Detonation Initiation After a Backward Facing Step

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1 Introduction

This study investigates detonation initiation driven by shock reflection of a decoupled detonation wave after a backward facing step. This occurs during the transmission of a detonation from a channel into a receiving chamber of larger transverse size. Pantow et al. [1] showed that wall reflection affects the critical detonation transmission condition. Sorin et al. [2] proposed that for sub-critical conditions, detonation re-initiation takes place shortly after reflection of the diffracting shock transitions from regular to Mach-reflection. They argued that when the flame reaches the wall the combustion products are entrained by the vortex behind the Mach stem and the rapid energy release from the turbulent mixing causes the generation of a detonation wave. Detonation re-initiation also occurs in the propagation of a detonation wave in a channel equipped with repeating obstacles; reported by Teodorcyk et al. [3] when the obstacles spacing was sufficiently large. Ohyagi et al. [4] used Schlieren video and soot foils (on the sidewalls) to study the critical condition required for detonation re-initiation in a rectangular channel with a backward facing step. Bhattacharjee et al. [5] studied the re-initiation process in a narrow channel following detonation diffraction around a cylinder. They proposed that localized ignition behind the Mach stem leads to mixing of the products in the vortex leading to the establishment of a detonation wave that overtakes the Mach stem shock, similar to that proposed in [2], and forms a transverse detonation wave that propagates between the decoupled shock and reaction front. The fine cell structure associated with the transverse detonation was captured on soot foils in [4]. From two-dimensional simulations, Oran et al. [6] showed that in some cases mixing of the hot and cold fluid could lead to a constant volume explosion that produces a strong shock that overtakes the Mach stem forming a detonation wave. Oran et al. [6] proposed that ignition occurs behind the Mach stem due to viscous heating in the shear layer that rolls up to form the wall-confined vortex. All of these experimental and numerical studies neglect the three-dimensional structure of the shock-flame complex that include transverse waves and shear layers that persist during the diffraction-driven decoupling of the detonation wave. In this study, the three-dimensional detonation re-initiation process is investigated using schlieren video and soot foils placed at both the sidewalls, similar to [4], and the bottom wall.

2 Experimental

Experiments were performed in a channel that included a detonation initiation section, consisting of a 1.27 m long, 7.6 cm inner-diameter tube equipped with 5.3 cm diameter orifice plates spaced at one-tube diameter. An automotive 14VDC glow plug (supplemented with a coil-over-plug multi-spark system for less reactive conditions) ignited the flame at the closed-end of the tube. The initiation tube connected to a 1.2 m long, 7.6 cm square-section channel that was equipped with two ionization probes to measure the detonation velocity. A Chapman-Jouguet (CJ) detonation wave entered the optically

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accessible test section that included a backward facing step, from the right of Fig. 1. The channel height, *h,* tested was 7.6 cm and 5.05 cm, as shown in Fig. 1.

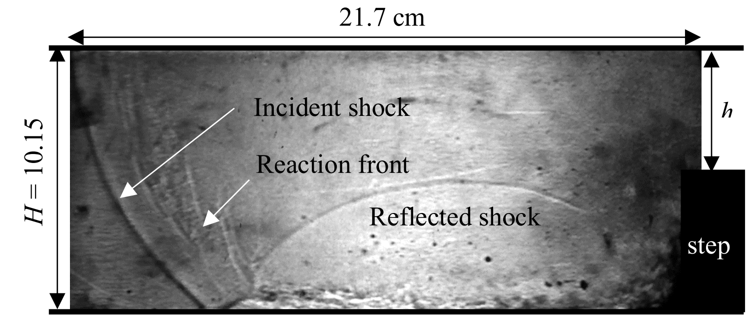

Figure 1: Schlieren image showing the side view of a decoupled detonation wave undergoing regular shock reflection on the bottom wall for $2H_2+O_2$ at 12 kPa (Test 126, h = 5.05 cm)

A single-pass Schlieren system with 25.4 cm elliptical mirrors recorded the detonation diffraction and re-initiation process at the bottom wall. A Photron SAZ camera was operated at 72-100 kfps and 0.16 µs shutter time. Soot-coated 0.5 mm thick aluminum foils were used to record the triple point trajectories associated with the CJ detonation wave before the step, and the failure and re-initiation processes after the step. The test mixture was prepared in a mixing chamber by the method of partial pressures using a 3 bar absolute pressure transducer with accuracy of 0.25% full scale. Four different mixtures were used $2H_2+O_2$, $2H_2+O_2+2Ar$, $C_3H_8+5O_2$, CH_4+2O_2, covering a wide range in detonation stability as observed in the soot foils obtained on the channel floor before the step, shown in Fig. 2. The mixture reactivity was varied via the initial pressure. Over 140 tests were done and in the current paper, we are focusing on methane and hydrogen mixtures for one step size and two different step sizes for hydrogen mixture. The parameters for these tests are presented in Table 1. It should also be noted that the dimensions of foils are slightly smaller than the actual dimensions of the detonation chamber.

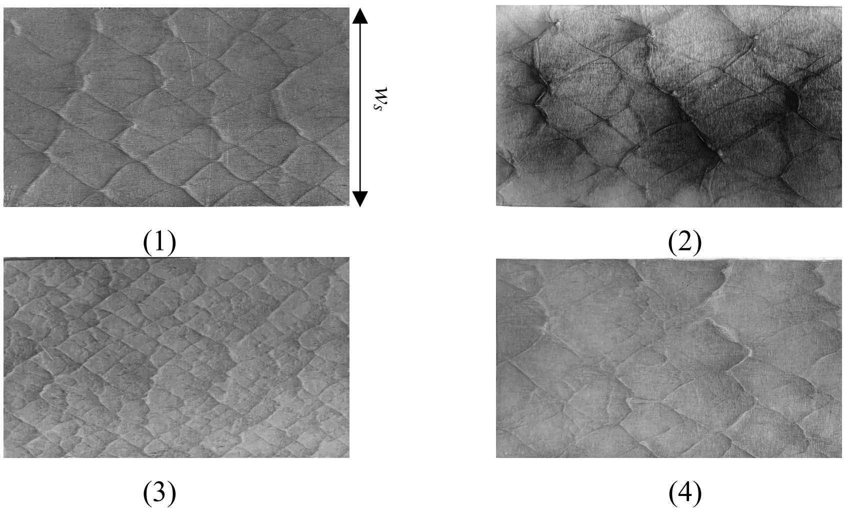

Figure 2: Soot foil images for steady CJ detonations (w_s = 7.3 cm) in 1) $2H_2+O_2+2Ar$ at 10 kPa, 2) $2H_2+O_2$, at 8.4 kPa, 3) $C_3H_8+5O_2$ at 10 kPa, 4) CH_4+2O_2 at 10 kPa. Detonation propagates to the left in all images.

Table 1: Tests parameters

Mixture	h, mm	Cell size λ, mm	h/λ	$(H-h)/\lambda$	w/λ
$2H_2+O_2+2Ar$	76	13	5.88	1.96	5.85
$2H_2+O_2+2Ar$	50.5		3.88	3.92	5.85

CH_4+2O_2	76	19	4	1.32	4

3 Results and Discussion

The diffraction of a CJ detonation wave propagating in argon diluted stoichiometric hydrogen-oxygen at an initial pressure of 9 kPa is shown in Fig. 3. There are transverse waves emanating from roughly eight triple points that move up and down the steady detonation wave in Image 1. Visualization of the transverse waves is possible in this wide cross-section channel (w = 7.6 cm) because for the very regular cell structure associated with argon-diluted hydrogen-oxygen, the triple points and transverse waves across the channel depth align. In image 3, there are two sets of triple points that collide and generate point light emissions on the front. As the expansion fan, anchored at the step corner, traverses the detonation wave it progressively decouples. In Image 6, the entire detonation wave is decoupled and only downward propagating transverse waves remain. The decoupled shock wave undergoes regular reflection in Image 4, the first part of the reflected shock travels in the compressed gas region between the shock and reaction front. Detonation initiation occurs between Image 6 and 7, and the detonation propagates along the bottom wall at approximately 2100 m/s while the CJ velocity for this mixture is 1948 m/s.

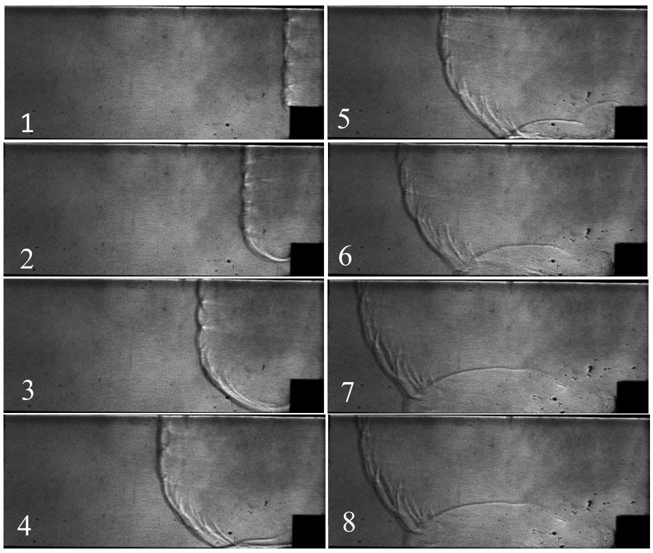

Figure 3: Schlieren image showing the decoupled detonation wave undergoing regular shock reflection on the bottom wall for $2H_2+O_2+2Ar$ at 9 kPa (h = 7.6 cm).

Figure 4 shows the soot foils that clarify the process of detonation re-initiation on the bottom wall for such mixture. The aforementioned triple points form the triple point lines on the side wall soot foils as they propagate across the advancing detonation front. As the channel expands, the detonation wave starts to decouple and all triple points located below a certain ascending line move down towards the bottom wall. It is important to remember that although we see a two-dimensional picture on the side foil (top image in Fig. 4), the process is three-dimensional in nature, and in fact there are several such decaying triple points across the channel width approaching the bottom wall. Their arrival at the bottom wall is accompanied by the formation of "mountain peaks" seen in the lower image on Fig. 4 (marked as "D"). In [7], it was shown how the reflection of a triple point at a solid surface reinitiates detonation. The authors studied detonation exiting a tube, hitting an obstacle and it was shown that if a triple point hits the obstacle, detonation is more likely to re-initiate. In this case, there is a layer of unburnt fuel at the bottom wall and we also see triple points reflecting from the bottom wall and forming detonation kernels (mountain peaks). Very fine cells form as the kernels coalesce into a front and overtake the leading shock, this interaction is marked by a thin line (marked as "S") that separates the light (right side) and dark (left side) regions of the bottom wall foil. There is no visible cell structure to the immediate left of line S, but some triple point lines survive as they can be traced further downstream on the bottom wall. Gradually, the number of triple point lines become visible, including those originating back at the "mountain peaks" and some originating in the middle of the bottom foil. The latter coincides with the arrival of transverse waves descending from above and hitting the bottom foil (see "furrows" across the foil width marked with a "T" in Fig. 4). Note 3D triple "points" actually project a line across the channel width. Such gradual cell structure formation is typical for mixtures with a regular cell structure [8]. From the schlieren video made for another test at the same conditions, the velocity of the wave propagating along the bottom wall is approximately 2300 m/s; the CJ velocity for this mixture is 1952.1 m/s, and thus this is an overdriven detonation wave.

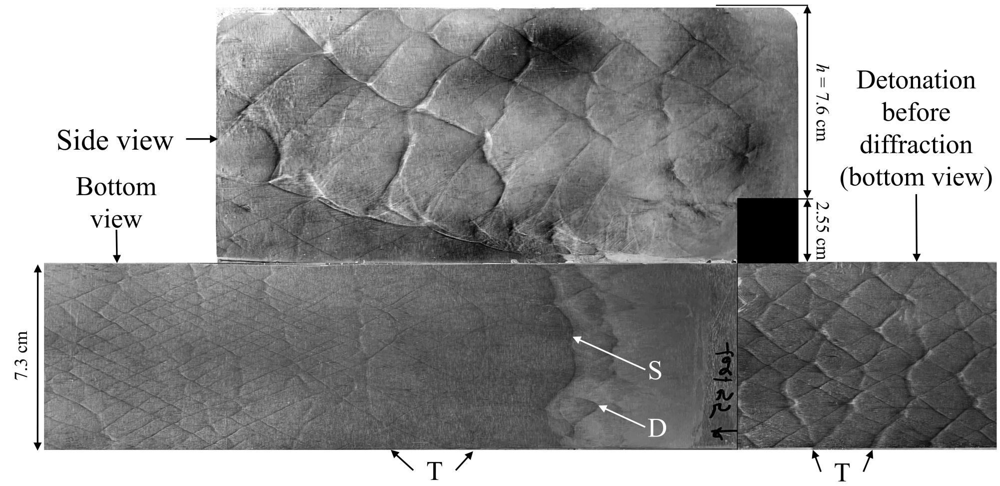

Figure 4: A side window soot foil and a bottom wall foil arranged as they are installed in the detonation chamber for a test with $2H_2+O_2+2Ar$ at 11.9 kPa.

Figure 5 demonstrates the soot foils made for the same mixture conditions with a larger step height (*h* = 5.1 cm). The decrease of the channel height before the step leads to a lower number of detonation cells across the channel height ($h/\lambda \sim 4$ versus $h/\lambda \sim 6$ in Fig. 4). Note, both these cases correspond to the condition just above critical ($2h/\lambda \sim$ 3-10 for 2D), i.e., around failure of the detonation upon diffraction [8]). The lower limit refers to the case of a wide rectangular channel and the upper limit is for detonation propagation from a square channel into unconfined space. In this case, the presence of side walls makes propagation more likely. The recent 2D study [9] shows that the prediction of limits of detonation failure may be enhanced with analysis of the curvature of the expanding incident shock.

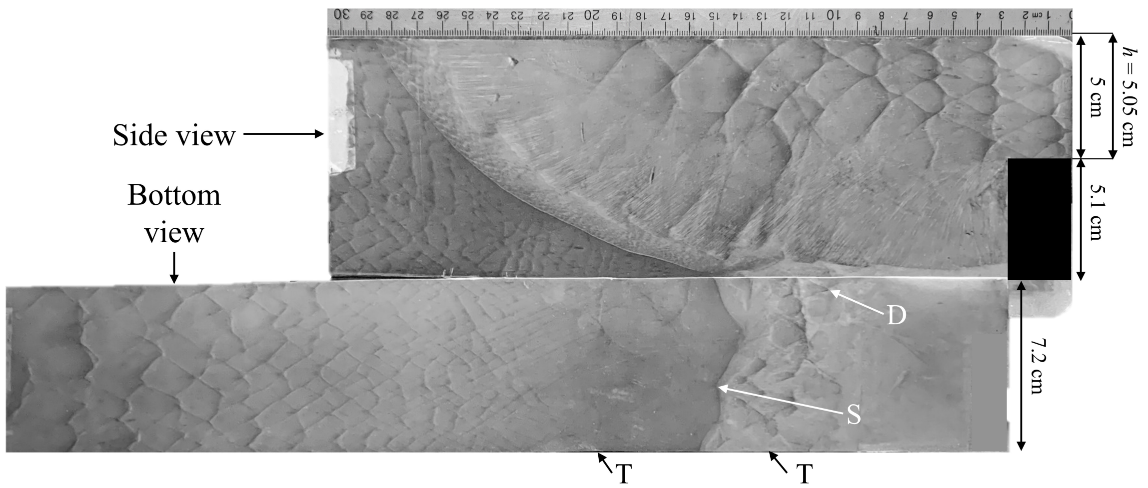

Figure 5: A side window soot foil and a bottom wall foil arranged as they are installed in the detonation chamber for a test with $2H_2+O_2+2Ar$ at 11.9 kPa (*h* = 5 cm).

A lower value of h/λ means that there are fewer triple point lines that reach the bottom wall. At the same time, the triple point travels a longer distance to reach the bottom wall and weakens before reflection. As was observed for the shorter step test in Fig. 4, the triple point lines intersects the bottom wall forming "mountain peaks" (marked "D" on Fig. 5) and fine cell structure (visible in some of the foils) up to where the detonation overtakes the shock (line S). Very fine cells are also produced on the side foil, in the region between the decoupled lead shock and reaction front, by a transverse detonation wave (see Fig. 5). A similar fine-cell structure is observed on the side foil in Fig. 4; however, due to the smaller step size, the lead shock and reaction front are less decoupled (less separated), and the transverse detonation only propagates in the small triangle-shaped pockets of unburnt mixture between triple points.

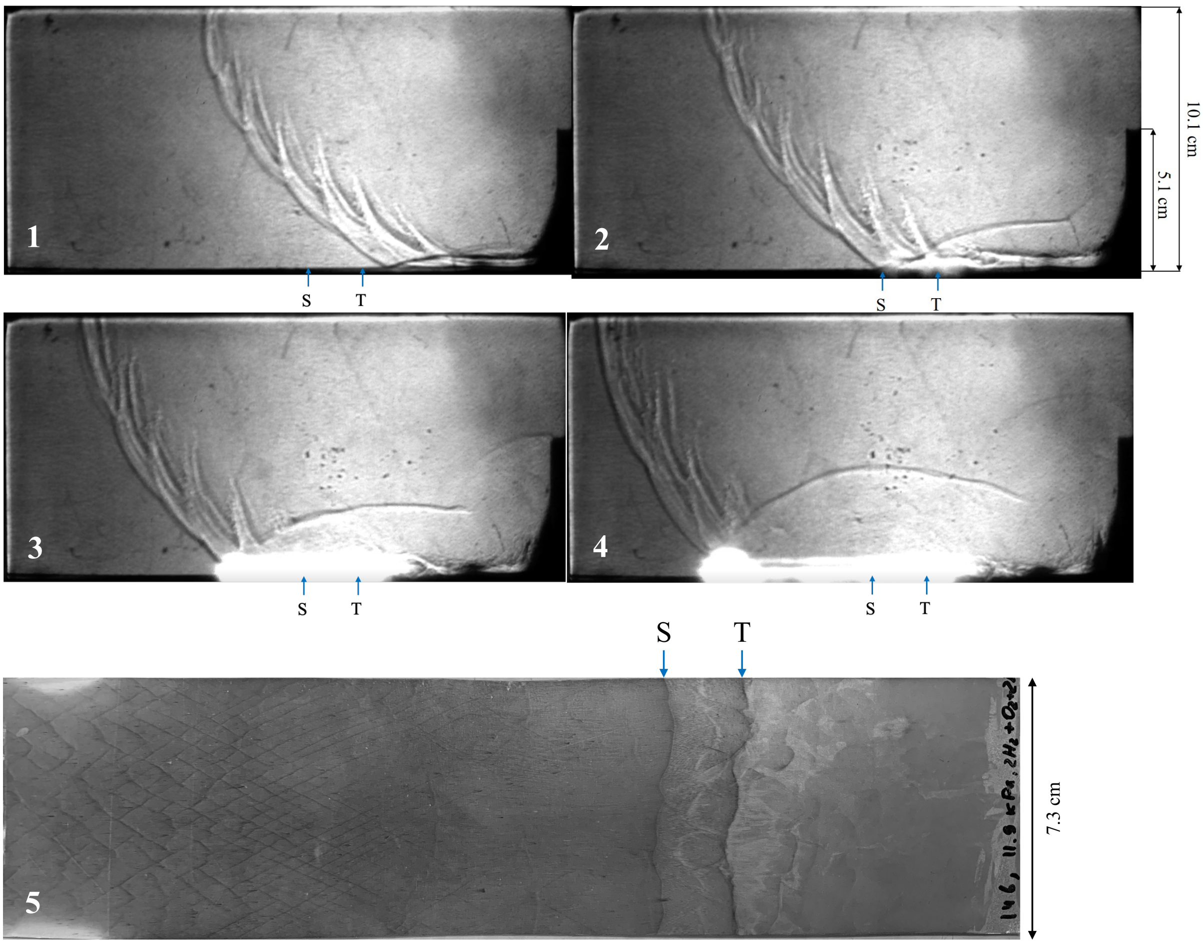

Figure 6: Detonation reinitiation for $2H_2$+O_2+2Ar mixture for p = 11.9 kPa after diffraction at the sharp corner, h = 5.1 cm. Consecutive schlieren images (1 – 4) and the bottom wall foil (5).

The results for a test with the same argon diluted hydrogen-oxygen mixture but with a larger step is provided in Fig. 6. In this test, a schlieren video was captured with a sooted foil placed on the bottom wall. The bright light that can be seen on the bottom of the schlieren images is from the incandescence of the lofted fine-soot particles behind the initiated detonation wave. The detonation wave appears in Images 3 and 4; however, light emission is first seen in Image 2, indicating detonation initiation happens before the Mach stem forms. Furthermore, the first flash of light coincides with line T on the bottom foil where the transverse triple point reflects.

In contrast to the mixtures with regular cellular structure, the detonation re-initiation starts abruptly in mixtures where the cellular structure is irregular [10]. This can be seen for a methane-oxygen mixture in Fig. 7. Similar to the previous cases, we can trace the triple point lines descending after diffraction (see side foils). Local explosions are seen on the bottom foil, i.e., two mountain peaks, both starting in the corners of the channel (points "D" in Fig. 7). The two explosion centers correspond to the axial position where the triple point lines "T" hit the bottom wall. Based on the pre-diffraction foil there are 3-4 cells across the width so there should be should be at least 6 triple point reflections, however, explosions happen only at some of them. A cell structure immediately emerges from both these points. The irregular cell structure evolves with distance to that observed before diffraction.

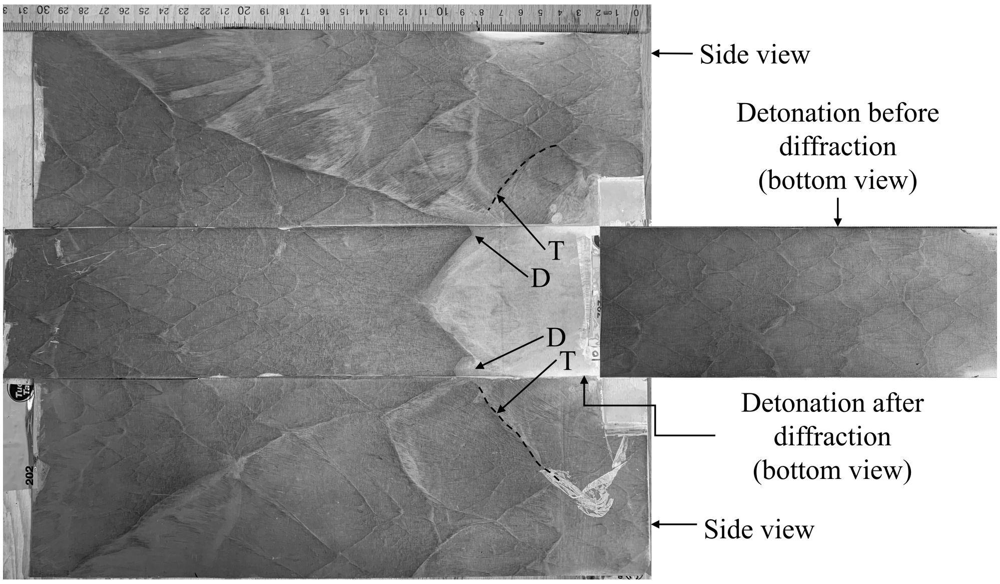

Figure 7: Two side window soot foils, two bottom wall foils placed before and after diffraction, arranged as they are installed in the detonation chamber for CH_4+$2O_2$ at 10 kPa (h =7.6 cm).

4 Conclusion

Detonation re-initiation driven by shock reflection after diffraction around a back facing step was analyzed experimentally for mixtures with a regular and irregular cellular structure for two step sizes. Bottom wall soot foils show that for both types of mixtures three-dimensional effects are of importance. Detonation re-initiation happens when the decaying triple point lines reach the bottom wall. For regular cell structure mixtures, detonation re-initiation occurs at each transverse triple point reflection on the bottom wall across the channel width and the cell structure develops slowly over time. For irregular mixtures, re-initiation occurs mainly at the channel corners and the cell structure develops immediately.

References

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