# Visualization of Deflagration-to-detonation Transitions in a Channel with Repeated Obstacles

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## 1 Introduction

It is generally known that combustion waves propagated in a premixed gas can be classified as either deflagration waves or detonation waves. A detonation wave rarely initiated simultaneously with the ignition, unless an extremely high-ignition energy is supplied to the premixed gas. In a confined tube, a deflagration-to-detonation transition (DDT) [1] produces a detonation wave through a successive acceleration of the deflagration wave ignited by using a relatively small ignition energy. The existence of the DDT process has great importance for practical applications or explosion hazards involved with a detonation wave. Because a weak ignition source causes to initiate a detonation wave that produces a high-pressure combustion product. In a tube having a smooth inner wall, the distance from an ignition source to the point of the detonation onset becomes comparatively long. Inserting a spiral-coil (often called as Schelkin spiral) [2] into a tube is commonly used to shorten the DDT distance. The role of the spiral-coil is to produce turbulent flow ahead of the deflagration wave, thus increasing the propagation velocity of the deflagration wave, causing DDT via a local explosion. It has been argued that an obstacle influences the flame acceleration by causing positive coupling between the flame and a turbulence [3]. An induction time gradient obtained by the turbulent mixing leads to the initiation of a detonation wave, and this is proposed as the SWACER mechanism [3]. A deflagration wave, propagated at about half of the Chapman–Jouguet (C–J) detonation velocity, has been shown to cause successful detonation initiation.

The numerical simulation [4] of the flame acceleration and detonation transition in the channel with repeated obstacles demonstrated that an eddy behind an obstacle increased an area of flame surface and hence a flame velocity. The detonation transition occurred when the Mach-stem created by the reflection of the leading shock wave from the bottom wall collides with an obstacle. Experimental investigations of turbulent flames and DDT in a channel with obstacles have been widely conducted [5-8]. The comprehensive propagation regimes were classified into four regimes such as quenching, choking, quasi-detonation and detonation by detecting the terminal flame velocity [5, 6]. The flame acceleration of a re-circulation zone between obstacles has been pointed out [7]. The effects of scale on the detonation onset have shown that the detonation cell-width $\lambda$ is a reliable parameter for scaling the detonation onset conditions [8]. Recently, Obara et al. [9] conducted the multi-frame visualization of the DDT process above repeated obstacles using a high-speed video camera. Their results demonstrated that the flame front was accelerated by the vortex behind the obstacles, and the interaction between the accelerated flame front and the shock wave triggered the local explosion that lead to onset of detonations.

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The present study addresses issues concerning DDT mechanisms above repeated obstacles in a stoichiometric premixed oxy-hydrogen gas, and the experiments are carried out primarily by time-resolved visualization of DDT phenomena using a high-speed video camera. Visualization from two orthogonal directions was conducted to discuss the three-dimensional spatial evolutions of a deflagration wave behind obstacles and the final onset of detonation wave.

## 2 Experimental Setup and Conditions

Figure 1 shows the schematic diagram of the experimental setup. The detonation tube having 0.58 m length was connected with the dump tube of 4 m length. The inner cross-section of the tube was rectangular with 100 mm width and 100 mm height. A plate of 15 mm thickness was installed on the whole length of the bottom wall of detonation tube, and thus the inner cross-section of the channel became 85 mm height by 100 mm width. The equally-spaced repeated obstacles were able to set up on the whole length of the bottom plate. However, in the results of visualization shown later, only three or four obstacles were installed. Each obstacle had 5 mm width and a defined height. The spacing between the obstacles was 60 mm which was defined as the distance between upstream faces of adjacent obstacles. Note that the first obstacle was placed at 20 mm downstream from the end wall regardless of a spacing of the obstacles. The detonation tube was filled with an oxy-hydrogen premixed gas, and the dump tube was evacuated in advance. The two tubes were separated by inserting a Mylar film. A pair of optical glass windows of width 200 mm and height 100 mm was installed in the detonation tube for an optical access. The field of view existed 115 to 315 mm downstream from the end-wall. A spark plug was installed at the end-wall of the detonation tube, thus combustion wave propagates rightward. A double-mirror Z-configuration schlieren system was used for visualizing the flow field. A high-speed video camera (Ultra Cam HS-106E, nac Image Technology, Inc.) was used for time-resolved recordings, with an inter-frame time of 2 μs and an exposure time of 100 ns for each frame. This video camera can capture high-speed sequences of a total of 120 frames with resolutions of 410 × 360 pixels.

In this study, the flow filed was visualized from two orthogonal directions, as shown in Fig. 2. In the (a) transverse view, the obstacles were visualized from a lateral direction. Therefore, the flow field along the depth of the obstacle was superimposed on the recorded images. In the (b) underside view, the obstacles were equipped in such a way that the bottom surface of the obstacles was on the glass window. Therefore, the obstacles were visualized from underneath, and the flow field along the height of the obstacle was superimposed on the recorded images.

The experimental conditions are shown in Table 1. The test gas used to fill the detonation tube is a stoichiometric premixed gas of oxy-hydrogen, and the initial pressure is constant at 70 kPa. Every experiment is conducted with a room temperature. The spacing and width of the obstacles are constant at 60 and 5 mm, respectively. The height and number of the obstacle were varied as 5 or 15 mm and 3 or 4, respectively.

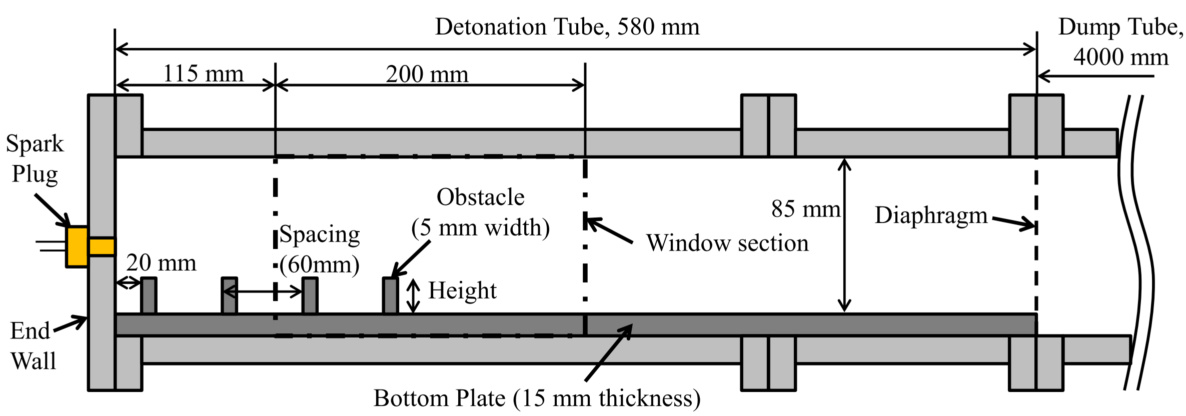



Figure 1. Schematic of experimental setup (cross section view)

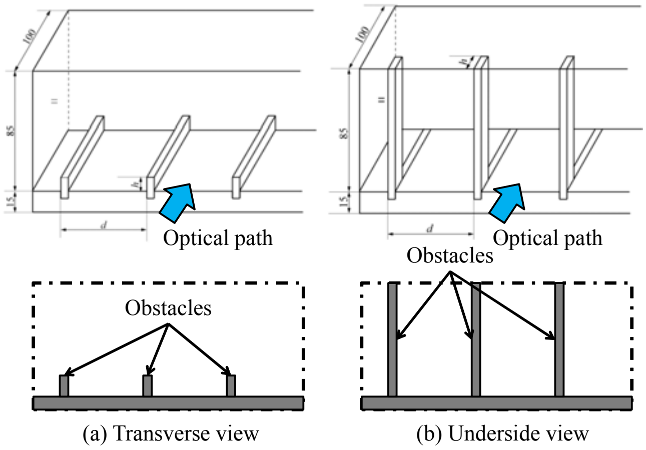



Figure 2. Schematic of optical view

Table 1. Experimental condition

| Test gas | Repeated obstacles | | | |
|---|---|---|---|---|
| | Spacing | Width | Height | Number |
| | mm | mm | mm | - |
| $2H_2 + O_2$, 70 kPa, room temp. | 60 | 5 | 5 | 3 |
| | | | 15 | 4 |

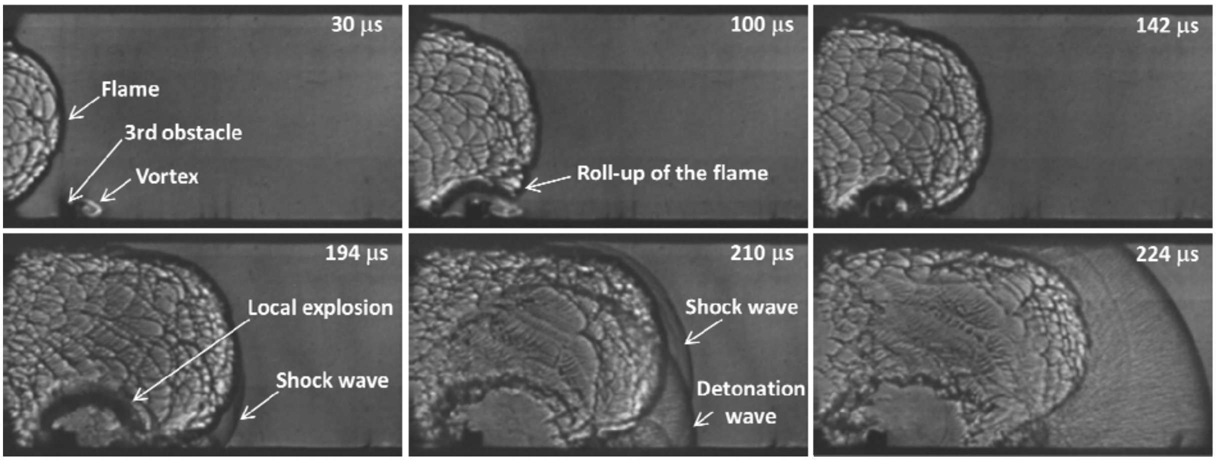
## 3 Results and Discussion

In the preliminary experiments, the conditions of repeated obstacles (spacing, width and height) were listed in Table 1, and were installed on the whole length of the detonation tube. In these conditions, DDT was observed within the range of the window section. The detonation transition followed by a local explosion was observed just downstream of the third or fourth obstacle for the case of obstacle height of 5 or 15 mm, respectively. Dorofeev et al. [8] suggested the characteristic geometrical size $L$ required for a detonation transition inside a channel with repeated obstacles. The size $L$ was defined as the following equation,

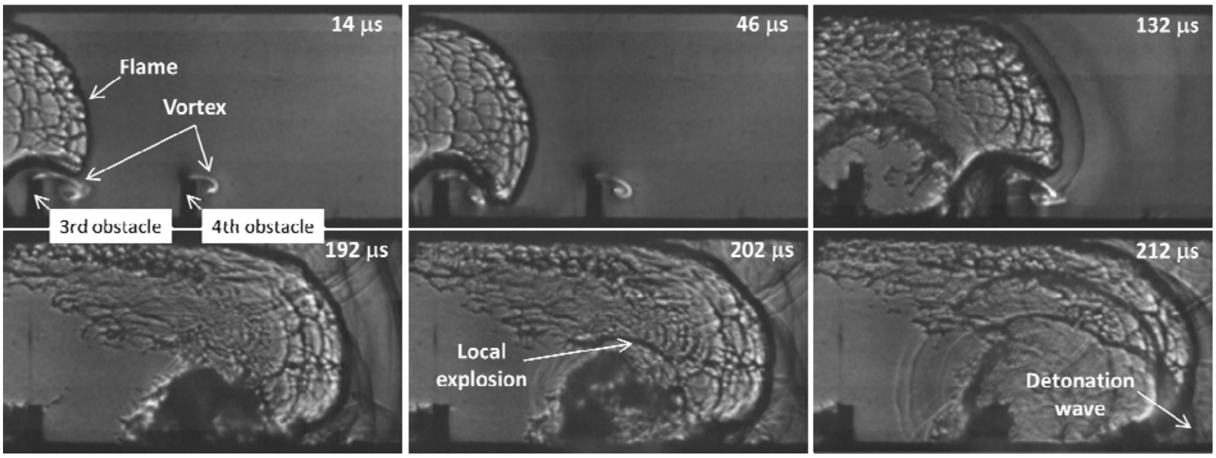
$$L = \frac{S}{1 - d/H}$$

where $S$ was the spacing between two opposite faces of the adjacent obstacles, $H$ was a channel height and $d$ was an opening channel height above obstacles. In our experiments, the parameters were $S$ = 55 mm, $H$ = 85 mm, $d$ = 80 mm or 70 mm for 5 mm or 15 mm of the obstacle height, respectively. Dorofeev et al. empirically demonstrated that detonation transition required the minimum value of $L$ to be seven times a cell width of an initially filled premixed gas. The $L \geqq 7\lambda$ criterion was derived from the experimental implication of the required minimum distance for a detonation formation, that is the minimum size of a sensitized unreacted mixture. In our experiment, the channel height was comparatively large to the obstacle height, and the test gas used was a stoichiometric oxy-hydrogen mixture as a very reactive gas, therefore the value of $L$ was extremely high as a few hundred times the cell width. The concept of the characteristic size $L$ was not related to a DDT distance which was the distance from an ignition point to a location of detonation transition, however, such the very reactive condition of our experiment led to short DDT distances within few obstacles. One of the trigger for a detonation transition in a channel with repeated obstacles were numerically demonstrated by Gamezo et al. [4]. Sufficiently strong leading shock ahead of a turbulent flame front created a hot spot by reflection with an upstream face of an obstacle. In this paper, we show the results of the case for removing the obstacles which were installed downstream the obstacle where DDT was occurred (third or fourth obstacle for the obstacle height of the 5 mm or 15 mm, respectively) in the preliminary experiments. Therefore, the effect of reflection of a leading shock with the obstacle was removed as the trigger for detonation transition.

Figure 3 shows the multi-flame schlieren images in the transverse view obtained in two cases of the obstacle heights. Figure 3 (a) and (b) are the results for the obstacle height of 5 mm and 15 mm, respectively. The time addressed on each frame is an elapsed time from triggering the high-speed camera. Note that the time intervals between each frame are not constant. Figure 3 clearly shows convoluted flame front and the detonation transition from the localized strong explosion behind the obstacle. The location of the DDT was the same as that observed in the case in which the obstacles were installed on the whole length of the detonation tube. In these conditions, the averaged propagation velocity of the preceding flame front above the repeated obstacles was about 400 to 500 m/s. This velocity is much lower than an acoustic speed of combustion products (over 1000 m/s) which is commonly observed flame velocity prior to a detonation transition while a DDT event. Therefore, the leading shock ahead of the flame front is not considered to be so much strong as creating a hot spot that leads to a detonation transition. From Fig. 3, the local explosion and following detonation transition occurred downstream of the obstacle where the flame front was convoluted. Mixing of the unreacted and reacted gas in the convoluted turbulent flame front was considered to be the dominant factor for the detonation transition, as indicated in studies of a jet initiation [10]. The hemi-spherical detonation wave observed in the last frame of Fig. 3 propagated with the velocity of about 3000 m/s which was higher than the Chapman-Jouguet velocity (2800 m/s) calculated for the initial unreacted gas, therefore the detonation wave just after the DDT onset was overdriven state.




(a) Obstacle height: 5 mm

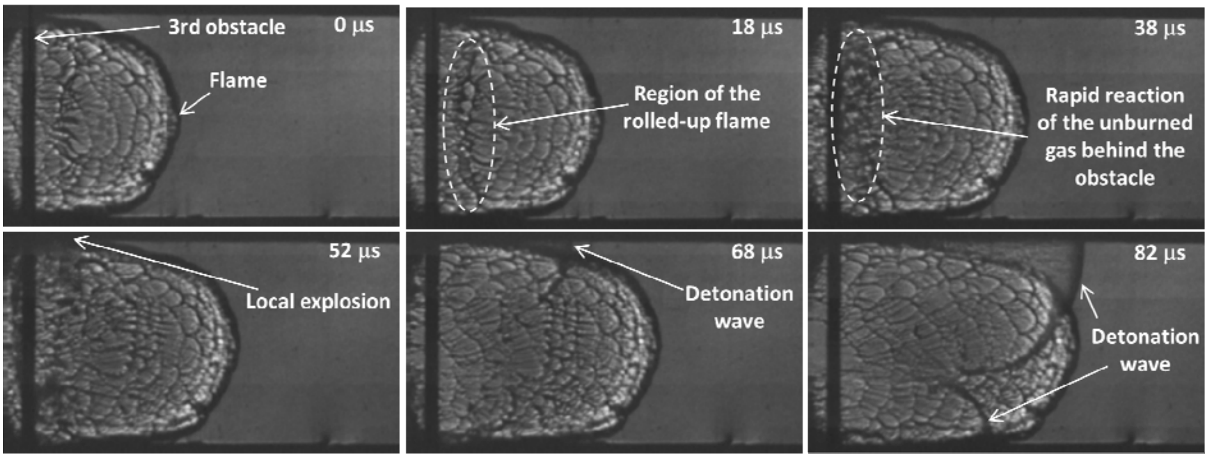



(b) Obstacle height: 15 mm

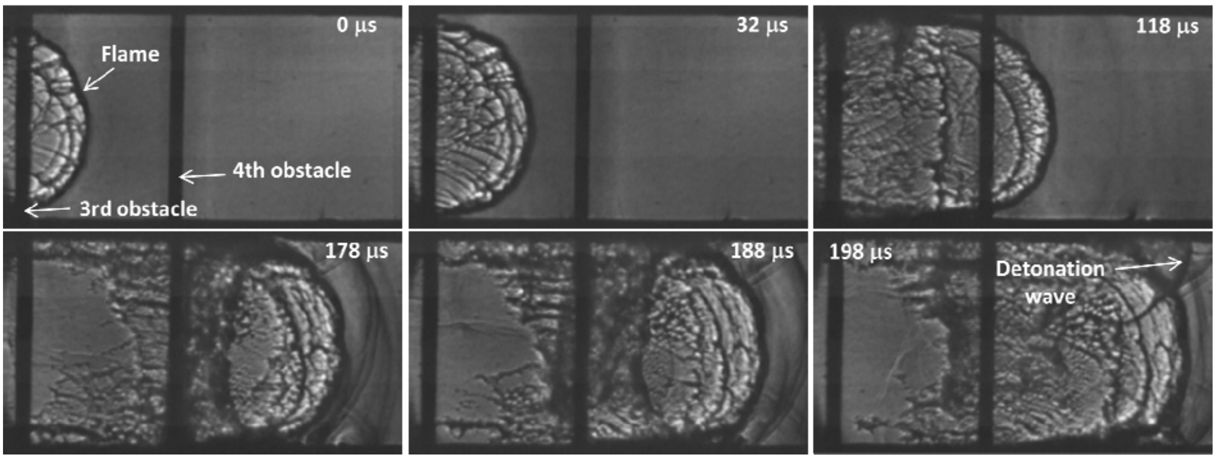
Figure 3. Multi-flame recordings from the transverse view ($2H_2 + O_2$, 70 kPa, obstacle spacing 60 mm)

The detonation transition would occurred as the localized phenomenon at somewhere behind the obstacle, however, the transverse view shown in Fig. 3 could not present where the local explosion occurred along the channel depth.

Figure 4 shows the underside view obtained in the same conditions as Fig. 3. Figure 4 (a) and (b) are the results of the obstacle height of 5 mm and 15 mm, respectively. The underside view shows the evolution of phenomena along the channel depth which could not be detected in Fig. 3. The first frame in Fig. 4 (b) is chosen so as to almost accord the location of the tip of the preceding flame front with that in the first frame of Fig. 3 (b), and the time intervals between each frame also coincide with Fig. 3 (b). The first frame in Fig. 4 (a) is chosen so as to almost accord the location of the tip of the preceding flame front with that in the third frame (142 μs) of Fig. 3 (a). Figures 3 and 4 are the same condition, however they are obtained by different shot. During 38 to 52 μs in Fig. 4 (a), it is observed that a rapid reaction was progressed from the center to upper and lower direction where an unreacted gas remained downstream the third obstacle. Accordingly, the detonation transition occurred at the upper and lower position of the frame, that is the corner surrounded by the obstacle, the side and bottom wall of the detonation tube. This would be understood from the shape of the hemi-spherical detonation wave in 82 μs. Figure 4 (b) shows similar phenomena behind the fourth obstacle. These new observation from the underside view demonstrated that the three-dimensional effects behind the obstacle would trigger the detonation transition phenomenon.




(a) Obstacle height: 5 mm




(b) Obstacle height: 15 mm

Figure 4. Multi-flame recordings from the underside view ($2H_2 + O_2$, 70 kPa, obstacle spacing 60 mm)

## 4 Conclusions

In the present study, an oxy-hydrogen premixed gas with an initial pressure of 70 kPa was ignited, and behaviors of a deflagration-to-detonation transition phenomenon above repeated obstacles were visualized using a high-speed video camera. The rectangular obstacles with 5 mm width were attached at regular intervals of 60 mm in the bottom wall of the detonation tube which had the rectangular

cross-section with 85 mm height and 100 mm depth. The obstacle height was varied as 5 or 15 mm. The flow field was visualized from two orthogonal directions using a schlieren system. These are the transverse view and underside view observing the obstacles from a lateral view and from underneath, respectively.
Detonation transition occurred at a short distance from the ignition at the end wall of the detonation tube. The location of the transition was the third or fourth obstacle for the obstacle height of the 5 mm or 15 mm, respectively. Because of the very reactive premixed gas conditions, the detonation transition occurred without a strong leading shock or its reflection with obstacles which was previously pointed out by Gamezo et al. (2007) as the one of mechanisms for a detonation transition. In this study, this was also confirmed by removing the obstacles which were installed downstream the obstacle where the DDT was occurred. Visualization from the transverse view showed that the local explosion and following detonation transition occurred downstream of the obstacle where the flame front was convoluted. Mixing of the unreacted and reacted gas in the convoluted turbulent flame front would be the dominant contributing factor to trigger the detonation transition, as indicated in studies of a jet initiation. The visualization from the underside view showed that a rapid reaction was progressed along the obstacle depth where the unreacted gas remained downstream of the obstacle. Accordingly, the detonation transition occurred at the corner surrounded by the obstacle, the side and bottom wall of the detonation tube. The new observation from the underside view demonstrated that the three-dimensional effects were of significance on the detonation transition.

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