Detonation Structural Modulation Using Waveguides: An Experimental Study

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1 Introduction

Gaseous detonations are characterized by a cellular structure that ranges from regular to irregular depending on the reactant mixture [1,2]. Regular detonations exhibit a narrow distribution of cell width, λ, across the global detonation structure, and burn primarily via adiabatic shock compression with rapid heat release occurring behind the frontal shock [3]. Irregular detonations exhibit a cellular structure comprised of a range of cell widths, with fine structures often appearing within the larger cells [4] and diffusive burning of unburned gas pockets behind the detonation front [2]. One important consequence of cellular regularity is the difference in propagation characteristics between regular and irregular mixtures in fundamental problems such as the critical tube diameter [5]. Detonations with irregular structures are more "robust" than detonations with regular structures; irregular cell structure detonations can survive diffraction for diameters larger than $\approx 13\lambda$, whereas regular cell structure detonations typically require a diameter greater than $\approx 30\lambda$ for successful diffraction [5,6]. It is of interest to determine the root mechanisms that lead to the robustness exhibited by irregular cell structure detonations.

In a previous series of studies by Tang-Yuk et al. for ICDERS 2023 [7-9], a method for geometrically modulating detonation cellular structure was proposed and investigated numerically. This method involves imbedding micro-plates, or "waveguides" into the reactor geometry. The waveguide matrix aims to induce transverse gasdynamic perturbations into the detonation to "regularize" the cellular structure. The numerical analysis showed that it was possible to regularize the cell structure in irregular mixtures such as stoichiometric H_2-air (modelled using two-step chemistry) using a waveguide matrix. A series of numerical simulations were performed to determine the optimal waveguide spacing for regularization. Once regularization was achieved, the optimized matrix was applied to problems such as propagation across an inert layer and the critical tube diameter diffraction.

In the present study, we aim to experimentally replicate the conditions in the numerical study. A physical matrix of waveguides was installed in a high-aspect ratio detonation channel following the optimal specifications determined by the numerical study. The goal of this study is to experimentally regularize a naturally irregular cell structure detonation using geometric modulation. This technique will ultimately be used to explore the underlying mechanisms of detonation reignition and aid in determining whether detonation robustness is a product of cellular gasdynamics or intrinsic to the mixture chemistry.

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2 Experimental setup

A rectangular detonation channel with an inner width of 19.05 mm and height of 203.2 mm was used to conduct the experiments. The apparatus consisted of a 965 mm long driver section, a 965 mm long flow development section, and an 800 mm long test section with cast acrylic windows for flow visualization. A schematic of the apparatus is shown below in Fig. 1.

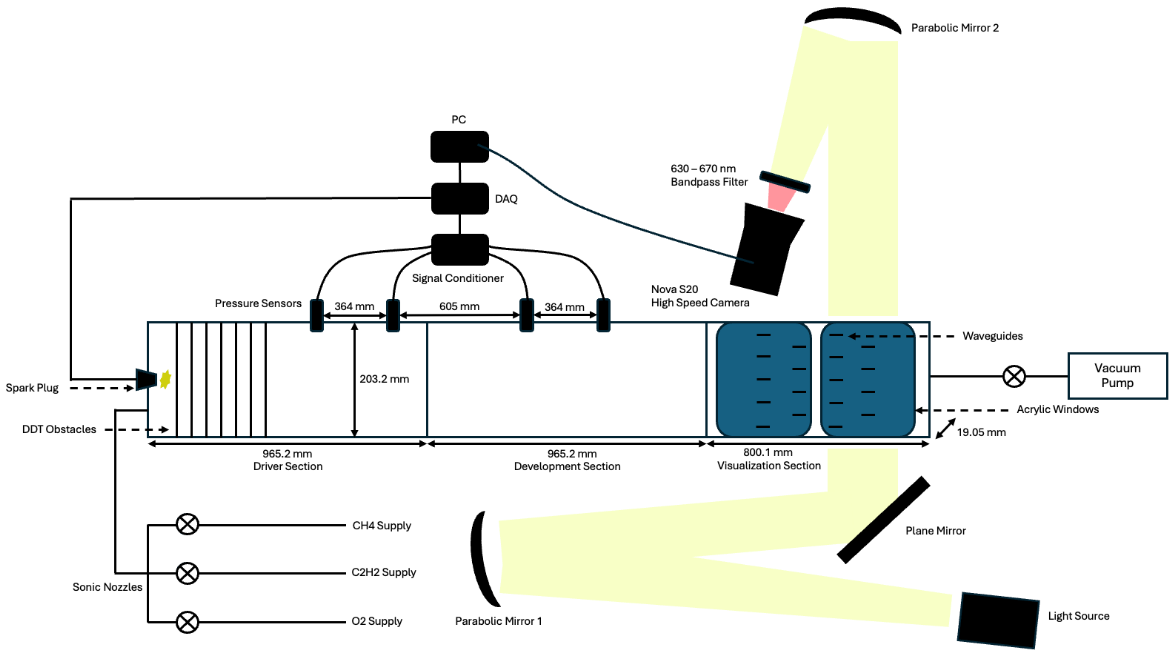

Figure 1: Schematic of the high aspect ratio linear detonation apparatus. Included is the Z-type shadowgraph setup used to visualize detonation structure.

The waveguides were imbedded into the acrylic windows and spaced in a matrix with an aspect ratio of 2:1, designed based on the matrix used in the numerical study [9]. Waveguides consisted of 20.32 mm long plates with a thickness of 1.02 mm and a sharp leading edge to minimize flow disturbance. The waveguide matrix is shown in Fig. 2.

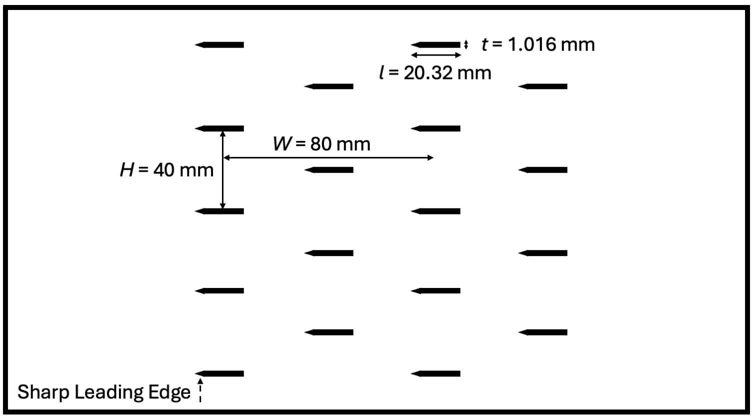

Figure 2: The waveguide matrix with W and H set based on the numerical simulation in [9]. Each guide has thickness t and length l, with a sharpened leading edge.

The mixture considered in this work is stoichiometric methane-oxygen, a mixture with known irregular cellular structure [4]. Prior to filling, the apparatus was evacuated to less than 80 Pa. Mixture mass flow rates into the apparatus were controlled via choked flow sonic nozzles and gases were mixed in a high Reynolds number turbulence generator, as in [10]. A small amount of acetylene-oxygen was introduced near the spark as a driver mixture to encourage detonation initiation. Mixtures were ignited using a spark plug located on the flange of the driver section. Obstacles consisting of a series of perforated plates were installed in the driver section to promote deflagration-to-detonation transition (DDT).

Detonation was confirmed based on the average velocity measured from shadowgraph video compared to the theoretical Chapman-Jouguet (CJ) velocity of the mixture calculated using the SDToolbox [11]. Four pressure sensors (PCB Piezotronics 113B26) were used in the driver and development sections. High-speed video (Photron Nova S20) was captured using a Z-type shadowgraph setup in the visualisation section to record the detonation front structure and average velocity. A 630 - 670 nm narrow bandpass filter (THORLABS FBH650-40) centered at the LED light source wavelength was used in several tests to minimize chemiluminescence contamination of the video. The bandpass filter will be used in all future testing.

3 Results and discussion

The waveguide matrix was designed to accommodate a detonation with 5 cells spanning the channel height (corresponding to a cell width λ of 40 mm). To predict ‘natural’ detonation cell widths, the following linear correlation was used, based on the ZND induction length Δ_i (calculated using SDToolbox [11]:

$$\lambda = 21 * \Delta_i$$

The proportionality constant was determined using experimental cell size values in the Detonation database [12]. To achieve the desired cell size, an initial pressure (p_o) of 14.0 kPa was targeted resulting in a natural cell width of 40.05 mm, and a CJ velocity of 2304.7 m/s.

Fig. 3 shows a comparison between the natural frontal structure and waveguide modulated frontal structure of stoichiometric methane–oxygen detonations at 13.9 and 14.2 kPa, respectively. The detonation velocity determined via high-speed shadowgraph imaging was 2272 m/s across the wave front for the natural detonation, yielding a velocity deficit compared to the CJ velocity of 1.4%. The modulated detonation propagated at 2168 m/s, yielding a velocity deficit of 5.9%. The waveguides therefore lead to a reduction in global velocity, presumably due to losses from the waveguide boundary layers.

The detonation front triple points and corresponding transverse waves can clearly be seen in Fig. 3. The bandpass filter was not used for this series of tests; bright regions correspond to chemiluminescence associated with the high reaction rates near the triple points. Bright regions also appear just downstream from the guides; we believe this is incandescence from fine debris present on the guides and subsequently entrained and heated by the burned gas. The structure of the detonation wave is clearly affected by the waveguide matrix. The modulated detonation front is highly corrugated, i.e., higher local curvature (resulting in larger reaction zones) with pronounced unburned gas pockets visible behind the shock fronts. The natural detonation exhibits a more planar front with smaller unburned gas pockets.

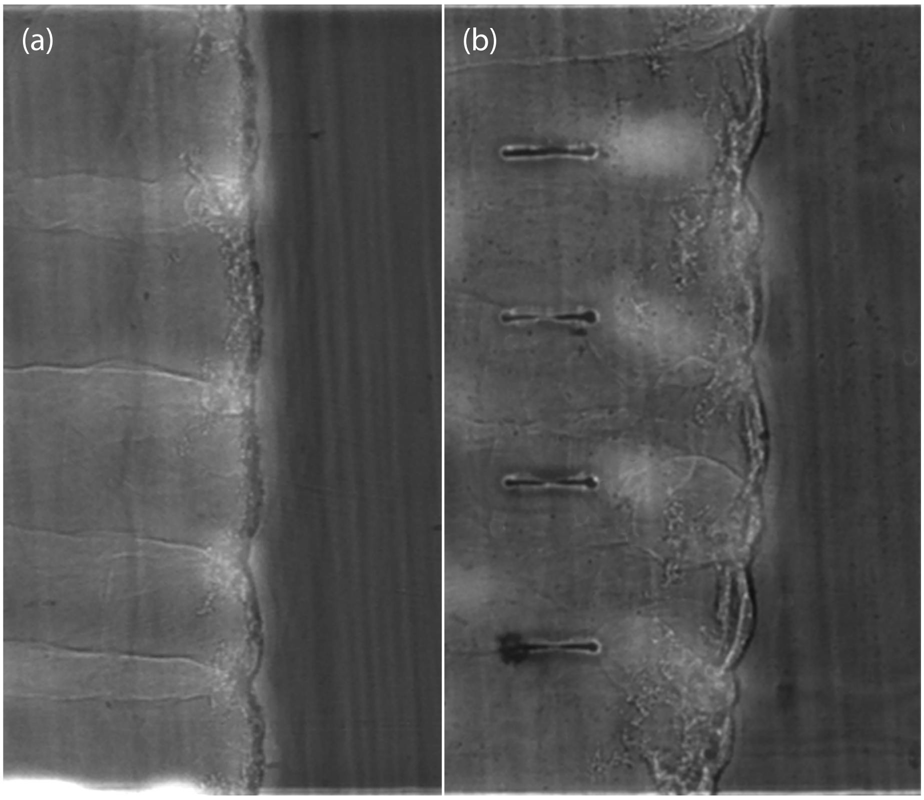

Figure 3: A comparison of shadowgraph images captured for an unmodulated detonation (a) and a modulated detonation (b) front. Initial pressures were 13.9 kPa and 14.2 kPa for (a) and (b), respectively. Detonation (a) propagated at a 98.6% CJ and (b) at 94.1% CJ. The modulated detonation shows a more corrugated front with more pronounced pockets of unburned gas compared to the natural detonation.

Further testing suggested that the waveguide matrix aspect ratio, chosen based on the numerical simulation [9], is at least partly responsible for the inability of the guides to regularize the detonation. Fig. 4 shows an instance where the waveguide matrix fails to capture a transverse perturbation due to the aspect ratio discrepancy. The sequentially overlaid detonation frontal structure can be seen on the left, and the triple point trajectories of interest are shown as red dotted lines on the right. A triple point initially reflects off waveguide B, but misses waveguide C, escaping the waveguide matrix and ultimately colliding with another triple point. The detonation modulation is clearly sensitive to geometric parameters, primarily the guide geometry aspect ratio (*H/W*). Additional optimization is required to replicate the regularization results from the numerical study. A revised waveguide matrix would have a larger *H/W*, i.e., the distance between waveguide rows reduced to match the experimental cell length. The proposed geometry is shown in Fig. 4 by the location of the optimized waveguide C^* at length W^* from the previous row.

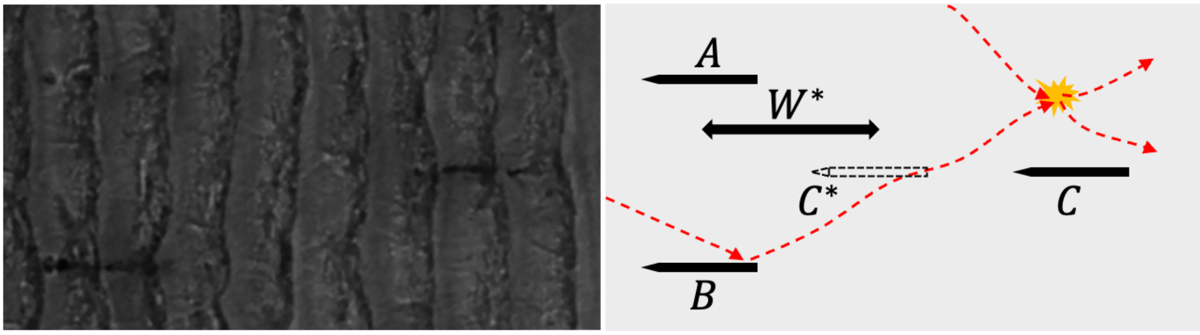

Figure 4: Superimposed shadowgraph images (left) captured at 150 kHz of a detonation at p_o = 14.0 kPa which shows a triple point reflection off waveguide B. Triple point trajectories are traced (right) and show that with an optimized aspect ratio, the waveguide matrix could have captured the reflected triple point.

Though the waveguide matrix failed to globally regularize the cellular structure, promising triple point–waveguide interactions were recorded. Fig. 5 shows the results from a test at 10.0 kPa initial pressure in which transverse perturbations are captured by waveguides A and B and redirected into a collision, with overlaid shadowgraph images on the left, and triple point trajectories traced in red on the right. The shadowgraph images show simultaneous triple point reflections off waveguides A and B. The triple points go on to collide, starting a new cell. The width of the modulated cell λ therefore becomes the designed matrix cell width of 40 mm; note, the natural cell width at the initial test pressure is 59.39 mm. Had the waveguides been geometrically optimized, with C^* location as determined in Fig. 4, the next waveguide would be positioned at the apex of the detonation cell, as desired.

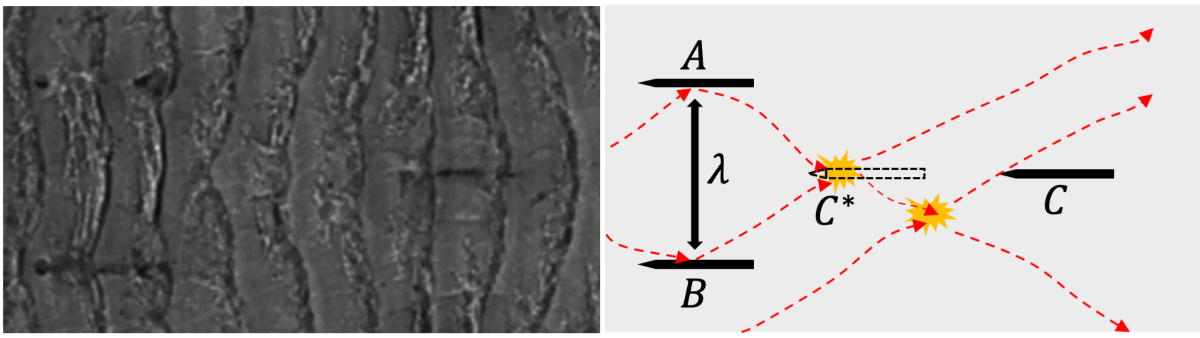

Figure 5: Shadowgraph images (left, 150 kHz) of a detonation at p_o = 10.0 kPa. Triple point tracing from images (right) shows two triple points reflecting simultaneously off of waveguides A and B. These triple points then collide, creating two more triple points. Subsequent triple point paths are also shown.

4 Conclusions

A matrix of waveguides was designed to regularize nominally irregular detonation cell structure. The waveguides were tested with a test mixture of CH_4-$2O_2$ (a mixture with irregular cell structure). An initial pressure of 14 kPa was determined to be optimal for the waveguide geometry and reactive mixture. Experiments conducted at this pressure revealed that the waveguides induced a velocity deficit of 5.9% as compared to CJ velocity (relative to 1.4% for the unmodulated detonation), and the waveguides had a strong effect on the resulting detonation front and triple point trajectories. The modulated detonation front downstream of the waveguides appeared more irregular as compared to the unmodulated detonation, showing corrugated and broken frontal shocks, as well as pronounced pockets of unburned gas downstream of the guides. This suggests that waveguides can increase cell structure irregularity rather than reduce it when not well-optimized. A detailed characterization of triple point trajectories suggested an improved geometry to aid in regularization. Promising triple point–waveguide interactions were recorded that suggest that with an adjusted matrix, the waveguides could effectively capture transverse perturbations and force the detonation into a regular structure. Further work is planned to implement the optimized waveguide geometry found in this study, as well as a new geometry consisting of plates which are several cell lengths long, and spaced with H equal to λ. The long plate configuration will approximate a waveguide matrix where all triple points are successfully captured, and will provide insight on cellular aspect ratios and cellular evolution in a waveguide matrix. Reactant mixtures with regularity ranging from highly regular to highly irregular will be investigated. Furthermore, fundamental studies looking at the collision of individual triple points with a waveguide will be performed to study the effect of the guide length.

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