11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

IGNITION OF DETONATION BEHIND REFLECTED SHOCK STRUCTURES

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ABSTRACT

We use numerical simulations to study the decay and reignition of detonation which occurs when a detonation propagates past an increase in cross-sectional area in a rectangular detonation tube. We solve the time-dependent two-dimensional Euler equations coupled to a two-step induction-parameter model of the reaction kinetics in an Ar diluted stoichiometric H_2/O_2 mixture. If the primary detonation is strongly overdriven we find that reignition occurs via an interaction between the reflected shock and the original contact surface, while for more weakly driven systems reignition occurs via Mach reflection of the decaying blast wave off the walls of the detonation tube. Our calculations have sufficient resolution to resolve the cellular structure of the front, when the detonation is in its steady, propagating mode .

INTRODUCTION

The diffraction, decay, and subsequent reignition of a detonation front as it interacts with a bounding explosive layer or expands into a less confining geometry is of interest in several areas of detonation physics. Liu et al. (1987, 1988) recently examined the detailed mechanism of the transmission process in gaseous explosive layers using a specially constructed detonation shock tube. Figure 1 shows a schematic of the arrangement, a layered detonation shock tube three metres long ending in a test section which allows the detonation in the upper tube to diffract into the explosive mixture in the lower tube. Laser schlieren photography was used to visualize the transmitted shock and detonation structures and a variety of different interaction modes were found. The simplest interaction results in an oblique shock reflecting regularly off the lower wall of the detonation tube, but more energetic mixtures can result in either direct initiation of material in the lower tube, or ignition only after Mach reflection of the induced oblique shock off the lower wall. Some of these interaction patterns are shown in Figure 1.

Over the last few years we have performed an extensive series of numerical computations using a reactive two-species Flux-Corrected Transport code (Jones et al. 1990, 1991, Oran et al 1992a, 1992b) to model the experiments of Liu et al. and have been able to simulate many of the interaction patterns seen experimentally. These computations concentrated primarily on the nature of the explosive in the detonation tubes and the effect of different combinations of explosives on the dynamics of the interaction. The computations were initiated using either a steady state detonation which was computed in a one-dimensional code and the solution introduced on the two-dimensional grid, or by depositing an excess amount of energy into several cells of the grid, and it was noticed that in some cases the method of initiation influenced the final steady state interaction picture. In this paper we use a one-species code and more finely resolved computations to make a detailed study of the effect of the strength of initiation on the final interaction pattern. We use a stoichiometric mixture of H_2 and O_2 diluted with Ar. The dilution has the same effect as reducing the pressure and essentially magnifies the details of the initiation process. This makes the initiation problem more amenable to numerical simulation. Considering a more energetic mixture could make it more difficult to observe the various ignition mechanisms.

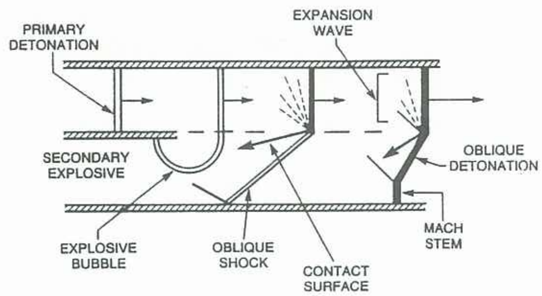

Figure 1. Schematic sketch of test section used and typical interaction patterns.

NUMERICAL MODEL

The simulations are based on solutions of the time-dependent Euler equations using the Flux-Corrected Transport (FCT) technique (Oran and Boris, 1987), an explicit, non-linear finite difference technique for solving generalised continuity equations. The chemical reactions which convert gaseous reactants into detonation products were approximated using a two-step induction parameter model originally described by Oran et al. (1981) and developed further by Kailasanath et al. (1985) and Guirgius et al. (1986). The gaseous explosive consisted of a stoichiometric mixture of H_2 and O_2 diluted with Ar, the exact ratios being 2:1:7 respectively. The experimental test section was model using a two-dimensional rectangular Cartesian grid. Operator splitting was used in both x and y directions and the end of the splitter plate dividing the two detonation tubes was modelled by splitting the y pass into two integration loops and applying solid wall boundary conditions at the end of each loop. The grid spacing was uniform with $\delta x = \delta y = 0.04$ cm (or 0.02 cm for the more finely resolved calculations), and the time step was limited to ¼ of the value given by the Courant condition, giving an average time step of 5.0×10^{-8}s (for more finely resolved calculations a time step of 2.0×10^{-8}s was used). The calculations were initiated either by reading in a detonation profile from a one-dimensional version of the code, or by depositing excess energy into the first few cells of the grid representing the upper detonation tube.

SIMULATION RESULTS

When the calculation is initiated using a strongly overdriven 1D detonation, the interaction of the reflected blast wave with the original contact surface results in considerable distortion to both the contact surface and the reflected shock. Figure 2 shows a sequence of temperature contours in the simulated test section at 15 μs intervals. The initiating detonation had a velocity 24.5% above the equilibrium value. Figure 2a shows the contours at t = 30 μs. At this stage the shock has just begun to reflect off the bottom wall of the test section and is about to collide with the contact surface. Also evident in Figure 2a is the formation of a strong vortex at the lip of the splitter plate, and the gradual separation of the shock front from the reaction front as the detonation expands into the test section and begins to decay.

In Figure 2b (45 μs) the reflected shock has passed through the contact surface, the reflection off the lower wall is regular, and a strong shock/vortex interaction is occurring at the end of the splitter plate. After 60 μs (Figure 2c) the interaction of the reflected shock with the contact surface has resulted in the formation of a strong exothermic reaction which is rapidly beginning to consume the unreacted material between the contact surface and the shock front. The exact nature of this reignition process is unclear from the sequence shown in Figure 2, but examination of more detailed contour plots shows that it is due to a complicated shock/flame interaction on the contact surface which is similar to the Mach reflection which occurs at the interface between two different media. Figure 2c also shows that the regular reflection of the shock at the lower wall has just transitted to a Mach reflection, but Figure 2d (75 μs) shows that this Mach reflection is soon overtaken by the strong exothermic reaction emanating from the shock/contact surface interaction. The final result of the collision of this strong exothermic reaction with the lower wall of the tube is the formation of a strong detonation wave which travels towards the upper surface of the tube and rapidly transits to a stable detonation spanning the full width of the test section.

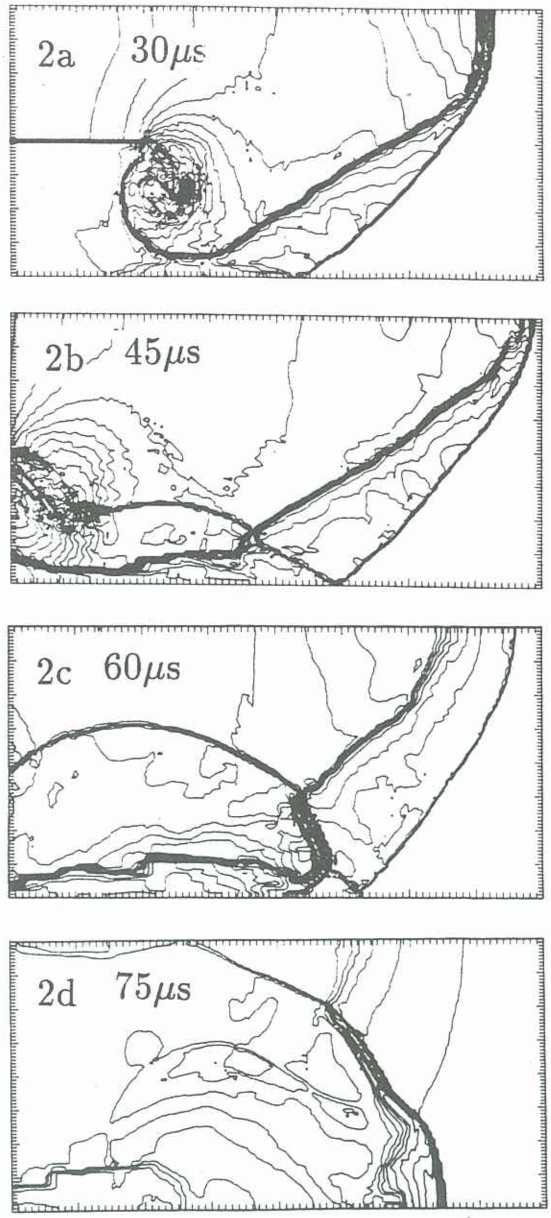

Figure 2. Simulated temperature contours in the test section for a strongly overdriven primary detonation.

As the strength of the initiating detonation is reduced a point is reached at which the interaction between the contact surface and the reflected shock no longer results in rapid exothermic reaction and the development of the Mach stem becomes the main feature of the flow. Figure 3 shows a sequence of temperature contours where the initiating detonation is only 1.2% overdriven. Figure 3a (60 μs) shows the simulation at the stage where the regular reflection at the lower wall has transitted to a Mach reflection, but the interaction of the contact surface and the reflected shock has failed to result in any significant distortion of the flow. Figure 3b (75 μs) shows that this failure to result in strong exothermic reaction has allowed the Mach stem to continue to grow, and now the development of an exothermic reaction along the slipline and stem of the Mach reflection can be clearly

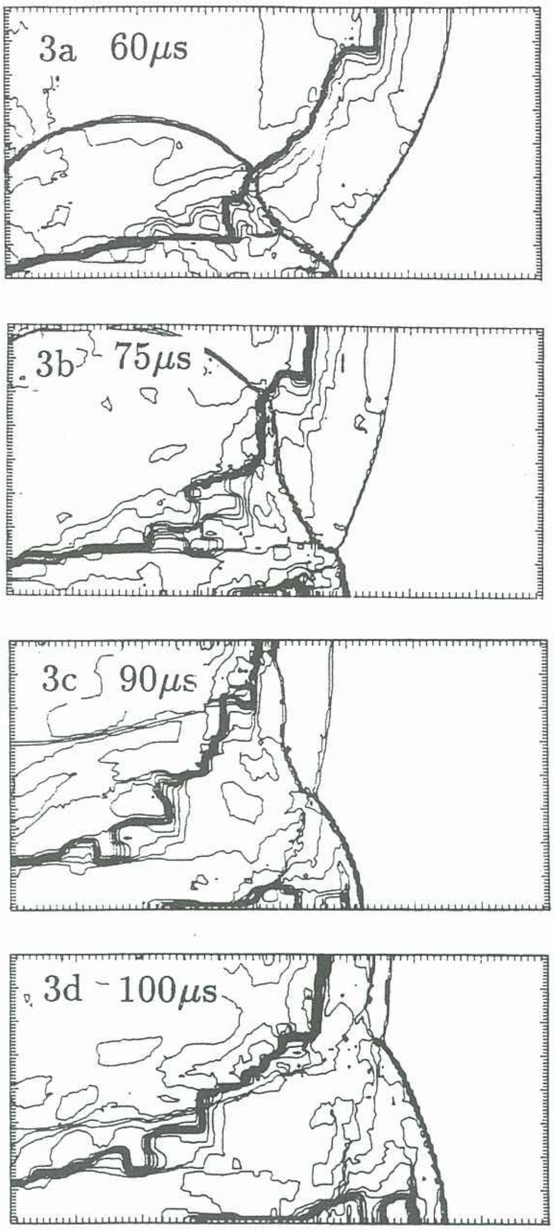

Figure 3. Simulated temperature contours in the test section for a weakly overdriven primary detonation.

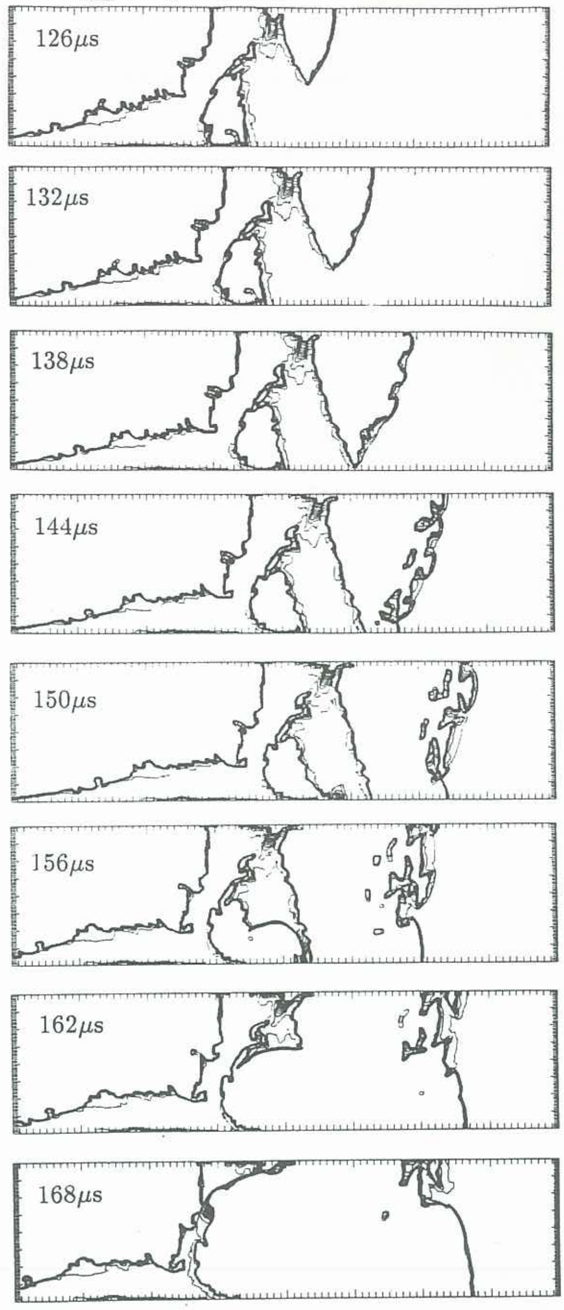

Figure 4. Simulated reaction variable contours between 126 μs and 168 μs for a weakly overdriven primary detonation.

seen. Figures 3c (90 μs) and 3d (100 μs) show continued growth of these reactions but they also demonstrate that the detonation will fail to be reignited by Mach reflection off the lower wall as the separation between the shock front and the reaction front is continuing to grow.

We have continued this calculation for 260 μs and shown that the final state of the simulation does consist of a steady detonation spanning the full width of the tube, but this pattern takes approximately 200 μs to become fully established. The detonation is first reignited after approximately 114 μs when the reflected blast wave undergoes a second Mach reflection off the top wall of the tube. At this stage the explosive material has been shock heated by the passage of the decaying shock from the initiating detonation and so the second Mach reflection is able to ignite an exothermic reaction which remains coupled to the shock front and forms a detonation wave which rapidly spans the width of the detonation tube. This detonation is unstable however and spontaneously breaks up into a series of transverse waves which travel across the detonation front and disrupt the detonation. The reflection of these transverse waves off the lower wall of the tube provides some stabilisation however, and after approximately 200 μs a steady detonation is finally established in the tube. Figure 4 contains a sequence of reaction variable contours showing the development of the detonation from the Mach reflection off the upper wall, the spontaneous break up of the detonation, and then the growth of a steady detonation from the lower wall.

DISCUSSION

The calculations presented here demonstrate several different interaction mechanisms by which a decaying detonation can be reignited. Which of these will be seen in any given situation will depend in part on the energetics of the explosive studied, and the strength of the initiating shock or detonation. If a slightly more energetic mixture had been used for these simulations, it is likely that detonation would have been reignited behind the first Mach stem formed on reflection of the blast wave off the bottom of the tube. This mechanism has been studied by Oran et al. (1992b) using a stoichiometric H_2/O_2 mixture and finer grid resolution, and the simulations clearly showed that the highest temperatures occurred from heating along the slip line and at the wall where the vortex rolled up. The temperature contours in Figure 3 also show heating along the slipline, but have insufficient resolution to resolve the vortex roll up. With more energetic mixtures and a more strongly overdriven initiating detonation, it would then be possible for reignition to occur either via the shock/contact surface interaction or along the slipline of the Mach reflection. Further simulations would be required to determine which of these would be most relevant to experimental systems of interest.

ACKNOWLEDGMENTS

The computations were performed on a Cray Y-MP/216 with funding provided by the Materials Research Laboratory. This work was sponsored in part by the Office of Naval Research through the Naval Research Laboratory and in part by US Army Research Office under grant number DAALO3-87-0019.

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