

# Re-initiation Mechanisms of Gaseous Detonation Wave Propagated through Double Slits

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## 1. Introduction

The study to investigate quenching mechanism of a detonation wave utilizing a slit is of particular importance by considering safety devices to suppress the detonation wave in industries, where flammable gases are handled [1,2]. The detonation wave is disintegrated into a shock wave and reaction front propagated through the slit, since expansion waves generated at a corner of the slit have effects to decrease a temperature and reaction rate behind the shock wave. However, it is understood that the shock wave diffracted from the slit causes re-initiation and transited to detonation wave at downstream region, even though a diameter of open-area is smaller than critical tube diameter [1,2]. It is also well known that the reaction front can accelerate rapidly to a supersonic velocity by propagating over an obstacle. Mitrovanov and Soloukhin [3] reported and it was also confirmed by Edward et al. [4] that the critical value to distinguish the propagation of detonation wave is about  $13\lambda$  for circular tube and about  $10\lambda$  for rectangular channel, where  $\lambda$  is a cell size of stable detonation wave. A fundamental observation carried out by Moen et al. [5] clarified that if the turbulence intensity is maintained by placing obstacles, the reaction rate and degree of turbulence become highly coupled. On the other hand, it is also discussed that higher turbulence intensity can inhibit flame propagation by inducing local quenching at the reaction front. Furthermore, experiment and numerical simulation of decoupling and recoupling processes behind sudden expansion of a tube were done by Pantow et al. [6], Ohyagi et al. [7] and Khasainov et al. [8] to show re-initiation processes of detonation wave after decoupled by diffraction processes. These results showed that reflected shock wave and Mach reflection could be a source to re-initiate a detonation wave. However, fundamental mechanisms of re-initiation processes of detonation wave by the interaction of shock wave with another shock waves or tube-wall are still open questions.

In this study, experiments were conducted in order to elucidate the re-initiation mechanisms of detonation wave by installing slit-plate into a detonation tube filled with premixed gas mixture of hydro-gen and oxygen. A width of slit, a distance between two slits and initial pressure of test gas mixture were varied and re-initiation processes were visualized using high-speed video camera with schlieren optical system.

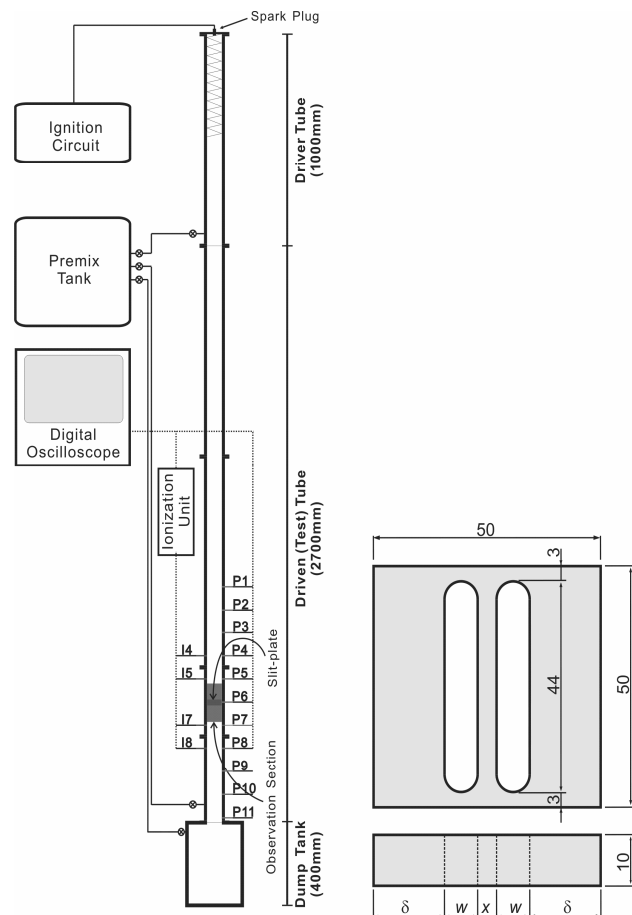


Fig. 1 Schematic diagram of experimental setup and configuration of slit-plate

## 2. Experimental Setup

Figure 1 shows schematic diagram of experimental set-up and configuration of a slit-plate. The detonation tube has square cross section of 50 mm and 4100 mm in total length. The tube was divided into three sections, i.e. driver section of 1000 mm, driven section of 2700 mm including observation section and dump tank of 400 mm to decay the detonation wave. In observation section, measuring stations named from P1 to P11 were mounted with an interval of 100 mm. Mylar film of 25  $\mu\text{m}$  thickness was inserted between driver section and driven section to separate driver gas and test gas, which were filled with different initial pressure. A Shchelkin spiral coil of 500 mm length and 38 mm pitch was inserted at the top of driver section to decrease detonation induction distance. An automobile ignition plug was also installed at the top of driver section to ignite driver gas. A slit-plate having of 50 mm length and 10 mm thickness was inserted at position P6 of observation section. A width of slit  $w$  and a distance between two slits  $x$  were varied as shown in table 1. To record pressure profile, four pressure transducers (PCB, model 113A24) were installed at position P4, P5, P7 and P8 as shown in fig. 1. The arrival time of the reaction front was detected by four ionization probes I4, I5, I7 and I8, which were oppositely installed to pressure transducers. Output signals of these probes were stored by digital oscilloscope (Yokogawa, model DL750) to record a profile of shock wave and reaction front. In order to visualize re-initiation processes of detonation wave, high-speed video camera (Shimadzu Corp., model HPV-1) was used with a help of schlieren technique. To evaluate a re-initiation distance of detonation wave from the end of slit-plate, soot track record was also acquired behind the plate. A stoichiometric mixture of hydrogen and oxygen with initial pressure of 100 kPa was used as driver gas and initial pressure ranged from 10 to 100 kPa was used as test gas.

Table 1 Code of slit-plate

| Slit-Plate Code | $w$<br>(mm) | $x$<br>(mm) |
|-----------------|-------------|-------------|
| 8-10-8          | 8           | 10          |
| 8-5-8           | 8           | 5           |
| 8-2-8           | 8           | 2           |
| 5-10-5          | 5           | 10          |
| 5-5-5           | 5           | 5           |
| 5-2-5           | 5           | 2           |

## 3. Results

According to an observation of soot track records, re-initiation of detonation wave is always occurred behind the slit plate, even though for low-initial pressure of test gas such as  $p_0 = 10$  kPa. Based on visualization and soot track record, re-initiation behind slit-plate can be mainly classified into two types, i.e. the detonation wave is re-initiated by the interaction of two diffracted shock waves or by the interaction of shock wave with tube wall. These two types of re-initiation process are described in the following sections.

### 3.1 Case detonation wave is re-initiated by interaction of two shock waves (Type SSI)

Figure 2 is sequential photograph of high-speed video camera showing diffraction and re-initiation process of detonation wave behind a slit-plate. A frame interval of these photographs is 1  $\mu\text{s}$  and exposure time of each frame was 500 ns. A detonation wave is propagated to downward direction. A slit-plate of  $w = 8$  mm,  $x = 10$  mm was used with initial pressure of  $p_0 = 40$  kPa. In this case, the cells size of detonation wave is about 5.5 mm, it means that  $w/\lambda$  ratio is larger than unity. Two shock waves (IS) diffracted from two slits are separated from a reaction front (RF) which is clearly identified in a frame of  $t = 6$   $\mu\text{s}$ . Incident shock waves, propagated ahead of reaction front with propagation velocity of about 2,370 m/s, interact each other at a center of slit-plate. This interaction produces high-energy enough to generate local explosion just behind the plate, which can generate local explosion shock wave indicated as ES. This local explosion shock wave propagated spherically as clearly shown in a frame of  $t = 9$   $\mu\text{s}$ . Since the local explosion shock wave propagating to upstream direction is not followed by reaction front, the velocity of the shock is decelerated to 1,500 m/s. However, explosion shock wave

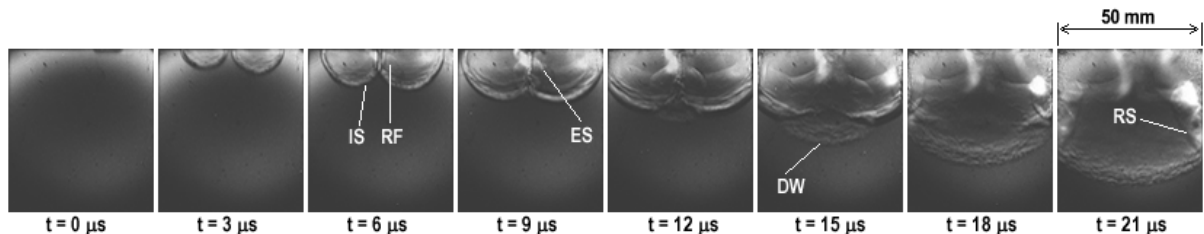


Fig. 2 Sequential schlieren photograph showing re-initiation process, where detonation wave is re-initiated by the first interaction of both shock waves, IFT = 1  $\mu\text{s}$ ,  $p_0 = 40$  kPa,  $w = 8$  mm,  $x = 5$  mm (IS: incident shock wave, RF: reaction front, ES: explosion shock, DW: detonation wave, RS: reflected shock)

propagated to downstream direction (unburned gas mixture region) has high-energy enough to produce detonation wave. According to frames from  $t = 9 \mu\text{s}$  to  $t = 21 \mu\text{s}$ , the propagation velocity of initial detonation wave is estimated as 3,200 m/s, which is greater than Chapman-Jouguet (C-J) detonation velocity of 2,794 m/s. Therefore, this detonation wave is classified as overdriven detonation wave and it is quickly decelerated to the propagation velocity of C-J velocity. These results indicate that local explosion shock wave, generated by the interaction of the diffracted shock wave behind slit-plate plays key role to re-initiate the detonation wave and this case is classified as type SSI1 (re-initiated by first interaction of shock wave with shock wave).

### 3.2 Case detonation wave is re-initiated by interaction of shock wave with wall (Type SWI)

Figure 3 is sequential schlieren photograph of high-speed video camera showing re-initiation process of detonation wave behind slit-plate. A frame interval and exposure time is same as Fig. 2, while slit-plate of  $w = 5 \text{ mm}$ ,  $x = 10 \text{ mm}$  is used with initial pressure of  $p_0 = 50 \text{ kPa}$ . In this case, incident shock wave is propagated with a velocity of 2,180 m/s before interaction of shock wave with shock wave. A local explosion shock wave (ES) is also generated at  $t = 13 \mu\text{s}$  and propagated with a velocity of 2,200 m/s. On the contrary, the detonation wave is not re-initiated by local explosion of interaction of diffracted shock waves, it might be due to the lower value of  $w/\lambda$  ratio than case of Fig. 2. The local explosion shock wave (ES) overtakes the incident shock wave (IS) at a frame of  $t = 19 \mu\text{s}$  and this coupled shock wave is reflected from a tube-wall at later stage from  $t = 19 \mu\text{s}$ . This shock wave reflection behavior reveals Mach reflection as shown in a frame of  $t = 28 \mu\text{s}$ , where Mach stem is observed along the wall. Eventually, overdriven detonation wave is re-initiated, indicated as DW in a frame of  $t = 34 \mu\text{s}$ . This behavior of re-initiation process is classified as type SWI1 (re-initiated by first interaction of shock wave with wall).

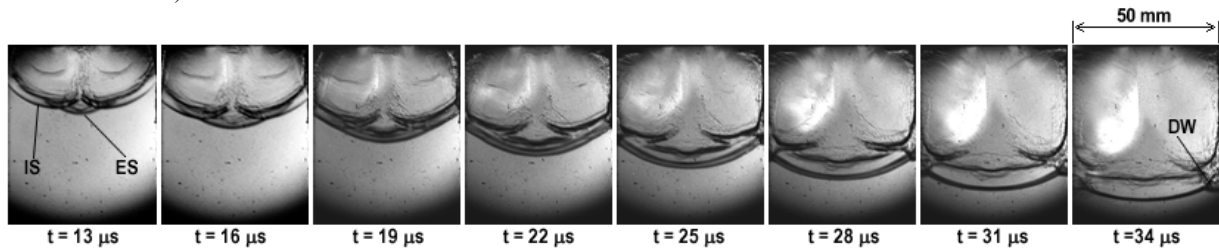


Fig. 3 Sequential schlieren photograph showing re-initiation process, where detonation wave is re-initiated by the first interaction of shock wave with wall, IFT = 1  $\mu\text{s}$ ,  $p_0 = 50 \text{ kPa}$ ,  $w = 5 \text{ mm}$ ,  $x = 10 \text{ mm}$  (IS: incident shock wave, ES: local explosion shock, DW: detonation wave)

### 3.3 Re-initiation processes observed by soot track record

Figure 4 shows soot track records and re-initiation processes of detonation wave of four representatives observed in this experiment. Figure 4(a) is a case of the first shock-shock interaction, named as type SSI1 where detonation wave is re-initiated by direct interaction of shock waves at center of the tube. This interaction induces overdriven detonation wave at a region indicated as RI, where fine detonation cellular pattern is observed. Since, incident shock wave and local explosion shock wave are coupled and interacted with wall, re-initiation of detonation wave characterized by type SWI1 is shown in fig. 4(b). Figure 4(c) is obtained by decreasing initial pressure of gas from 50 kPa to 20 kPa. In this case, re-initiation is not occurred by both types SSI1 and SWI1, but is occurred by second interaction of reflected shock waves at center. This type of re-initiation is named as SSI2. This collision produces hot-spot region at center of tube and strong Mach stem, which is identified with white region at position of shock-shock interaction. As shown in fig. 4(c), overdriven detonation wave is transited to stable detonation at downstream region, where cell size becomes relatively larger.

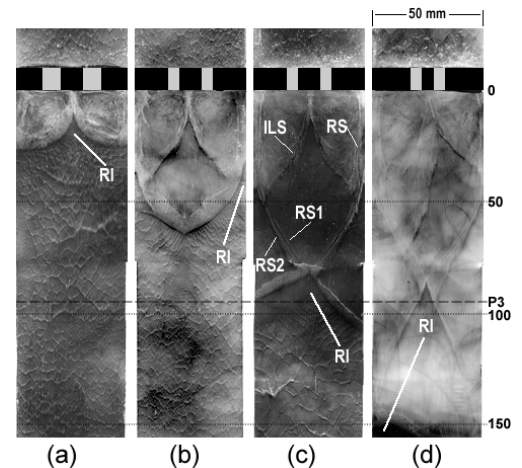


Fig. 4 Soot track record of detonation wave, (a) SSI1, slit-plate 8-10-8,  $p_0 = 40 \text{ kPa}$ , (b) SWI1, slit-plate 5-10-5,  $p_0 = 50 \text{ kPa}$ , (c) SSI2, slit-plate 5-10-5,  $p_0 = 20 \text{ kPa}$ , (d) SWI2, slit-plate 5-5-5,  $p_0 = 20 \text{ kPa}$

Figure 4(d) is a case where distance between the slit  $x$  is changed to 5 mm and initial pressure of test gas is same as fig. 4(c). In this case, interaction of incident shock wave, emerged from slits cannot produce strong local explosion below the slit-plate. The diffracted shock waves are reflected from the wall at second times, and then re-initiate of detonation wave is occurred. This type of re-initiation is named as SWI2.

#### 4. Discussion

As is described above, the re-initiation distance  $D_{ri}$  from the end of the slit-plate is changed by the width of slit  $w$ , distance between two slits  $x$  and initial pressure of test gas mixture  $p_0$ . The re-initiation distance of detonation wave  $D_{ri}$  may be correlated using width of slit  $w$  and cell size  $\lambda$ , which is inversely proportional to a reaction rate of the test gas. Figure 5 shows a relationship between re-initiation distance and width of the slit. A vertical axis is re-initiation distance  $D_{ri}$  normalized by the width of the tube  $L$ , horizontal axis is width of slit  $w$  normalized by cell size  $\lambda$ . Non-dimensional re-initiation distance is on the decrease as the  $w/\lambda$  is increased. Furthermore, most of the re-initiation type named SSI1 is occurred for the condition  $w/\lambda$  is greater than unity. Therefore, direct re-initiation of detonation wave by the first interaction of diffracted shock waves is occurred for experimental condition that at least one cell is emerged from the slit. When non-dimensional distance  $w/\lambda$  is less than unity, the detonation wave is re-initiated by the types SWI1, SSI2 and SWI2.

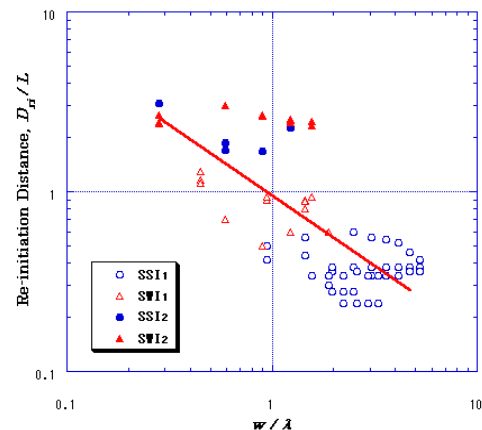


Fig. 5 Relationship of non-dimensional re-initiation distance  $D_{ri}/L$  and non-dimensional width of slit  $w/\lambda$

#### 5. Conclusions

Experiments were conducted in order to investigate the re-initiation processes of detonation wave utilizing slit-plate and schlieren photograph was obtained to show re-initiation processes of detonation. When a detonation wave is propagated through the slit, it is consistent that the detonation wave fails temporarily to transmit, even though at relatively high-initial pressure. Shock waves diffracted from the slit interact each other at center of the tube and local explosion generated by hot spot is observed and it produces an explosion shock wave. This explosion shock wave is enough to re-initiate the detonation wave for the case that  $w/\lambda$  is greater than unity. The detonation wave is re-initiated by shock-wall interaction for the case that  $w/\lambda$  is less than unity.

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