The unsteady dynamics of the head-on collision between a detonation and a shock wave

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1. Introduction

When a detonation collides head-on with a planar shock wave, theoretical analysis reveals the existence of a steady solution for the interaction where the transmitted detonation is a Chapman-Jouguet wave followed by a rarefaction fan, as confirmed from both experiments and numerical simulations [1]. However, it is well known that a detonation consists of a leading shock followed by an unsteady reaction zone and therefore, such a steady-state solution subsequent to the head-on collision will not be achieved "instantaneously" because of the presence of the finite detonation structure. The abrupt change caused by the shock will also have a significant effect on the detonation structure. This study thus aims at observing the immediate change and evolution of the detonation structure following the collision and its final cellular pattern.

2. Numerical simulation

The unsteady dynamics of the collision process between a detonation and shock wave has been examined using one-dimensional numerical simulation. Numerical results are obtained by solving the unsteady reactive Euler equations coupled with a two-step chain-branching kinetic mechanism, representing an idealized model of a chemically reacting system with a thermally neutral chain-branching induction zone. Equations are solved using a 2^{nd} order centered TVD scheme with adaptive mesh refinement technique (see [1] for details).

Typical results are displayed in figure 1 showing the leading front pressure of the detonation versus its position. The evolution of the pressure behind the leading front as the detonation collides with an incident shock wave M_s can give some indication of the wave processes and interactions that are occurring. After the collision of a Chapman-Jouguet (CJ) detonation with a shock wave, the pressure at the leading front experiences a rapid increase. This is followed by a decay in pressure, which drops below the Von Neumann pressure for the incident detonation.

These results can be explained by describing the wave interaction as the shock wave propagates through the detonation structure. Upon collision with the leading front of the detonation, the incident shock transmits into the induction zone. When the incident shock interacts with the density drop across the reaction zone, expansion waves are generated which will influence the leading front and attenuate it. A quasi-steady period follows, where lower pressure behind the leading shock front is observed and the detonation no longer propagates at CJ velocity. However, the pre-conditioning of the flow field can lead once again to a transition to a detonation. The resulting event appears to resemble a re-initiation process with the typical overshoot to an overdriven detonation followed by an asymptotic decay to a new detonation corresponding to the new conditions behind the incident shock.

Simulations have also been carried out with specified mixture properties such that the detonation is one-dimensional hydrodynamically unstable (figure 2). Similar results are obtained as compared to the stable case, i.e. the interaction first quenches the detonation and after a period of time produces a highly overdriven detonation propagating into shocked reactant. The overdrive is being degraded by a rarefaction overtaking the front and the detonation subsequently decays towards the steady-state solution. For the unstable case, the transmitted detonation begins to oscillate with growing amplitude as the detonation approaches the steady-state solution. However, the relaxation to the final saturated nonlinear behavior is achieved on a time-scale which is very long compared with both reaction time and period of oscillation. Also note that the transmitted detonation stabilizes after the collision, characterized by a reduction in oscillation amplitude but with higher frequency.

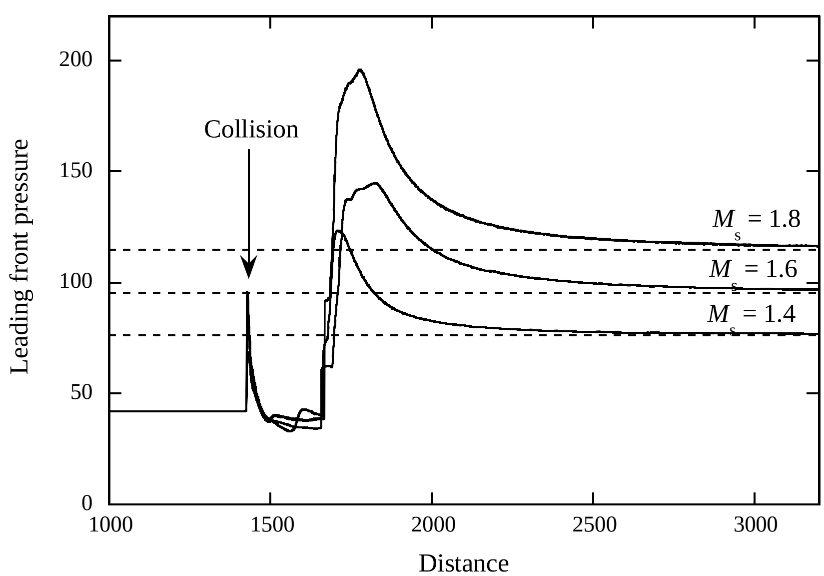


Figure 1. Leading front pressure versus position of the detonation colliding with an incident shock of different strength M_s. Dashed Line represents the Von Neumann pressure based on the CJ solution from steady-state analysis for transmitted detonation.

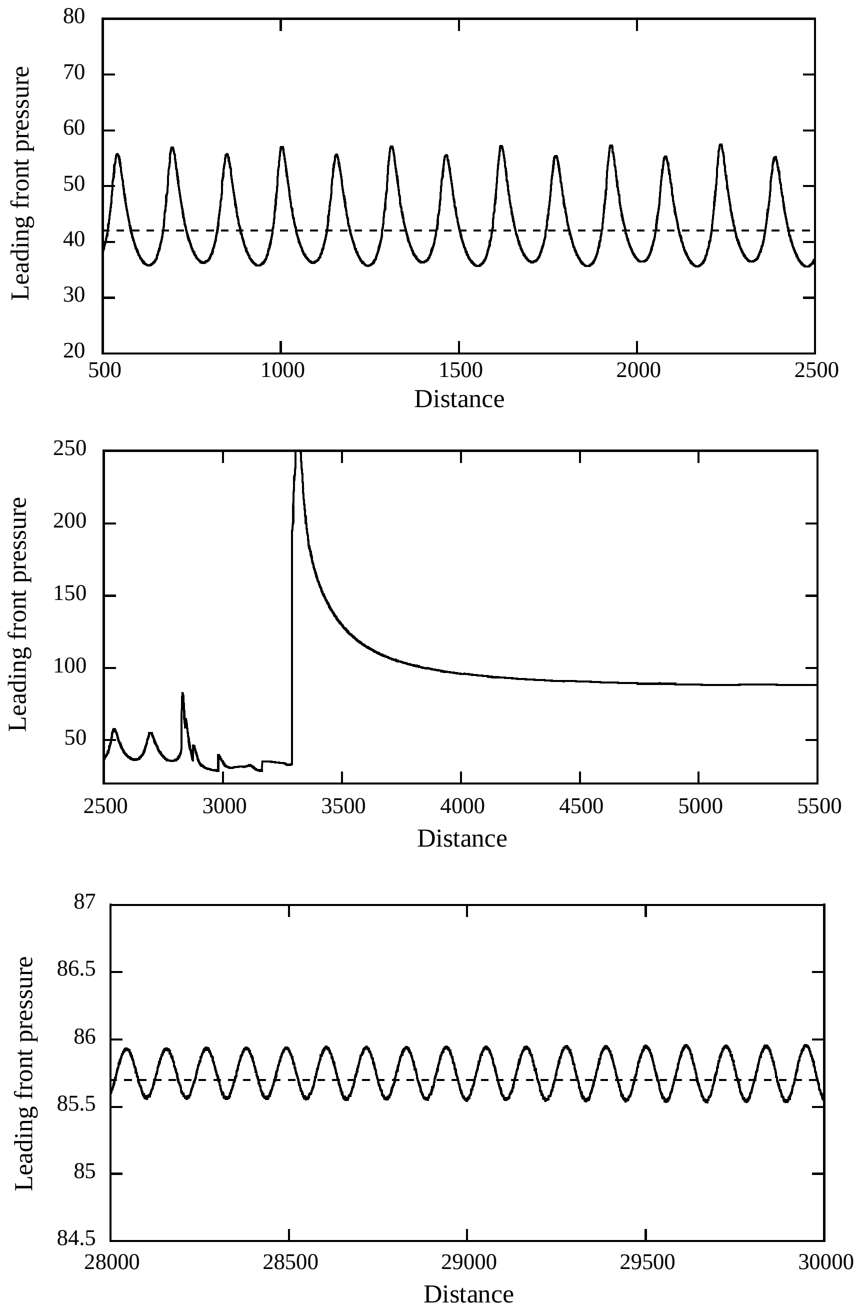


Figure 2. Leading front pressure versus position of the unstable detonation colliding with an incident shock of different strength M_s; (top) before collision; (middle) early development subsequent to the collision; and (bottom) after long-time evolution subsequent to the collision. Dashed Line represents the Von Neumann pressure based on the CJ solution from steady-state analysis for both incident and transmitted detonations.

3. Experimental investigation

In this experimental study of the head-on collision of a shock wave and detonation, a 6 m long steel tube with a 6 cm inner diameter was used. The schematic for the laboratory set-up of the experiment is given in figure 3. The 2 m long high-pressure driver section is used to generate the incident shock wave. A thin diaphragm separates the driver and test sections. The driver section is pressurized with air and the diaphragm is ruptured by a pneumatic plunger, generating an incident shock that propagates into the test section. Piezoelectric pressure transducers mounted along the length of the shock tube measures time of arrivals, where the signal from the first pressure transducer is used as a trigger to initiate the detonation at the other end of the shock tube after an appropriate delay.

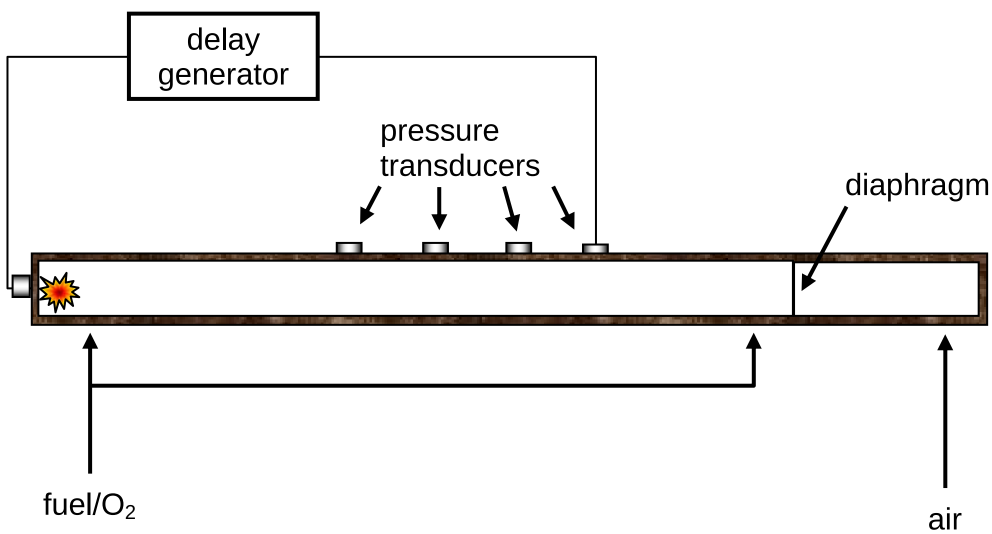


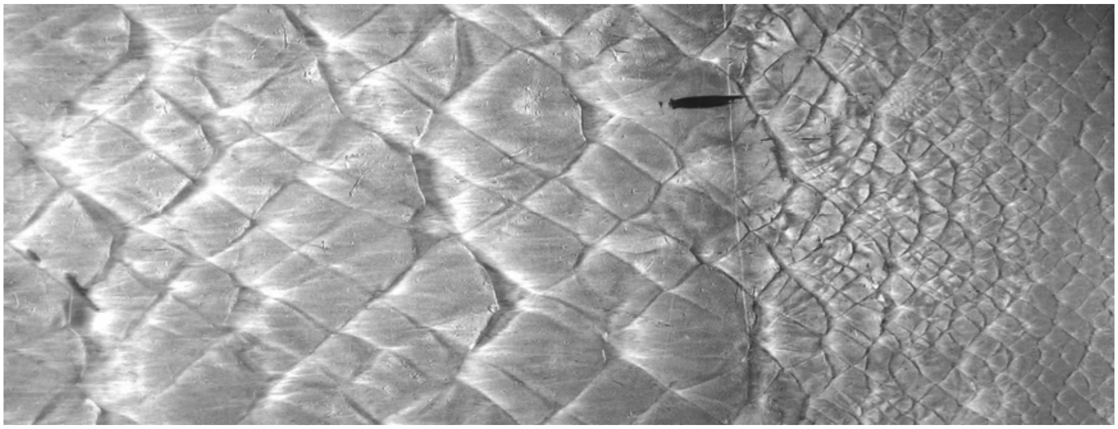
Figure 3. Schematic of experimental apparatus

3.2 Cellular pattern subsequent to collision

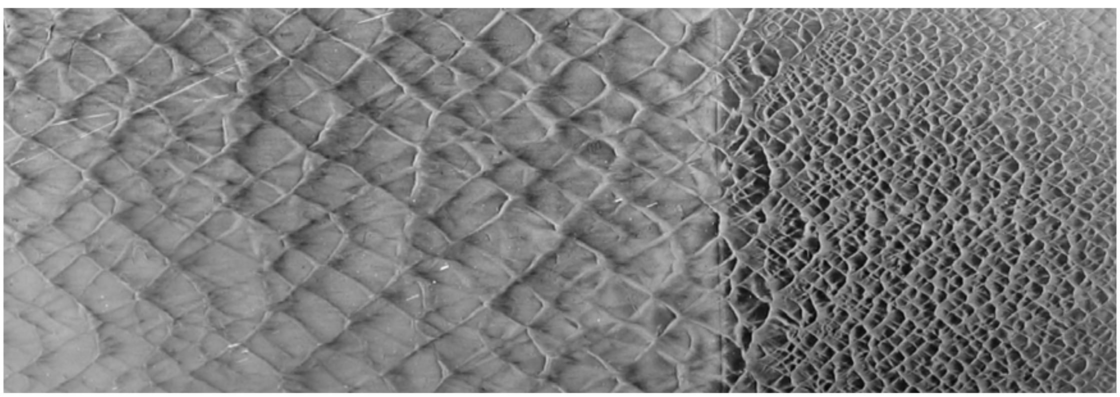
The early unsteady development of the interaction and the response of the cellular detonation structure to the weak shock perturbation can be examined more clearly from the smoked foil records. Figure 4 shows typical foils obtained for stoichiometric C_2H_2-O_2 mixtures at different initial pressures and incident shock strengths.

Before the interaction, an incident cellular detonation, which travels from left to right, can be observed. Upon the head-on collision with the shock wave, a variable cellular pattern can be identified corresponding to the transient processes involved with the collision. It is observed that within 1 or 2 cell lengths following the collision, new triple points or tiny re-initiation cells are being generated in localized regions. These small cells continue to develop and eventually produce a final cellular pattern. However, this pattern is shown to be significantly finer and more regular than that of the incident detonation (also observed in [2]).

(a) Stoichiometric C_2H_2-O_2 mixture with P_o = 2 kPa and M_S = 1.62



(b) Stoichiometric C_2H2-O_2 mixture with P_o = 2kPa and M_S = 1.70



(c) Stoichiometric C_2H_2-O_2 mixture with P_o = 1kPa and M_S = 1.98

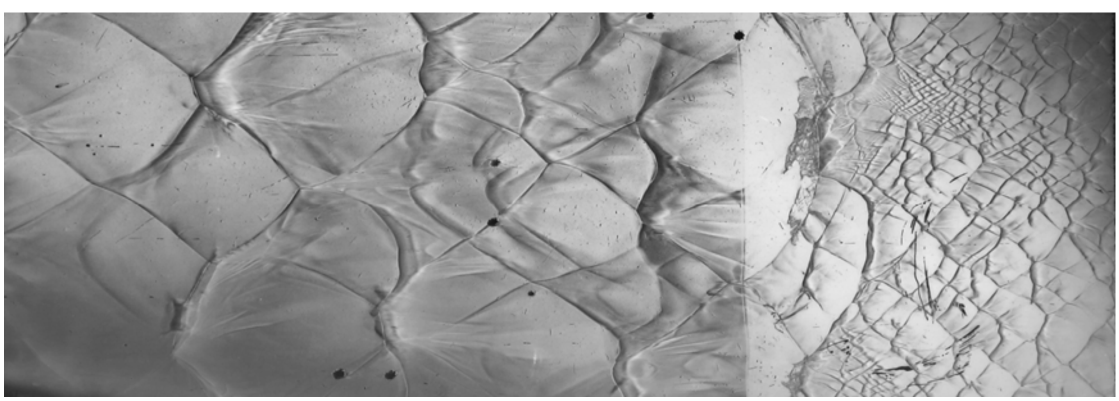


Figure 4. Smoked foil records showing the evolution of cellular pattern of the detonation after collision with a shock wave

4. Chemical kinetic analysis

To analyze the change in the final steady-state detonation cell size after the interaction, a chemical kinetic analysis can be performed. Correlation with the chemical induction length scale has been established as an accepted technique for estimating the detonation cell size. By computing the induction length for the thermodynamic conditions established by the incident shock of different strengths, we can obtain some estimate on the change in detonation cell size. Figure 5 illustrates the change in induction length (hence cell size λ) for different incident shock Mach number in stoichiometric acetylene-oxygen mixture. From this plot, there is a good agreement between the predictions in the reduction of cell size with experimental results, taking into consideration that the experimental errors in deducing a characteristic cell size value for acetylene-oxygen at low pressure.

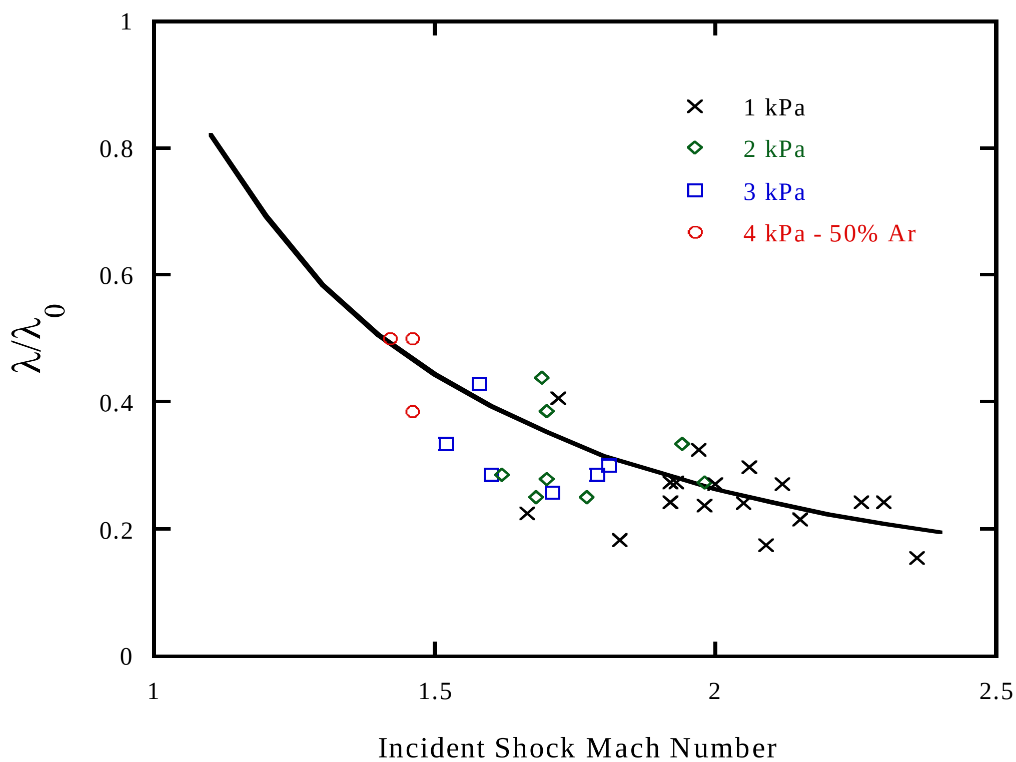


Figure 5. Chemical kinetic analysis determining the change in detonation cell size for stoichiometric C_2H_2-O_2-diluent mixtures

5. Summary

Investigations have been carried out to study the head-on collision between a detonation and a planar shock wave with consideration of the detonation structure and chemical kinetics. Smoked foil records are used to examine the development of cellular structure and its regularity for the detonation propagation. It is observed that there is a significant reduction in cell size for the steady transmitted detonation. As confirmed from chemical kinetics, this effect is due to the change in the thermodynamic state of the reactive mixture caused by the shock resulting in a change of chemical kinetics and hence, the characteristic cell size. A re-initiation region immediately following the collision is observed before the final steady state pattern is reached. This is in agreement with numerical simulations that also describe a re-establishment of steady detonation after a certain period.

References

1. Ng, H.D., Nikiforakis, N. and Lee, J.H.S., *Proc. 24th Int. Symposium on Shock Waves*, Vol. 2, pp. 745-750 (2004)
2. Terao, K., Yoshida, T., Kishi, K. and Ishii, K., *Proc. 18th Int. Colloquium on the Dynamics of Explosions and Reactive Systems, Seattle, USA* (2001)