Detonation Propagation in a Layer Laterally Confined by Combustion Products

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1 Introduction

Rotating Detonation Engines (RDE) are a novel means of propulsion which uses detonations, rather than the deflagrations found in conventional engines, to release the energy of a combustible gas [1]. The detonation cyclically rotates around the annulus, through a layer of fresh gas injected from the base of the combustor. This layer is weakly-confined by the combustion products of the previous cycle on the exhaust side of the engine. The resulting flow field has been previously studied in numerical and experimental work, however, experimental data pertaining to the inherent gasdynamic structure of the phenomenon remains limited.

Experimental studies of detonation waves propagating through reactive layers weakly-confined by inert gases have mainly been conducted using a thin plastic film, less than 10 μm in thickness [2–5]. The inert gas used varies between experiments, however this is typically air, helium, or nitrogen. A wave structure similar to that identified in RDEs was observed, although Adams' study which used a low-impedance inert confiner has identified a transverse wave propagating through the reactive-inert interface ahead of the shock due to the high sound speed of the inert confiner. More recently, Metrow and co-workers [6, 7] have studied the structure of a wave propagating in a reactive channel weakly-confined by an inert gas, but designed the experiment to remove the thin plastic film from the experiment as it has been argued that the presence of such a plastic film would affect the structure of the wave [4, 8]. Regardless, the issue arises that the temperature of the inert gas is not representative of the post-combustion temperature found in RDEs, which affects the structure of the detonation by promoting hydrodynamic instabilities [9].

The current study revisits the problem of experimentally studying a weakly-confined detonation. Unlike previous studies, the reactive layer will be weakly confined by its own product gases by igniting a flame in the centre of the shock tube. This flame will elongate and flatten due to preferential convection towards the extremities of the shock tube, creating a thin reactive layer at the bottom of the shock tube as shown in Figure 1. This setup will be the most accurate reproduction of the operating conditions found within a rotating detonation engine, and will allow unobstructed visualization of the wave structure resulting from the weak confinement of a thin reactive channel by its own combustion products.

2 Experimental Method

Detonation experiments are performed in a 3.4 m shock tube with a 203 mm by 19 mm rectangular cross-section. Mixtures of stoichiometric ethylene-oxygen are studied, with an initial pressure of 6 kPa.

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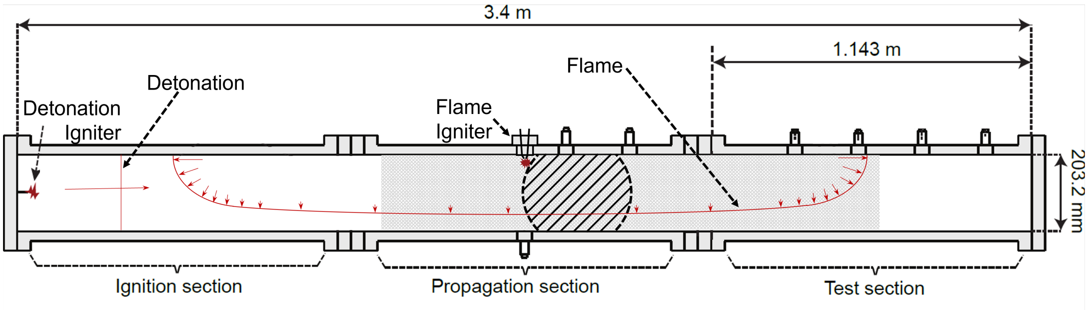

Figure 1: Schematic of the shock tube. The hatched region represents the field of view of Schlieren visualization, whereas the shaded region represents the field of view of direct luminescence. The flame and detonation are sketched in red, showing the elongation and flattening of the flame due to preferential convection towards the extremities of the shock tube. A thin layer of reactive gas remains at the bottom of the shock tube, its height is controlled by the time delay of the detonation ignition.

A high voltage igniter is used to initiate a detonation at an extremity of the shock tube. A second igniter is located in the centre of the shock tube which is sufficient to ignite a flame in the quiescent mixture. The detonable mixture is prepared using the method of partial pressures, after emptying the mixing tank to a pressure of at most 40 Pa. Before each experiment, the shock tube is emptied to a pressure of no more than 80 Pa to minimize the effect of impurities remaining from previous experiments.

Direct luminescence visualization is used to study the evolution of the system on a large scale by using a high-speed camera to directly observe the light produced by chemical reactions. A 50 mm lens is used to observe a flow field comprising up to 2202 mm by 203 mm with a resolution of 1280 px by 200 px. The vertical resolution is set to be the minimum required to capture the height of the shock tube. An aperture of 1.8 is used, with an exposure time varying between 0.7 μs and 2 μs.

Z-type Schlieren is used to directly study the gasdynamic waves, rather than the luminosity produced through chemical reactions. This allows one to observe phenomena which cannot be directly seen using direct luminescence. This setup uses an 80 mm lens to visualize a field of view of 330 mm by 203 mm with a resolution of 384 px by 256 px at a frame rate of at least 77481 frames per second. This technique is further detailed in Settles' book [10].

3 Direct Luminescence Results

Characterizing the evolution of the flame in the channel is possible using direct luminescence, the wide field of view being ideal to study the interaction of the detonation and the flame over long distances. Issues arise when using this technique to visualize both the flame and the detonation, as the latter is much brighter than the flame and over-saturates the camera. Figure 2 shows the evolution of a flame, shown in 20 frame increments with a frame rate of 47976 frames per second. In this experiment, a flame originally ignited in the centre of the shock tube grows radially as a cylindrical flame. In frame e), acoustic waves reflecting off the bottom wall of the shock tube interact with the flame, resulting in the apparent flattening of the flame. The length of this flattened surface continues to increase until the flame reaches the bottom wall of the shock tube. The flatness of the flame is quantified as the length over which the position of the flame in the channel varies less than a set number of pixels. By this criteria, the height of the flame shown in Figure 2 e) varies by less than 2.6 mm (2 px) over a distance of 150 mm. This distance increases to 360 mm in frame h) and 540 mm in frame i).

The evolution of pressure as the flame propagates in the shock tube is measured to characterize the cell size of the detonation interacting with the flame, shown in Figure 3. The initial pressure increases from

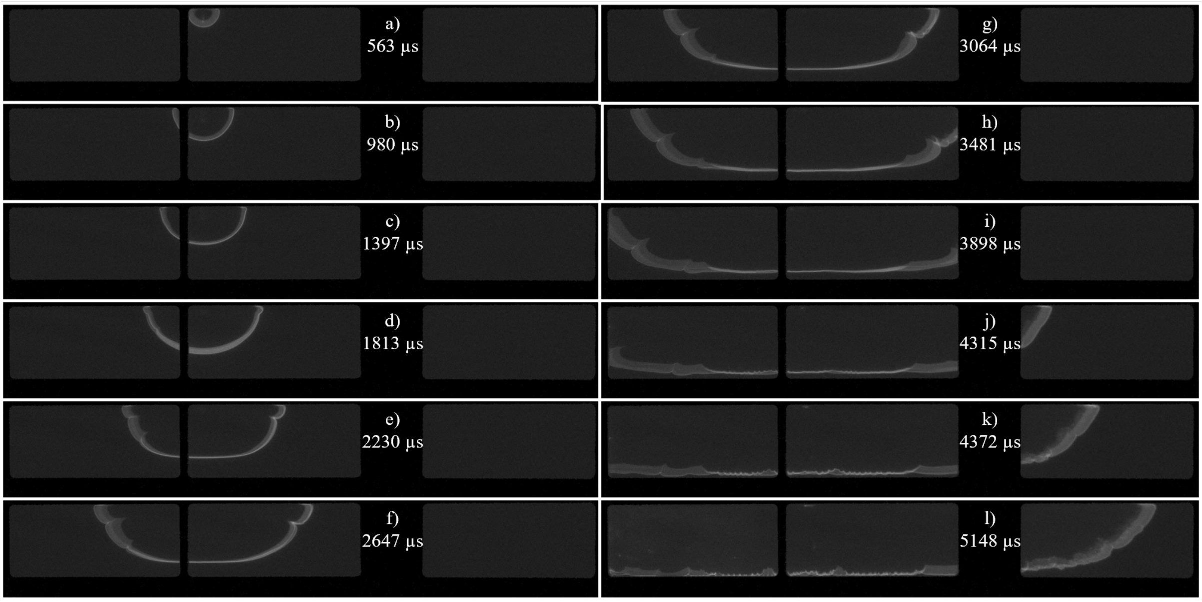

Figure 2: Direct Luminescence visualization of a flame ignited in the centre of the shock tube.

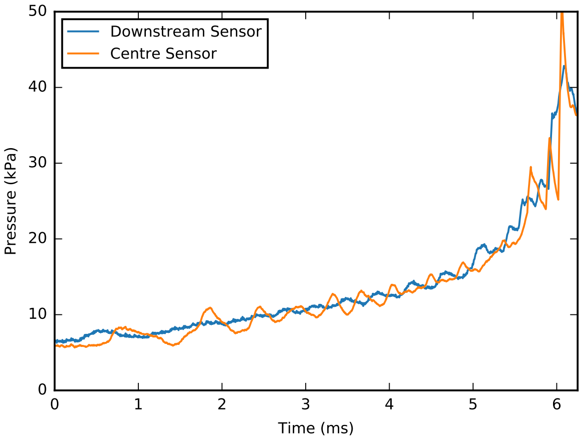

Figure 3: Pressure evolution measured by pressure sensors located under the ignition point and 102 mm downstream from the flame igniter.

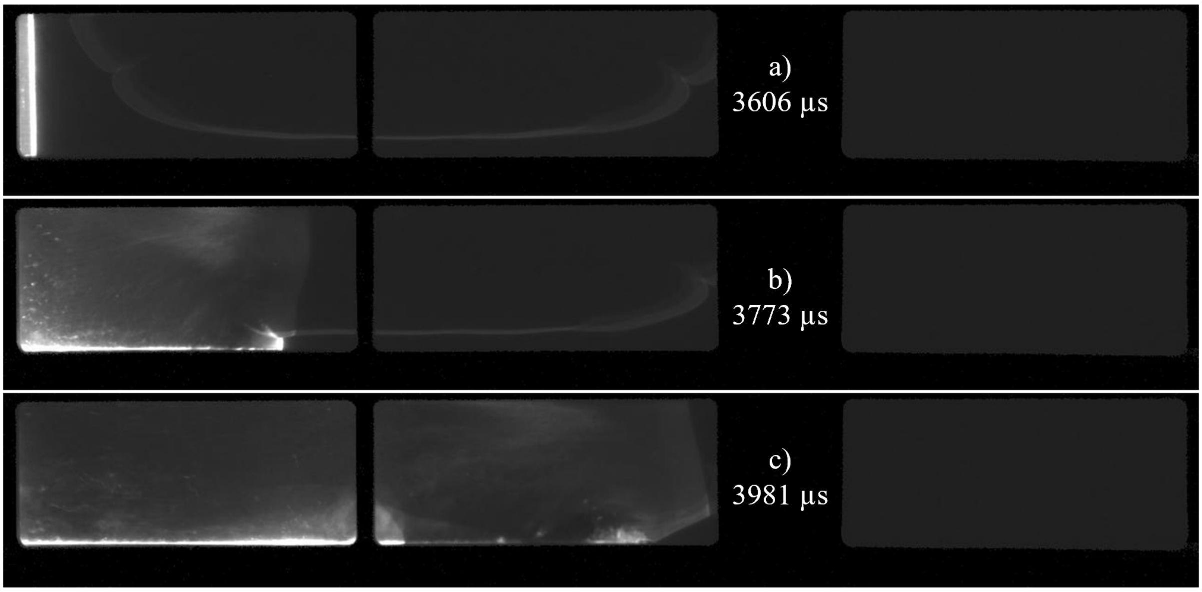

Figure 4: Direct Luminescence visualization of a detonation passing through a reactive layer weakly confined by combustion products. The detonation is initiated 3 ms after the flame. The flame propagates around 2.7 mm (≈ 2 px) in the amount of time taken by the detonation to propagate through the channel.

6 kPa to 29 kPa in the centre of the shock tube, where the detonation interacts with the flame. This gives a cell size around 3 mm according to Knystautas [11]. Open-shutter photographs of the experiment confirmed a cell size between 3 mm and 4 mm.

The visualization of the interaction between a flame and a detonation is shown in Figure 4. Frame a) shows the shape of the flame prior to the interaction with the detonation propagating from left-to-right. The detonation propagates through a reactive channel with an initial height of 24 mm, or 8 cell heights. The height of the channel varies less than 2 pixels over a distance of 556 mm, comparable to a length of 185 cell sizes. The flame propagates less than one cell size towards the bottom wall over the amount of time the detonation takes to propagate the length of the flattened channel. Frame b) shows the structure obtained through the interaction of the weakly-confined detonation with products of combustion. The shock propagating through the product gases can clearly be seen, connected to the oblique shock at the flame. This oblique shock then connects to the detonation at the product-reactant interface. The detonation propagating in this experiment quenches in frame c). By this frame, the oblique shock has lengthened a considerable amount due in part to the mismatch in propagation speeds between the shock propagating through the product gases and the incident detonation.

4 Schlieren Results

To better visualize the gasdynamic wave structure, experiments are repeated using Z-type Schlieren photography. A similar wave structure appears in Figures 5 - 6, consisting of a vertical incident detonation propagating in a reactive channel, connected to an oblique shock wave followed by a reaction wave. This oblique shock is in turn connected to the shock wave propagating through the products at the flame surface. This appears as a quasi-steady structure that evolves on a length and time scale greater than that which can be studied in this experiment. The oblique shock slowly lengthens as the inert shock wave propagates in the products at a higher velocity than the incident detonation propagates through the reactive channel.

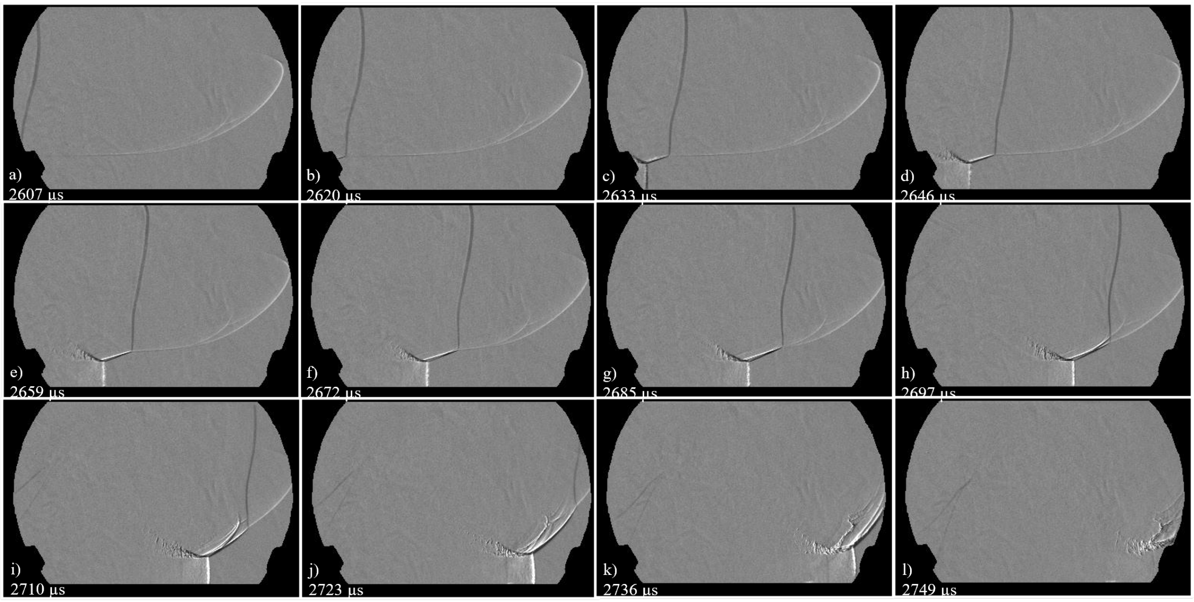

Figure 5: Schlieren visualization of a detonation passing through a reactive layer weakly confined by combustion products. The reactive layer has a height of 37 mm (12λ). The detonation does not quench, nor does its height significantly as it propagates through the channel.

Figure 5 shows the interaction between a weakly-confined detonation and a flame, with an initial reactive channel height of 37 mm, or 12 cell sizes. The detonation propagating through this channel does not quench before reaching the end of the flattened length. In this experiment, the height of the detonation does not significantly decrease as it propagates through the channel. Figure 6 has a slightly decreased initial channel height of 30 mm, or 10 cell sizes, achieved by increasing the delay between the flame ignition and the detonation initiation. The height of the detonation in this experiment noticeably decreases until the structure is entirely replaced by an oblique shock followed by a reaction zone connected to the inert shock at the flame surface, in frame k). This structure is similar to that seen in Figure 4 c). The quenching of this experiment corresponds with the 10λ criterion suggested by Metrow and co-workers.

5 Concluding Remarks

An experimental procedure for studying the propagation of a weakly-confined detonation through a reactive channel bounded by its own products is proposed. This study improves on previous studies by using product gases as the inert confiner, and by omitting a thin membrane from the setup. This allows the observation of the gasdynamic structure as found in rotating detonation engines. Quenching of the detonation occurs when the channel height is around ten cell sizes, agreeing with the quenching criterion proposed by Metrow and co-workers.

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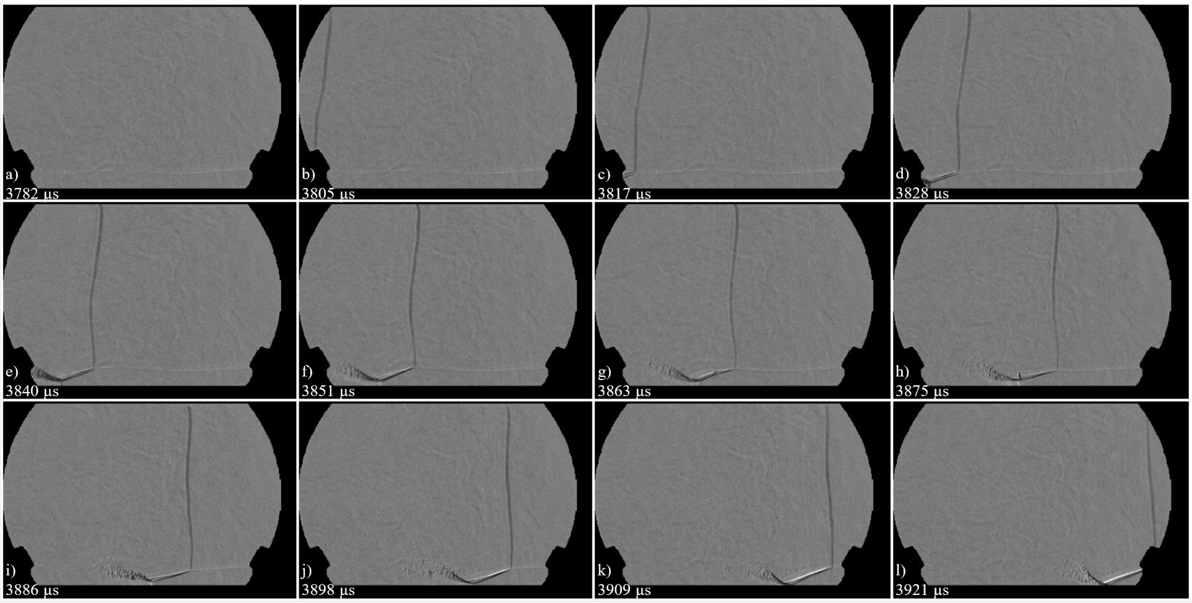

Figure 6: Schlieren visualization of the interaction between a weakly-confined detonation and a flame. The reactive layer has an initial height of 16 mm (5λ). The height of the incident detonation decreases until being replaced by an oblique shock spanning the entire height of the reactive channel in frame i).

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