Effects of Unequal Blockage Ratio and Obstacle Spacing on Wave Speed and Overpressure During Flame Propagation in Stoichiometric H_2/O_2

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1 Introduction

Flame propagation and explosion behavior of hydrogen-based mixtures remain critical issues for explosion safety in nuclear power plants and refineries. Research in this area has shown that the presence of confinement and obstruction in the flame path may enhance flame acceleration due to an increase in flame instabilities resulting from flame-obstacle interaction [1]. In addition, as the combustion process progresses, unburnt gases ahead of the flame are put into motion, generating turbulence downstream of an obstacle. This induced turbulence increases the reaction rate, further accelerating the flame [2]. Extremely fast explosion flames can be caused by this mechanism, giving rise to severe overpressures. From the perspective of explosion safety, it is fundamental to understand what conditions a premixed deflagration accelerates and eventually leads to more severe overpressures and even, as the worst case, to a transition to detonation.

For this purpose, experimental studies have been guided towards investigating the effects of obstructions on the flame acceleration phenomena. It has been found that many variables play roles in the explosion severity, such as confinement, obstruction configuration (shape, blockage ration, and spacing), etc. Although extensive efforts have been made to understand the underlying mechanisms affecting flame acceleration in obstructed enclosures, most of the studies address obstacles with uniform distributions [1-4]. This uniformity is characterized by constant obstacle spacing, shape, and blockage ratio, and may not be representative of the layout in actual industrial facilities. Therefore, this study aimed to investigate the influence of unequal area blockage and obstacle spacing on the leading shock wave speed and overall overpressure during flame propagation.

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2 Experimental Details

Experiments were carried out in a horizontal tube with a length of 2.77 m and a 38-mm internal diameter, as shown in Fig. 1. The tube is closed at both ends, and ignition was via a low-voltage, automotive glow plug operated at 10 A positioned centrally at the left-endplate. An expansion volume is located at the end-wall opposed to the ignition point, enabling the use of multiple spacers with different widths; see [5] for details. A spacer with 25.4-mm width was maintained during all tests to minimize disturbances from reflected shocks propagating ahead of the flame. The pressure was recorded at seven different locations along the tube (P1, P3, P5, P7, P10, P13 and P17) using piezoelectric pressure transducers, PCB 113B22, with a measurement range of 34.5 MPa, a rise time of less than 1 µs, and a resonance frequency ≥ 500 kHz. Data were recorded using a PC oscilloscope board (GaGeScope) at a sampling rate of 1 MS/s.

All tests were conducted at ambient temperature, roughly 20°C. Stochiometric hydrogen/oxygen mixtures were prepared by the method of partial pressures in a separate mixing tank and left overnight. Two ring-shaped obstacles with 5-mm thickness were used during each test, with the first obstacle fixed at a distance of 80 mm from the ignition point. The arrangement between obstructions in the test vessel was changed in terms of blockage ratio (increasing, decreasing, and equivalent) and obstacle separation distance (1D, 2D, and 3D). Table 1 summarizes all conditions tested in this study. A full factorial design was conducted, resulting in 27 different experimental conditions. Each experimental condition was repeated at least three times.

Table 1. Summary of experimental conditions

Variable	Level 1	Level 2	Level 3
1st Obstacle blockage ratio	25%	40%	80%
2nd Obstacle blockage ratio	25%	40%	80%
Obstacle Spacing	1D	2D	3D

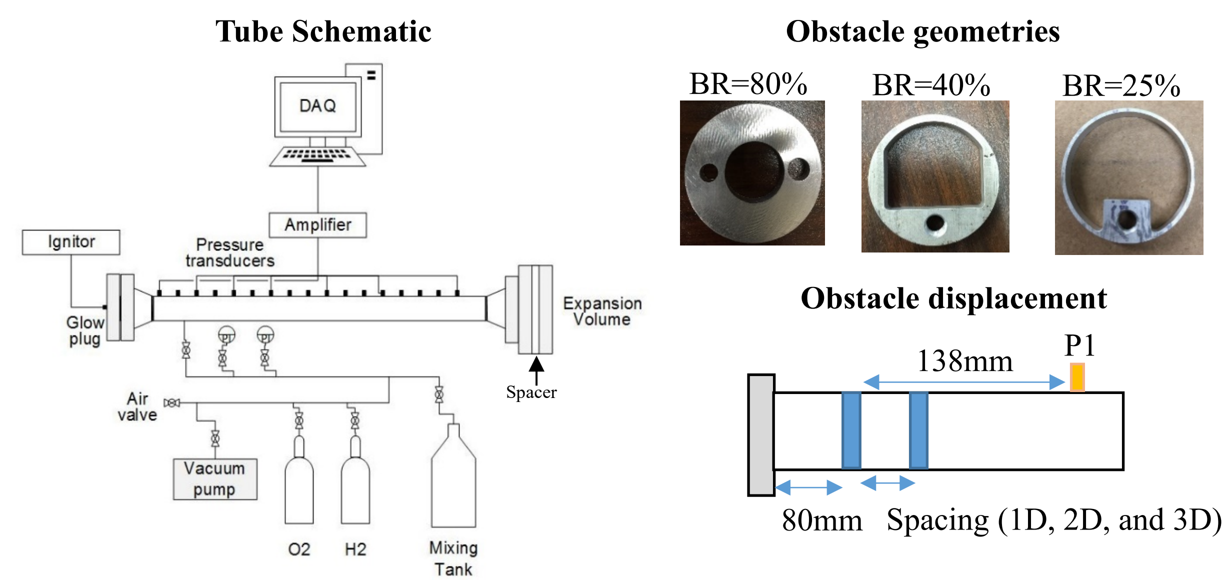

Figure 1. Schematic illustration of the detonation tube utilized in the tests.

3 Results and Discussion

The goal of this study was to identify conditions that facilitate the onset of DDT and enhance turbulent combustion propagation. An initial test was performed with the tube emptied to analyze flame propagation without the presence of obstacles at 150 torr. According to Dorofeev *et al.* [6], at this initial condition, the flame front is likely to accelerate, reaching high-speed combustion regimes. Figure 2 depicts the overpressure profile with time along the tube. A series of sonic waves traveling toward the right-end plate are observed, indicating an early flame acceleration. Then, a rapid transition to detonation takes place in the second half of the tube (after 1.5 m from ignition location) creating overpressures around 4 bars. For all three tests, detonation occurred in the same region (between P13 and P17) resulting in the following criteria for run-up distance in the current set-up: $X_d \approx 300\ \lambda$. This run-up distance scaling with cell size follows the same order of magnitude of the criteria proposed by Kuznetsov *et al.*[7].

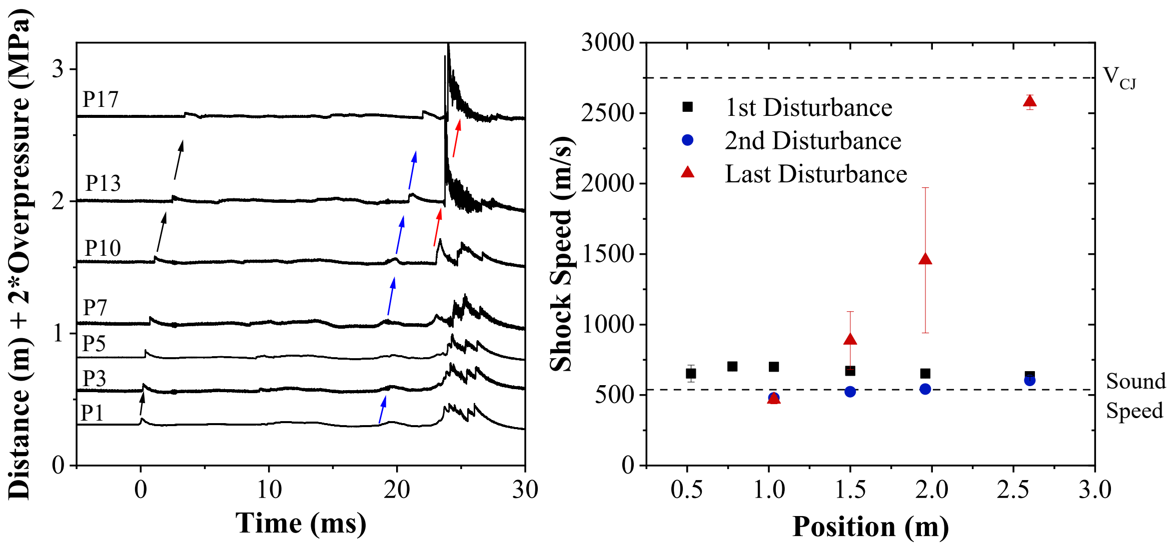

Figure 2. Pressure results (left) and shock speed (right) obtained for a stoichiometric hydrogen-oxygen mixture initially at 150 torr and with the tube emptied. Pressure is normalized by side-on pressure measured (MPa) multiplied by 2 and added the pressure sensor distance (m). Chapman-Jouguet detonation velocity (V_{CJ}) was calculated via the Chemical Equilibrium with Application (CEA) software [8].

After confirming that DDT is possible even with the absence of obstacles, experiments were carried out to investigate the effects of varied blockage on the explosion characteristics. As expected, deflagration-to-detonation transition was observed in all 27 experimental cases. Overall, four general propagation behaviors were identified (see Fig. 3) based on the time between the leading wave and the onset of DDT.

In case I, a preceding wave continuously accelerates until it reaches a final speed near the Chapman-Jouguet detonation. This case can be further divided into two, I-A and I-B. The former consists of a strong shock that is created in the wake of the second obstacle and is detected early by sensor P1 or P3 located at 190 mm and 460 mm from the 1st obstacle, respectively. Since the detonation onset occurs earlier, there is no sign of retonation propagating backward towards the ignition point. This is similar to the case of a turbulent jet-triggered DDT as observed by other researchers[9]. In the case of I-B, DTT takes place within the second half of the tube near the leading shock front. Gaathaug *et al.* [10] reported a similar phenomenon that was caused due to shock accumulation resulting from multiple local explosions which, at some point, overtakes the leading shock triggering DDT.

For combustion type II, a shock wave is formed and accelerated up to speeds of 1500 m/s in the first half of the tube and later decelerated to final speeds around 800 m/s towards the closed end. The leading wave is not strong enough to ignite the mixture via shock compression and, as a result, the onset of DDT takes place after it passes. This behavior is typical for conditions when detonation onset occurs in the turbulent flame brush [1]. Case III is very similar to case II; however, in Case III, two major pressure waves are observed before the transition to detonation. The fact that the second pressure front is accelerating indicates that a flame-shock structure is formed, and that detonation takes place after the flame passes due to hot spot ignition and shock focusing. In case IV, on the other hand, numerous pressure waves are formed and travel near the sonic velocity in the medium; this indicates a slow flame acceleration followed by a sudden transition that takes place towards the end of the tube.

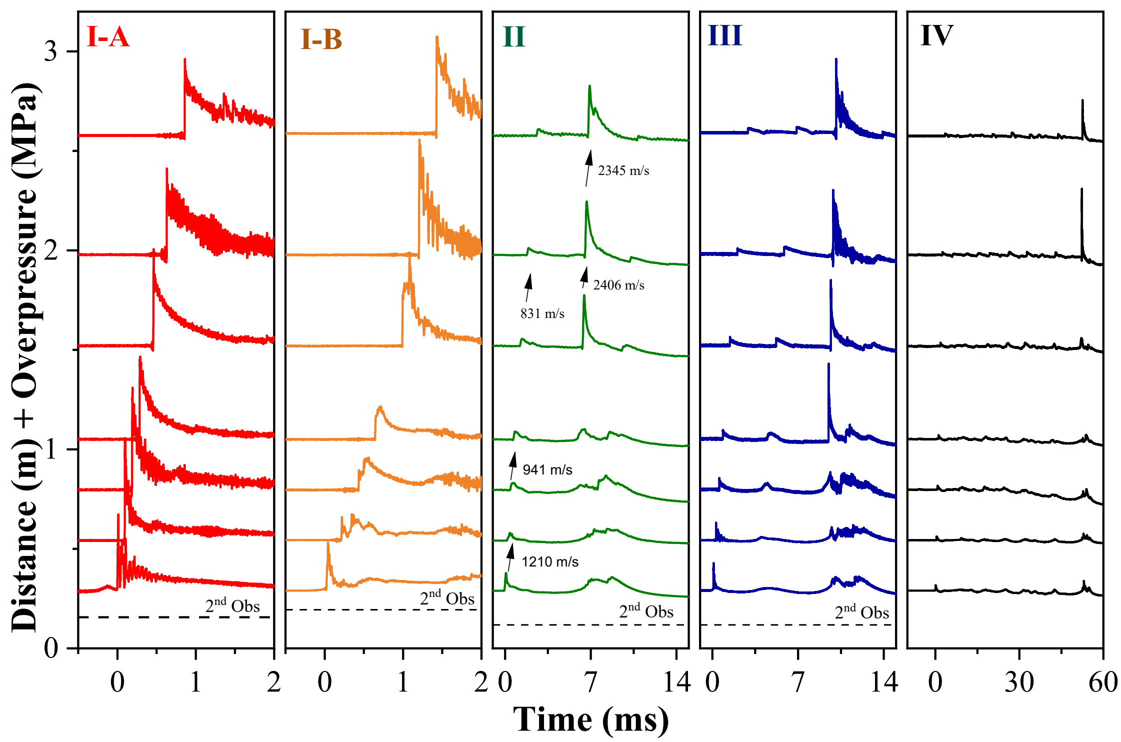

Figure 3. Representation of the four different types of combustion propagation behaviors identified.

Table 2 summarizes the predominant propagation behavior for each condition tested. The most robust combustion regime (Case I) occurred for obstructions with a higher blockage in the second obstacle (80-80, 40-80, and 25-80). It is reasonable to assume that narrower obstruction gaps may generate faster and stronger shocks as the flame front passes the solid obstruction. This strong shock can ultimately lead to detonation onset. Another important aspect is the distance between the obstacle and the ignition point — longer spacing results in faster flames before reaching the obstacle surface. For instance, cases with higher BR closer to ignition (80-40 and 80-25) resulted mostly in combustion type III, in which the leading shock front was significantly lower.

Another interesting observation is that obstacle pairs with the same average blockage ratio resulted in distinct combustion characteristics, especially when BR variation was more abrupt. For instance, comparing the results from the obstacle pair 40-80 with its equivalent on average blockage (but transposed), 80-40, one may observe that the increasing obstruction leads to a stable detonation within the first three sensors (see

Fig. 4). Conversely, in the decreasing blockage case, DDT takes place mostly within the second half of the tube (after P4), and it is preceded by two major pressure waves. Similar conclusions were obtained for obstacle pairs 80-25 and 25-80. Contrarily, obstacle pairs with smoothers changes in BR (40-25, 25-40) in general did not demonstrate significant differences in behavior.

Table 2: Summary of prevailing propagation conditions for each obstacle characteristic.

Blockage Distribution	Average ABR	d/λ *	d_{mean}/λ	Obstacle Spacing 1D	2D	3D
80-80	80%	2.0	2.0	II	I-B	I-B
80-40	60%	3.5	2.8	III	III	I-B
40-80	60%	2.0	2.8	II	I-A	I-A
80-25	53%	4.2	3.1	III	III	III
25-80	53%	2.0	3.1	I-B	I-B	I-B
40-40	40%	3.5	3.5	III	II	II
40-25	33%	4.2	3.8	III	III	II
25-40	33%	3.5	3.8	II	III	III
25-25	25%	4.2	4.2	III	II	III
No obstacle	0%	4.5	4.5	IV	IV	IV

* d/λ was calculated for the second obstacle located further from the ignition point

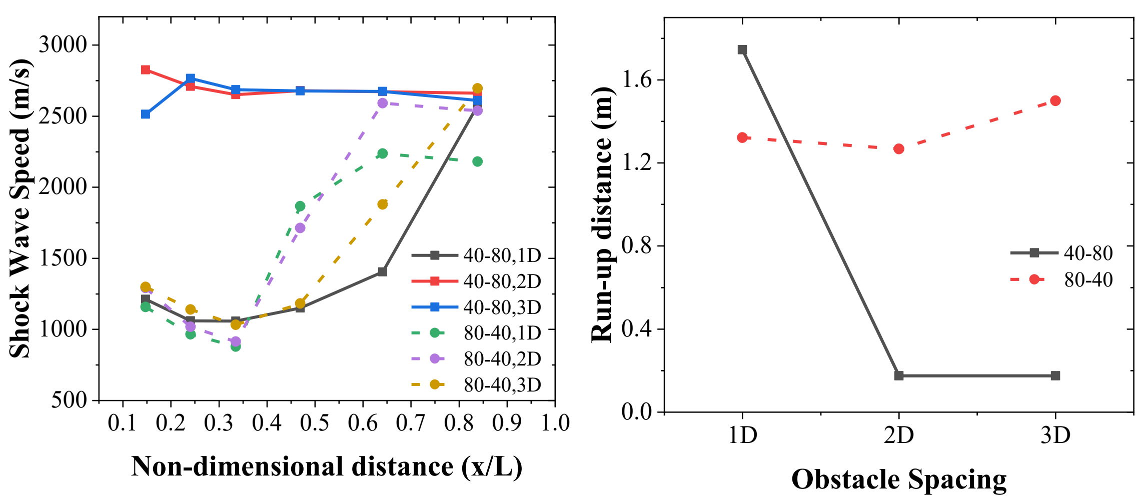

Figure 4. Comparison between obstacle pairs with an equivalent average blockage ratio.

4 Concluding Remarks

Experiments on flame propagation and DDT were carried out in stoichiometric, premixed hydrogen-oxygen mixtures at 150 torr in a closed tube with two obstacles of varying configuration. Round-shaped obstacles with three different blockages (25%, 40%, and 80%) were used, and the arrangement between the obstacles was changed in terms of blockage distribution (increasing, decreasing, and equivalent) and obstacle distance (1D, 2D, and 3D). Four distinct propagation behaviors were identified based on the time between the leading wave and the onset of DDT. From the conditions tested, obstacle pairs with a higher blockage in the second obstruction lead to stronger combustion. It was observed that obstructions with equivalent blockage resulted in distinct propagation characteristics and explosion strength. This study is still in progress, and additional experiments will be conducted to better understand the mechanisms underlining these different behaviors.

References

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