Response of Cellular Detonations of Finite Perturbations

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1 Introduction

Gaseous detonations are intrinsically unstable with characteristic cellular structure formed by the intersections of transverse waves with the leading shock front. Even in one spatial dimension, numerical simulations [1] show an unstable pulsating detonation executing periodic non-linear oscillations. It appears that instability is essential for the self-sustained propagation of the detonation. Damping of the transverse waves by reflections from the porous wall of the tube result in the failure of the detonation [2]. The formation of detonation waves is generally accompanied by the spontaneous appearance of the transverse waves to form the cellular structure. Although linear stability analysis is well established, the rapid growth of non-linear cellular instability is not well understood. Experimentally, it is difficult to investigate the growth of the instability from well defined initial conditions. In the present study we attempt to investigate the transient processes of the re-establishment of a cellular detonation after it has been significantly perturbed by a finite perturbation. This may provide some insight into the instability mechanisms and the parameters that control it.

Previous experiments by St. Cloud [3] and Donato [4] have observed that a spinning detonation fail when subjected to a finite perturbation by a few turns of a Shchelkin spiral. Clue et al. [5] have also carried out a numerical simulation of a pulsating detonation subjected to a large density perturbation. The pulsating detonation failed and a deflagration resulted. However these previous studies were concerned with the subsequent DDT process of the deflagration rather than the re-establishment of the perturbed detonation.

Perhaps the most widely studied study of the re-initiation of a cellular detonation subsequent to a large perturbation is the critical tube diameter problem [6]; the perturbation in this case is an abrupt area increase. However the critical tube diameter problem is primarily concerned with the transformation of an initially planar detonation to a spherical detonation. Although the re-establishment mechanisms may be similar to those of the present problem of the relaxation of a perturbed detonation, the present interest is focused on detonations in a constant area tube. The present study uses a perforated plate to perturb the detonation. Subsequent to the perturbation the detonation will acquire a structure determined by the geometry of the perforated plate. Thus the process of the transformation of the perturbed structure back to the original cellular structure is based on well controlled initial condition.

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2 Experimental Details

The experiments are carried out in a detonation tube of rectangular cross-section 38 by 64 mm and a length of 2.5m long. A short 0.3m long smaller diameter driver section is used to facilitate the initiation of the detonation. A sketch of the experimental apparatus is shown in Fig. 1. A strong spark from the discharge of a 4.5 µF low inductance capacitor charged to 12.5 kV is used for ignition. To promote rapid formation of the detonation wave, a Shchelkin spiral is inserted into the driver tube. Premixed mixtures of C_2H_2 + $2.5O_2$ + 70% Ar and C_3H_8 +$5O_2$ are used and the rationale for the choice of these two mixtures is based on the differences in their cell structure and the regularity of the smoked foils pattern. High Argon diluted mixtures have been shown to have a piecewise laminar detonation structure and a highly regular smoked foil pattern in general. Whereas the propane-oxygen detonations have a more irregular transverse waves pattern and a turbulent reaction zone [7]. The mechanisms of the re-initiation of detonation in the critical tube diameter problem also appeared to be different in these two mixtures.

Regularly spaced photo-detectors as well as piezoelectric transducers are used to monitor the detonation velocity and pressure to ensure a “steady” detonation is initiated upstream of the orifice plate. However the relaxation distance of the perturbed detonation (~10cm) downstream of the orifice plate is too short for meaningful velocity measurements to be made during the transient process of re-establishment. Thus the main diagnostic used in the present study is the photographic observation using a Z-type Schlieren system. A short duration spark light source is used and only a single frame is taken for each experiment to achieve high resolution Schlieren photographs. This necessitates numerous “shots” to be taken in order to compose a representative sequence of the transient re-establishment process. However it is found that the experiments are sufficiently reproducible to permit a progressive time sequence to be constructed.

Orifice plates of different hole diameters and spacing (hole spacing to hole diameter ratio is 0.5) are used to perturb the detonation, refer to Fig. 1 for a diagram of the geometry of the plates used. A wire grid (4mm x 4mm and 1mm diameter wire) is also used in some experiments when a less severe perturbation of the detonation is desired.

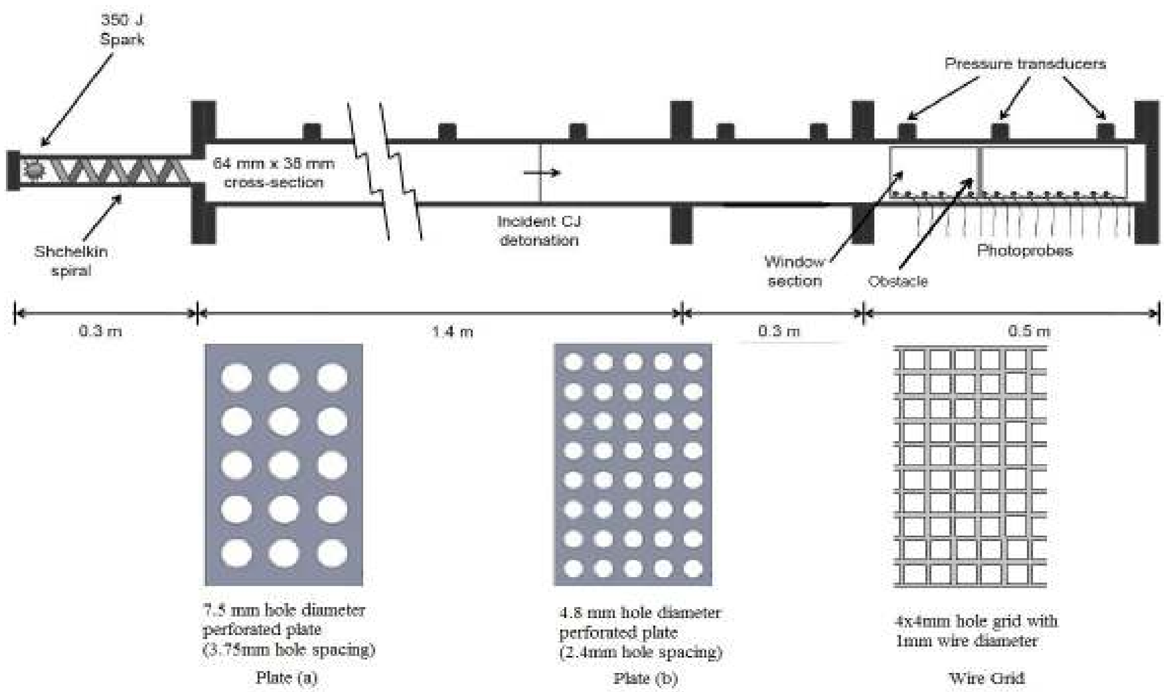

Figure 1: Schematic of experimental apparatus and orifice geometry

3 Results and Discussion

Fig.2 is a composite of the sequence of Schlieren photographs of a detonation in C_2H_2 +2.5O_2 +70% Ar downstream of the orifice plate. Each frame in the figure corresponds to a different experiment but at the same initial conditions. Prior to the orifice plate with the plate, the typical periodic cellular structure of the detonation can be observed. Immediately downstream of the orifice plate, the detonation takes on the characteristics of the perforated plate with a periodic structure corresponding to the hole spacing of the perforated plate. This initial structure of the perturbed detonation is seen to be progressively modified by the chemical energy release in the perturbed front. In the 4th frame (~8cm downstream), detonation re-initiation can be observed to occur at the Mach stems near the channel walls. The detonation "wavelet" formed then propagates towards the center. The central position of the detonation has by then decayed to a deflagration with leading shock separated the reaction zone. In the last two frames, the detonation can be seen to have resumed its initial structure. Thus, the re-initiation occurs locally at the stronger Mach stems near the channel wall in this experiment.

Fig.3 shows a similar re-initiation process for the case where a perforated plate with smaller diameter holes is used. The initial perturbed detonation now shows a smaller scale periodic structure corresponding to the different geometry of the perforated plate used. Again the initial structure is progressively modified as the detonation propagates downstream as shown in Fig.2. Re-initiation is seen to also originate locally near the channel wall and the detonation "wavelets" formed then propagate towards the center of the channel. The detonation is completely re-established in the last frame with a structure resembling the original structure upstream of the perforated plate. However the detonation is slightly tilted with respect to the channel wall.

Fig.4 shows the re-initiation process for a detonation in C_3H_8 +5O_2 mixture. A similar transformation process of the perturbed detonation with an initial periodic structure (determined by the geometry of the perforated plate) is observed. The "turbulent" structure of the unstable detonation in C_3H_8 +5O_2 can be observed to differ from the Argon diluted mixture shown in the previous figure. The detonation re-initiation process however, is similar and is again observed to originate at the channel walls.

In the above experiments with the perforated plate, the detonation is significantly modified by the perforated plate taking on a totally different structure initially.

For a less severely perturbed detonation, a wire grid is used instead of a perforated plate. Fig. 5 shows the perturbed detonation and it can be observed that the turbulence generated by the wire grid tends to "homogenize" the reaction zone. A more uniform structure result as compared to the initial larger scale cellular structure upstream of the grid. In the last frame, the detonation appears to resume its original large scale cellular structure. Contrary to the previous cases, the re-establishment process is gradual and no strong local initiation at the Mach stems near the channel wall is now observed. Instead, the relaxation process appears to be more progressive with the perturbed structure relaxes to its original structure without an abrupt onset of detonation.

Fig. 6 shows a similar case for "unstable" propane-oxygen detonations. The highly irregular "turbulent" structure upstream prior to the perturbations is illustrated in the first frame. The turbulence produced by the wire grid again tends to "homogenize" the reaction zone resulting in a more uniform detonation structure. The original irregular turbulent structure is rapidly recovered further downstream as the influence of the grid generated turbulence decays.

4 Concluding Results

The present experiments indicate that for more severely perturbed detonation where the original structure is significantly modified using a perforated plate, the re-establishment process is more abrupt occurring locally forming an overdriven detonation "wavelet" which then sweeps over the perturbed front to re-initiate the detonation. This is not unlike the typical onset of detonation process as seen in DDT. However for less severely perturbed detonations using wire grids, the turbulence generated by the grid tends to homogenize the cellular detonation resulting in a more uniform but smaller scale structure. The perturbed detonation then progressively evolved back to its original structure corresponding to the chemical kinetics and the gas dynamic flow field. Thus it appears fruitful to carry out further extensive experiments on relaxation of less severely perturbed detonations using wire grid of different geometry where the original structure is not significantly destroyed.

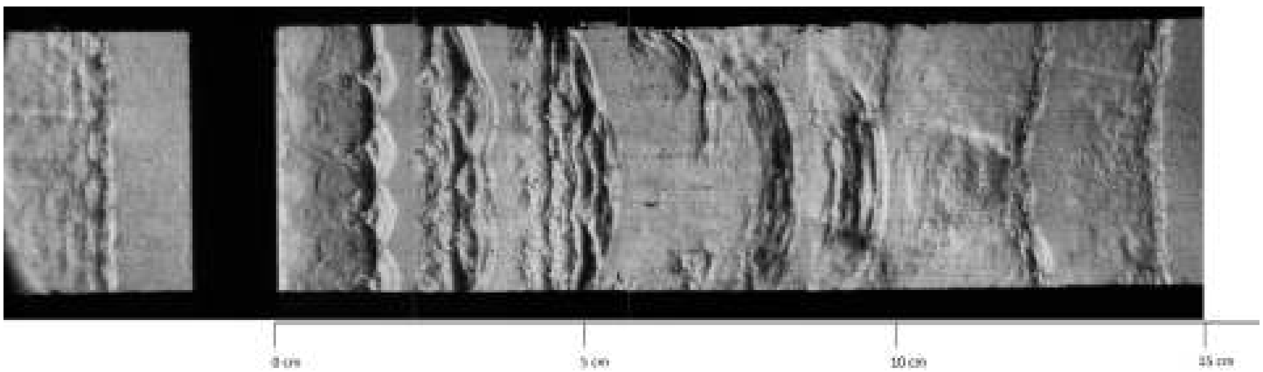

Figure 2: $C_2H_2 + 2.5O_2$ +70%Ar, Pressure 9kPa Plate (a)

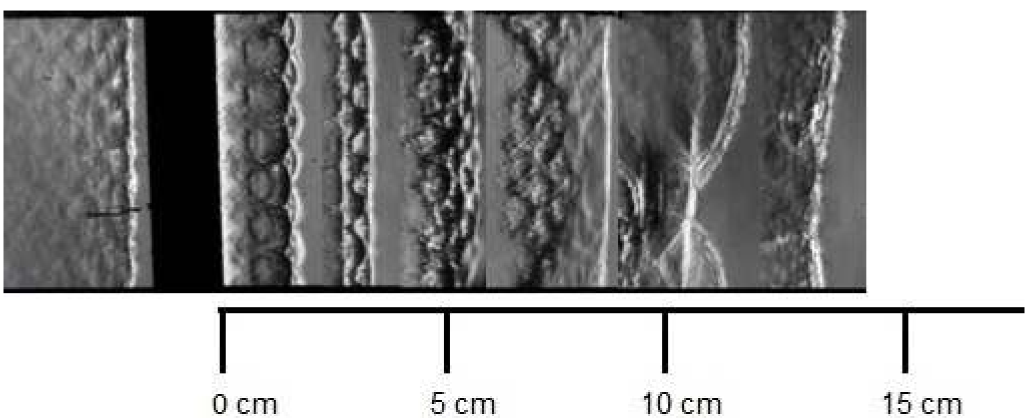

Figure 3: $C_2H_2 + 2.5O_2$ +70%Ar, Pressure 9.5kPa Plate (b)

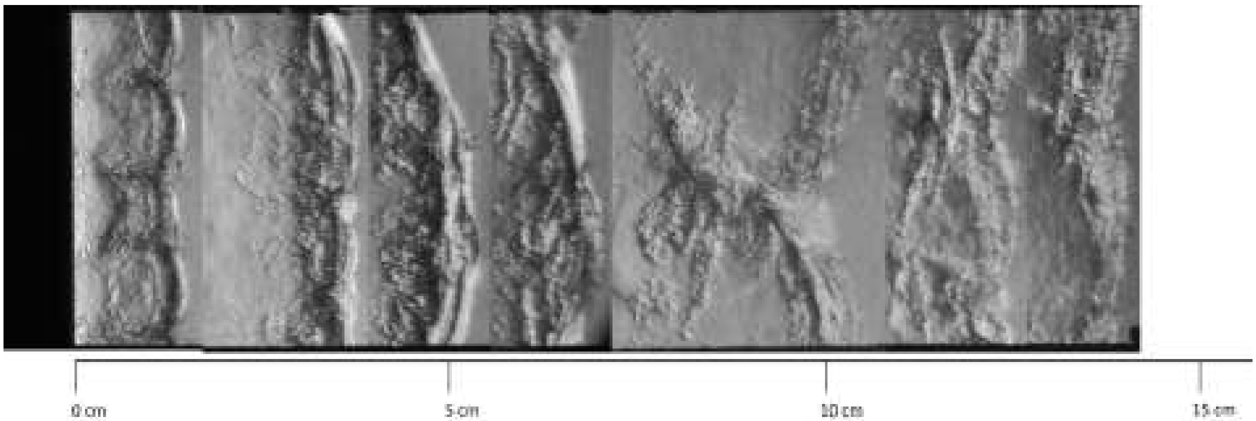

Figure 4: $C_3H_8 + 5O_2$, Pressure 7kPa Plate (a)

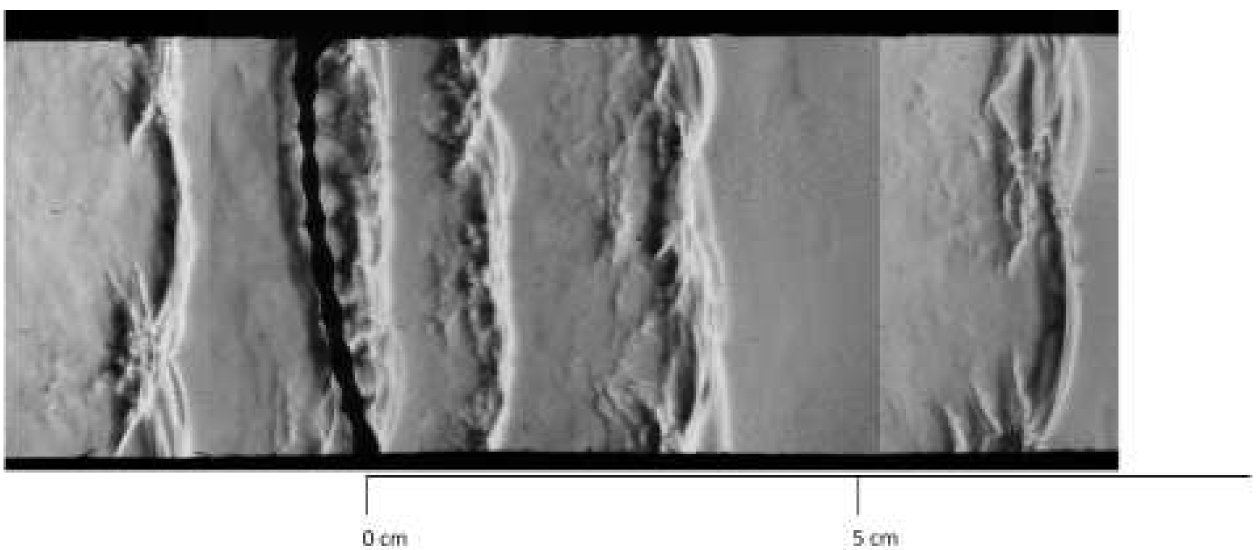

Figure 5: $C_2H_2 + 2.5O_2$ +70%Ar, Pressure 4kPa Wire Grid

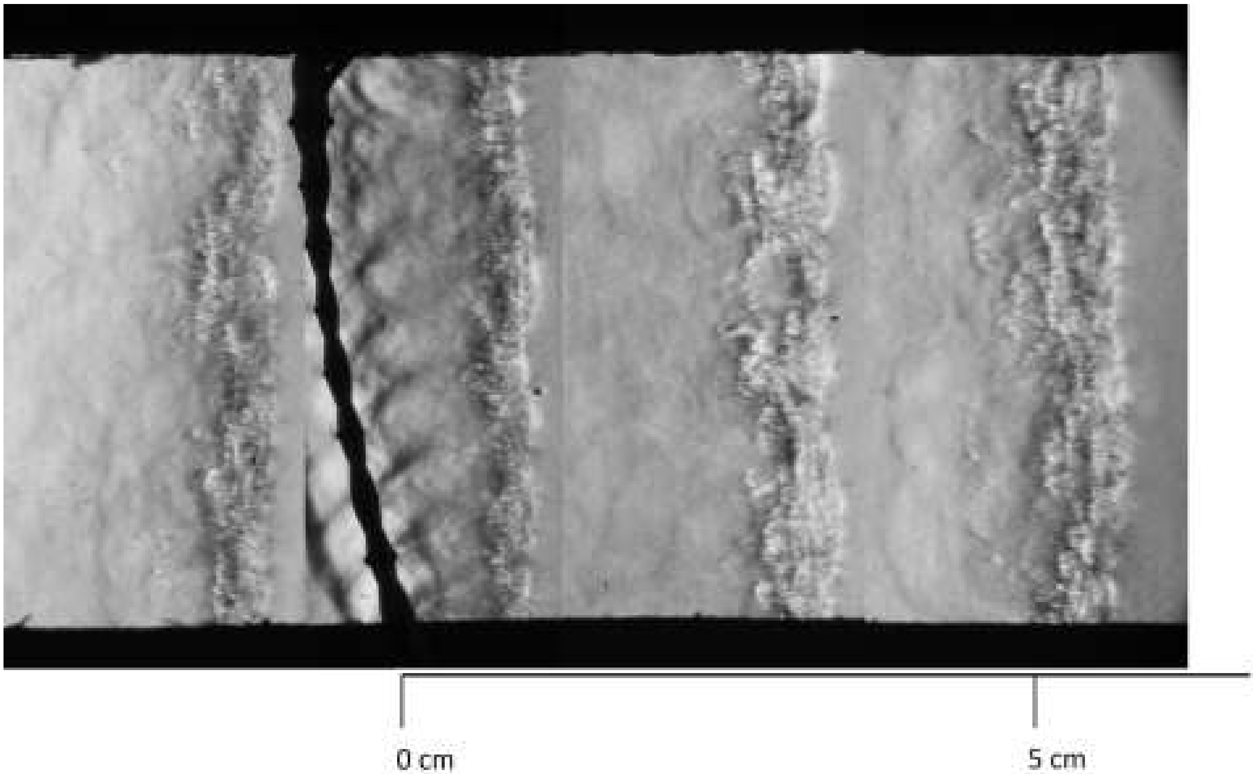

Figure 6: $C_3H_8 + 5O_2$, Pressure 6kPa Wire Grid

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