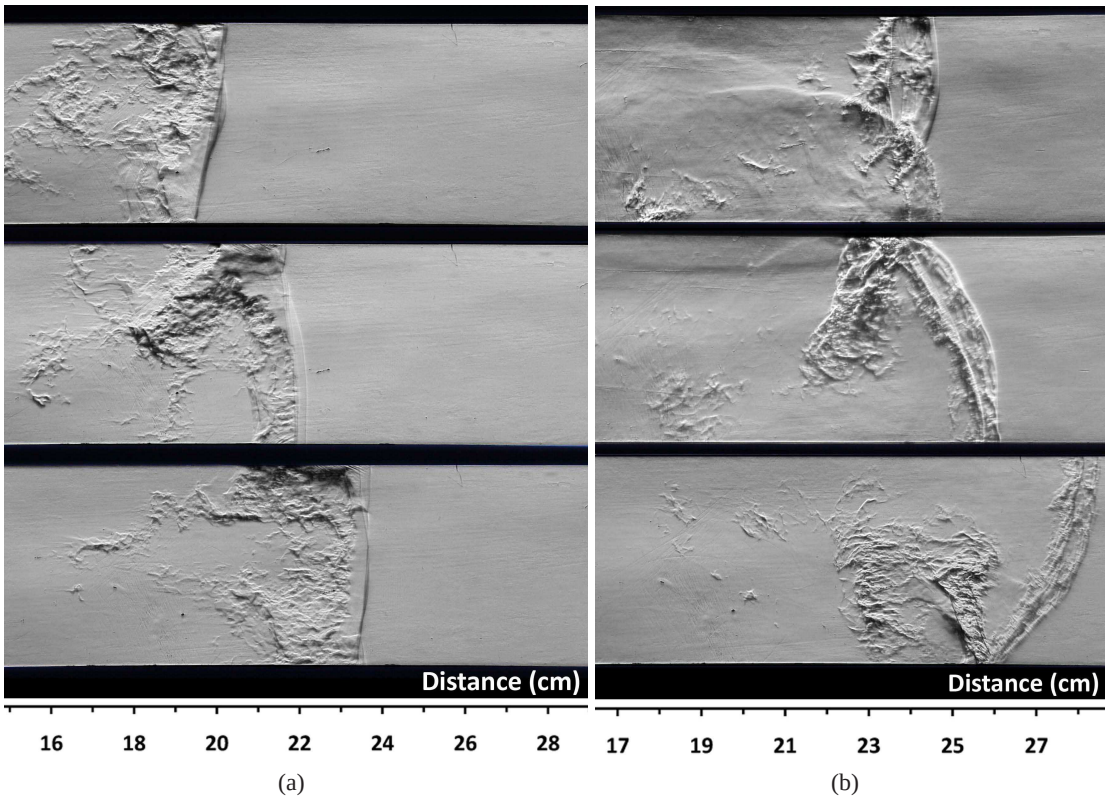
(a) (b)

Figure 3: a) Decay into a deflagration (subcritical) and b) onset of detonation (supercritical) downstream of the perforated plate. (C_2H_2 + 2.5O_2 + 70% mixture, Hole diameter=4.8 mm)



(a) (b)

Figure 4: a) Wave trajectories and b) schlieren photographs of the transmission of detonations through the perforated plate. (C_3H_8 + $5O_2$ mixture, Hole diameter=4.8 mm)



(a) (b)

Figure 5: a) Pre-detonation regime and b) the onset of detonation downstream of the perforated plate. (C_3H_8 + $5O_2$ mixture, Hole diameter=4.8 mm)