# Change in Quasi-detonation Wave Propagation Mechanism with Obstacle Blockage

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## Abstract

The intermittent detonation and failure of a combustion wave propagating in a partially obstructed channel has been observed to propagate by two distinct mechanisms. In this study, the interaction of the shock-flame structure with a series of repeated obstructions is investigated using a soot foils and high-speed schlieren photography technique. Experiments were conducted in a h = 7.6 cm by 2.54 cm cross-section aluminum combustion channel equipped with fence-type obstacles along the top and bottom surfaces, spaced equally at distances of h and 2h. Obstacle heights of 1.27 cm and 2.54 cm were utilized, yielding blockage ratios of 0.33 and 0.66 respectively. The 3.66 m long channel includes a windowed section, providing optical access for a high-speed schlieren photography system. Stoichiometric hydrogen-oxygen at initial pressures of between 10 kPa and 50 kPa were tested. A technique to obtain simultaneous soot-foil and schlieren photography was implemented to provide additional insight to the interaction of the shock-flame structure with the obstacles. The objective of this study is to examine detonation initiation and failure of the discontinuous detonation over an obstacle in a variety of geometric configurations. Varying obstacle spacing can affect this interaction with regards to the formation of a Mach stem along the channel wall and can influence the repeated initiation and failure in the quasi-detonation regime. As the detonation passes over an obstacle, shock diffraction causes the wave to fail. Upon reflection with the channel wall, a Mach stem can be formed which collides with the subsequent obstacle, reinitiating the detonation.

## 1 Introduction

Accidental gas explosions have raised a significant concern in the process and power generation industries. Deciphering the mechanisms underlying the explosions is of importance to mitigate their destructive potential, and therefore enhance property and personnel safety. Severe gas explosions normally involve flame acceleration in an obstructed passage, leading to transition to detonation (DDT). As a result, an understanding of detonation propagation in an obstructed channel is important. Kellenberger and Ciccarelli [1] recently conducted experiments in a 50% obstructed narrow rectangular cross-section channel using a novel simultaneous schlieren imaging and soot foil technique. As background for this study, the main results presented in [1] are briefly described here.

Several propagation regimes, i.e., fast-flame, discontinuous detonation, and continuous detonation were observed. Fast-flame is characterized by a leading shock wave followed by a trailing turbulent flame with a large separation

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distance between the two. For discontinuous detonation, detonation failure and initiation periodically takes places at the channel centerline over the width of channel, where detonation initiation is driven by shock reflection off the obstacle. For a sufficiently reactive mixture, a detonation can propagate in the core of the channel without the need for shock reflection-driven initiation, characteristic of the continuous propagation regime. At the DDT limit, two unique propagation modes were found. One mode was symmetrical about the channel centreline that involved detonation initiation at the obstacle face but not at the channel centreline. The other was asymmetric and involved detonation at one obstacle in each pair, alternating top and bottom as the front moved downstream.

Detonation re-initiation at the channel wall following shock reflection was reported by Teodorczyk et al. [2] in an obstructed rectangular channel and more recently by Rainsford et al. [3] in a round tube. The phenomenon of diffraction and re-initiation of detonations behind a backward-facing step was studied by Ohyagi et al. [4]. This mode of detonation re-initiation was not observed in [1] for the 50% blockage ratio (BR) obstacles tested.

It was established in [1] that detonation initiation due to shock reflection is not only governed by the incident shock strength, but also the shock-flame separation distance. Both are affected by the size of the obstacles. The objective of the present research is to investigate the influence of obstacle BR on the propagation mechanism of a quasi-detonation wave in the same narrow channel used in [1]. It is well known that the obstacle BR impacts the d/λ (ratio of obstacle opening and detonation cell size) value at the detonation propagation limit. For BR<50% $d/\lambda$ =1 and for BR >50% the critical $d/\lambda$ increases with BR [5]. It was recently shown that the change in critical $d/\lambda$ with BR is associated with a change in propagation mechanism at the limit [3]. In that study, experiments were performed in a transparent round tube with regular photography, while in this study schlieren photography is used to capture clearer evidence of a change in mechanism.

## 2 Experimental

Experiments were conducted in a 3.66 m long, 7.62 cm by 2.54 cm rectangular cross-section modular aluminum combustion channel, consisting of six sections including a dump tank. An optical section was located 2.46 m from the ignition endwall. The channel was equipped with 1.27 cm or 2.54 cm high obstacles along the top and bottom walls, spanning the entire channel width, yielding a BR of 0.33 and 0.66, respectively. A single-pass schlieren system, illuminated with a 35 W xenon arc-lamp, was used with a Photron SA-Z high-speed camera to record the propagation of detonation wave at up to 175,000 frames per second. Soot foils placed on the channel side-wall were employed to obtain a record of cellular structure. This was achieved by lightly sooting a 2.2 mm thick sheet of glass above a kerosene lamp and placing it on the inside of the optical section windows. A mixture of stoichiometric hydrogen-oxygen was used in all tests at initial pressures of 4-60 kPa. The gaseous mixture was ignited at one end of the channel using a 500 mJ automotive capacitive discharge system.

## 3 Results and Discussion

The measured average velocity of the combustion wave over 30.48 cm in the optical section is plotted in Fig. 1 (also shown for comparison are the 50% BR results from [1]). The detonation limit is characterized by an abrupt jump from values below the isobaric combustion products speed of sound to values above it. The detonation limit was found to be 12 kPa for 50% BR [1], and in this study, 4 kPa and 33 kPa for the 33% and 66% BR cases, respectively. As has been shown in the past, decreasing mixture reactivity or increasing obstacle BR leads to a more severe velocity deficit [1, 2, 3, 5]. Based on the detonation cell size data from the literature, the limits for the three geometries correspond to $d/\lambda\approx 0.6$, 2.1, and 6.0, respectively for 33, 50, and 66% BR. The increase in the $d/\lambda$ limit value with increasing BR is consistent with previous studies [2, 5]. Several propagation regimes were observed in the present 33%BR and 66% BR tests, the designations of which are provided in the Fig. 1 legend. Recall, discontinuous detonation is characterized by periodic detonation failure and re-initiation. The key features of the discontinuous detonation regime are now highlighted using high-speed schlieren and soot foil results.

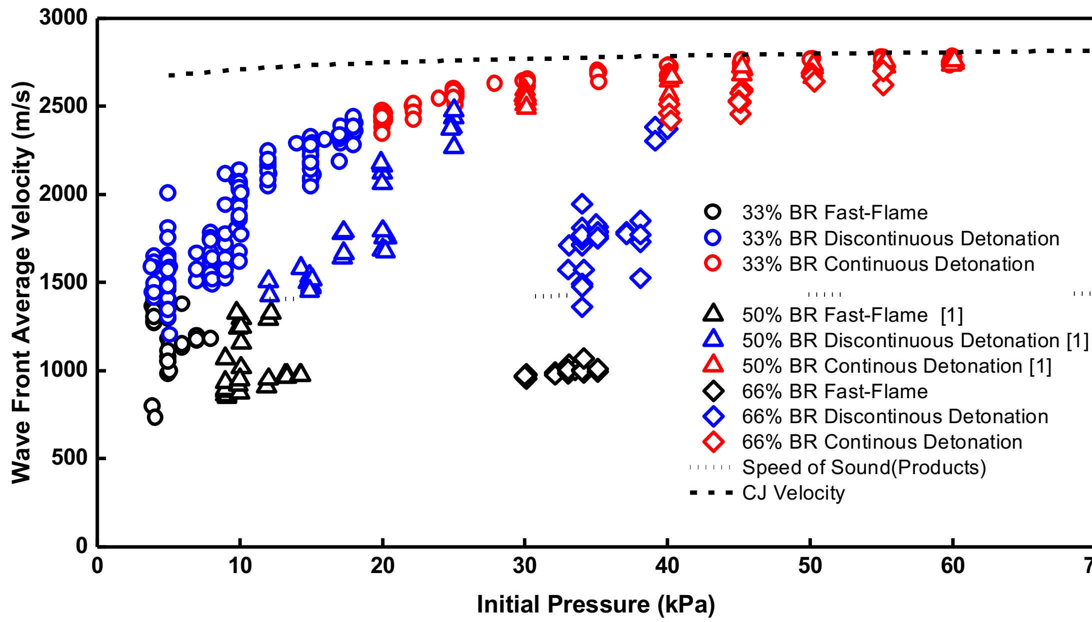
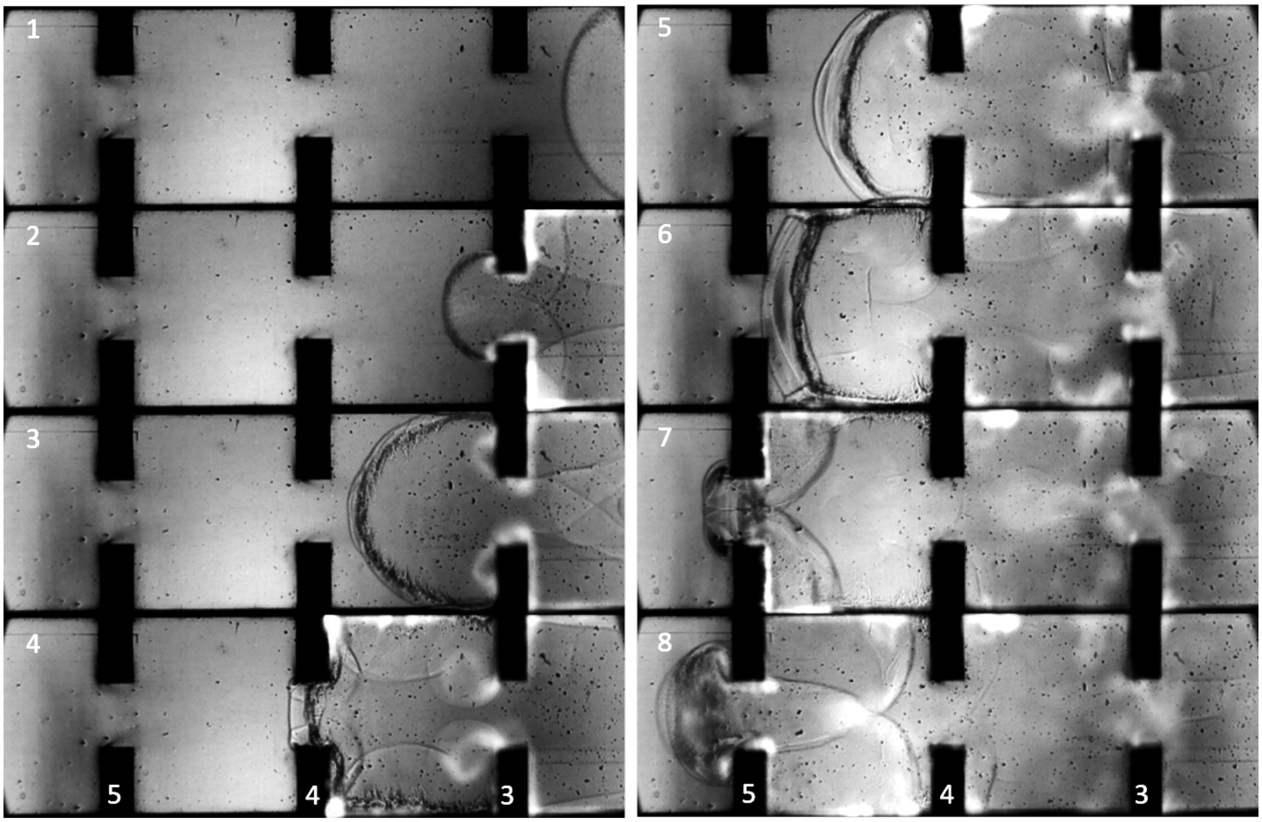


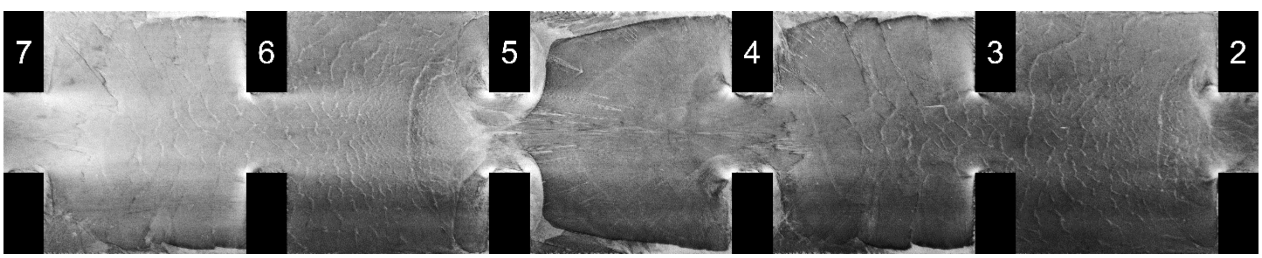

Fig. 1. Average combustion wave velocity for different BR obstacles, based on shock time-of-arrival measured across four obstacles. The 50% BR data is from the identical channel [1].

Shown in Fig. 2a are schlieren video images obtained in a 66% BR test performed at 34 kPa initial pressure, corresponding to the discontinuous detonation propagating mode. A detonation enters the right-side of the field-of-view in frame 1. After passing through obstacle 3, the detonation fails due to the diffraction around the obstacle, resulting in a shock-flame complex as seen in frame 3. Shock reflection off the face of obstacle pair 4 in frame 4 results in detonation initiation. The relatively small distance between the shock and the flame at the time of shock reflection leaves only a small pocket of unburned gas to sustain the initiated detonation. As a result, the detonation quickly quenches before it can propagate around the obstacle upstream face. The subsequent collision of the resulting decoupled shock waves at the channel centreline occurs between frames 4 and 5 (not captured due to camera frame rate) does not result in detonation initiation. As a result, a decoupled shock wave andflame approach obstacle 5 in frame 5. Prior to collision with obstacle 5, there is a large separation distance between the shock and the flame, see frame 6. This leaves a large pocket of shock-compressed unburned gas for the initiated detonation wave to propagate around the obstacle. Although the diffraction weakens the detonation waves (initiated at the top and bottom obstacle face), the collision of the decoupled shock waves at the centerline results in detonation initiation that overtakes the lead shock front in frame 8.

The soot foil shown in Fig. 2b was obtained in a different 66% BR test performed at an initial pressure of 34 kPa. The foil is highlighted by a bell-shaped region containing fine cellular structure just past obstacles 2 and 5 which illustrates the detonation initiation phenomenon that takes place between frames 6 and 8 in Fig. 2a. Within the bell-shaped region, the cells start off very fine and enlarge with axial distance, suggesting initiation of an overdriven detonation wave that decays in strength with propagation distance. Eventually the detonation wave fails, resulting in the disappearance of the cells leading up to obstacles 4 and 7. This formation and disappearance of the cellular structure is characteristic of the cyclical detonation initiation and failure typical of the discontinuous mode of propagation. This propagation mode was also observed in the previous study performed in the same channel equipped with 50% BR obstacles [1]. The fast-flame and continuous detonation mode phenomena observed in this 66% BR study were also similar to that observed in the previous 50% BR study.

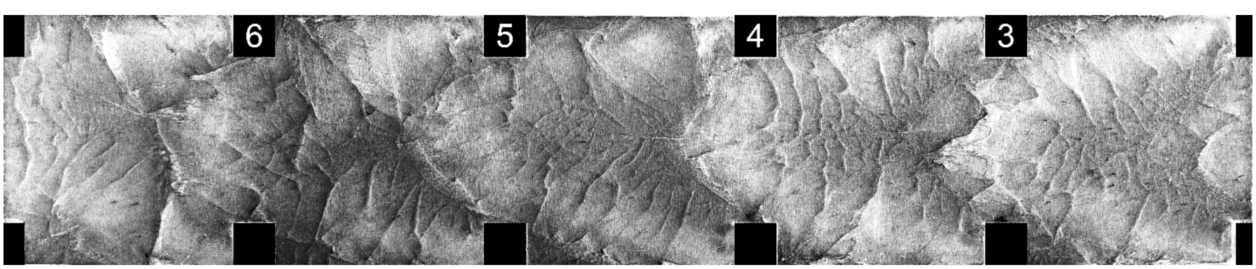



(a)

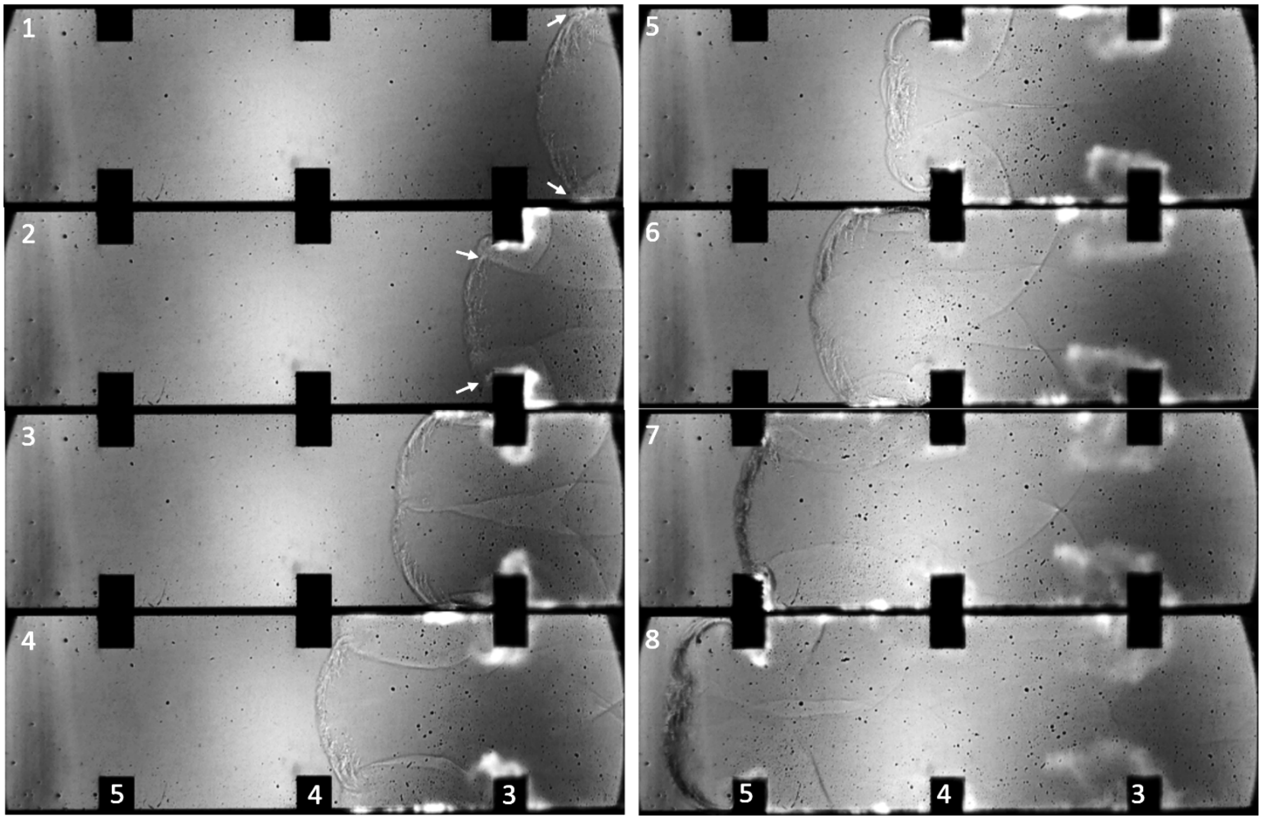



(b)

Fig. 2. Narrow channel tests with stoichiometric $H_2$-$O_2$ at 34 kPa for 66% BR showing discontinuous detonation propagation. (a) schlieren image sequence (test 140), and (b) soot foil (test 131). Inter-frame time is 17.1 µs.




(a)




(b)

Fig. 3. Narrow channel test with stoichiometric $H_2$-$O_2$ at 20 kPa initial pressure for 33% BR showing discontinuous detonation propagation. (a) Soot foil (test 420) and (b) schlieren image sequence (test 126). Inter-frame time is 11.4 μs.

Discontinuous detonation propagation in the 33% BR obstacles between 5 and 15 kPa was characterized by detonation initiation following shock reflection at the upstream face of the obstacle. The detonation then fails as it propagates around the obstacle with no re-initiation at the channel centerline. For pressures between 15 and 20 kPa the discontinuous detonation is characterized by detonation initiation at the channel wall. Soot foil and schlieren video obtained from tests conducted at 20 kPa initial pressure for 33% BR are presented in Fig. 3. The cellular structure recorded is very different from anything obtained with the 66% BR obstacles in this study, or 50% BR in the previous study [1]. Each obstacle pair has a chevron ("<") associated with it. Very fine cells are seen directly downstream of the apex of each chevron, indicating the formation of an overdriven detonation. Schlieren video frames taken from a test performed at the same conditions are provided in Fig. 3b. In frame 1, a diffracted detonation wave enters the field-of-view, i.e., coupled along the centerline but decoupled near the top and bottom walls. A detonating Mach stem propagates along the top and bottom channel walls, highlighted by arrows in frame 1. As the detonation propagates through the opening of obstacle 3 the detonation completely decouples, as shown in frame 2, where a gap between the shock and trailing flame is observed. Meanwhile, the Mach stem detonations reflect off the obstacle faces, producing a transverse detonation wave that propagates through the pre-compressed gas in the gap, see the arrows in frame 2. The finer cell structure associated with this transverse detonation wave produces the segment of the chevron between the obstacle pairs. The tails of the chevron near the walls are produced by a triple-point that bounds the Mach stem detonation wave, clearly seen in frame 4. The Mach stem detonation waves form when the diffracted detonation wave reflects off the top and bottom walls, see frames 3 and 4 in Fig. 3b. The Mach stem forms as the angle between the incident shock and wall increases past the critical value [4]. This mode of detonation initiation was observed for pressures above 15 kPa.

## 4 Conclusions

Experiments were carried out in an obstructed channel to reveal the influence of BR on quasi-detonation propagation. The fast-flame and continuous detonation propagation mechanisms were found to be the same as in the previous 50% BR tests [1]. In the 66% BR tests, the continuous detonation mode transitions to the discontinuous detonation behavior at around 38 kPa, where cyclical detonation failure and re-initiation occurs at the channel centerline, similar to that observed in the 50% BR tests. In the 33% BR tests, the transition from the continuous mode to the discontinuous mode was highlighted by detonation initiation off the top and bottom channel walls forming detonating Mach stems. As proposed by Rainsford et al. [3], for taller (higher BR) obstacles, inaccessibility of this initiation mechanism is responsible for the larger critical pressure, and thus $d/\lambda$ greater than unity, for the detonation propagation limit, as previously reported [2, 5].

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