Re-initiation of detonation wave behind slit-plate

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1 Introduction

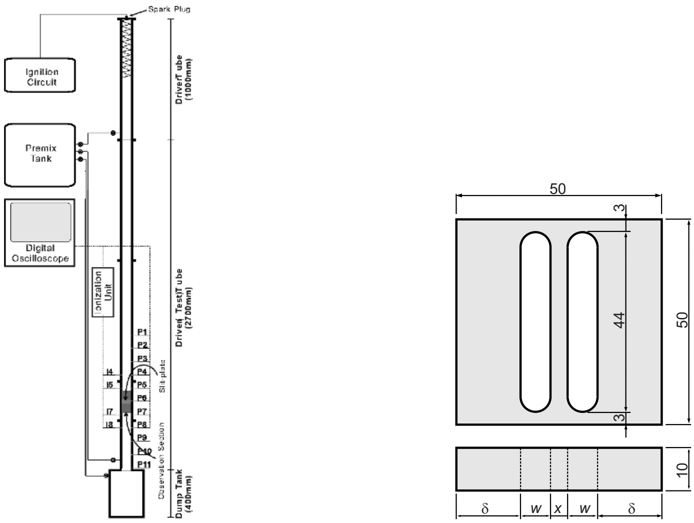
The study to investigate a quenching mechanism of detonation wave utilizing a slit is of particular importance by considering safety devices to suppress the detonation wave in industries where flammable gases are handled [1,2]. The detonation wave propagated through the slit is disintegrated into a shock wave and a reaction front, 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 reaction front can accelerate rapidly to supersonic velocity when propagating over obstacles. Mitrovanov and Soloukhin [3] reported and was also confirmed by Edward et al. [4] that the critical value to distinguish the propagation of detonation wave is about 13λ for circular tube and about 10λ for rectangular channel, where λ is a cell size of stable detonation wave.

A fundamental observation carried out by Moen et al. [5] clarified if the turbulence intensity is maintained by placing obstacles, the reaction rate and degree of turbulence become highly coupled. Furthermore, experiment and numerical simulation of decoupling and re-coupling processes behind sudden expansion of a tube were conducted by Pantow et al. [6] and Ohyagi et al. [7] to show re-initiation processes of detonation wave after decoupled by diffraction process. 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 wave or tube wall are still open questions.

In this study, experiments are carried out in order to elucidate the re-initiation mechanisms of detonation wave by installing the slit-plate into a detonation tube filled with premixed gas of hydrogen and oxygen. A width of slit w, a distance between two slits x and initial pressure of test gas p_0 are varied and re-initiation processes are visualized using high-speed image converter camera with schlieren optical system.

2 Experimental Setup

Figure 1(a) shows schematic diagram of experimental setup of detonation tube used in this study. The detonation tube has square cross section of 50 mm and 4,100 mm in total length. The tube was divided into three sections, i.e. driver section of 1,000 mm, driven section of 2,700 mm including observation section, and dump tank of 400 mm to decay the detonation wave. In observation section, measuring stations named from



(a) (b)

Fig. 1. (a) Schematic diagram of experimental setup and (b) configuration of slit-plate

P1 to P11 were mounted with an interval of 100 mm. Mylar film of 25 μm thickness was inserted between driver section and driven one to separate driver gas and test gas, which were filled with different initial pressure of gas mixture. The Shchelkin spiral coil of 500 mm length, 38 mm pitch was inserted at driver section to decrease detonation induction distance. An automobile ignition plug was also installed at top of the driver section to ignite driver gas.

Figure 1(b) shows configuration of slit-plate used as model in this experiment. A slit-plate having dimension of 50 mm square and 10 mm thickness was inserted at P6 of observation section. A width of slit w and a distance between two slits x were varied as shown in table 1(a).

To record pressure profile of shock wave, four pressure transducers (PCB, model 113A24) were installed at position P4, P5, P7 and P8 as shown in Fig. 1(a). The arrival time of reaction fronts were detected by four ionization probes I4, I5, I6 and I7, oppositely installed to pressure transducers. The outputs of these probes were stored by eight channels digital oscilloscope (Yokogawa, model DL750) to record a profile of shock

Table 1. (a) Slit-plate configuration and (b) initial condition of gas mixture

(a)

Slit-Plate Code	w (mm)	x (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

(b)

	Driver Section	Driven Section
Fuel	H_2	H_2
Oxidizer	O_2	O_2
Equivalence ratio	1	1
Initial pressure (kPa)	100	10 ~ 100

wave and reaction front. The phenomenon of re-initiation processes of detonation wave was visualized by using high-speed schlieren photographs with image converter camera (IMACON 792, Hadland Photonics). Soot track records of detonation wave at upstream and downstream region of slit plate were also taken in order to evaluate a re-initiation distance of detonation wave from the end of slit-plate.

A stoichiometric mixture of hydrogen and oxygen with initial pressure of 100 kPa was used as driver gas and initial pressure p_0 ranged from 10 $\sim$ 100 kPa was used as test gas. An initial condition of gas mixture is shown in Table 1(b).

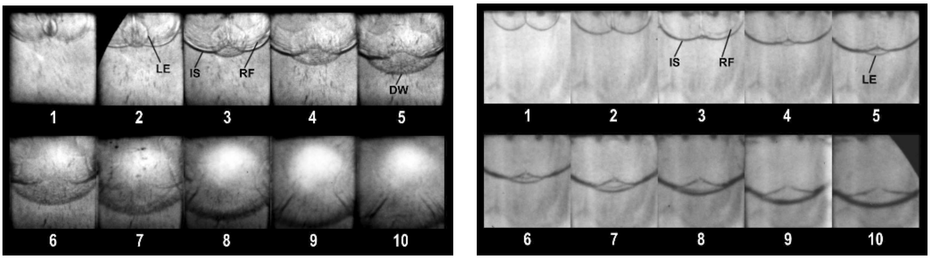
3 Results

Based on a photograph taken by high-speed image converter camera, soot track record and pressure histories, re-initiation of detonation wave behind slit-plate could be classified into mainly two types, i.e. the detonation wave is re-initiated by the interaction of two shock waves (SSI) and by interaction of shock wave with wall (SWI). Furthermore, based on repetition of interaction, re-initiation mechanisms are classified into four types, where first time of shock-shock interaction (SSI1), second times of shock-shock interaction (SSI2), first time of shock-wall interaction (SWI1) and second times of shock-wall interaction (SWI2).

3.1 The first shock-shock interaction (SSI1)

Figure 2(a) is sequential photograph showing diffraction and re-initiation process of detonation wave behind a slit-plate for case of $w = 8$ mm, $x = 10$ mm and initial pressure of $p_0 = 40$ kPa. This result corresponds to soot track record as shown in Fig. 3(a-I), which is obtained with same experimental condition. A detonation wave is propagated to downstream direction. In this case, the cell size of detonation wave is about 5.5 mm, it means that cell number of detonation wave inside the slit is more than unity. A diffracted shock waves (IS) emerged from the slit are decoupled from a reaction front (RF), which is clearly identified in frame number of 1 to 4. The incident shock waves propagated ahead of reaction front has a propagation velocity of about 2,300 m/s interact each other at a center of slit-plate. This interaction produces high-energy enough to generate local explosion just behind the slit-plate. Thereafter, this local explosion generates shock wave indicated as ES, propagated spherically as clearly visible in a frame number 1 to 3. Since the local explosion shock wave is also propagated upstream direction (burned gas region), it is not followed by reaction front and as a result the velocity of the shock wave is decreased to about 1,500 m/s. However, explosion shock wave propagated downstream direction (unburned gas mixture region) directly followed by reaction front with small separation distance, which is indicated as detonation wave. According to frame number 2 and 3, 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.

According to a measurement of velocity and soot track record as shown in Fig. 3(a-I), this detonation wave is classified as overdriven detonation wave. The overdriven detonation wave is quickly decelerated to the propagation velocity of C-J velocity as shown in soot track record image, where cell size becomes relatively larger. These results indicate that local explosion shock wave generated by the interaction of the diffracted shock wave plays key role on the re-initiation of the detonation wave and this is classified as type SSI1 (re-initiated by first interaction of shock wave with shock wave).



(a) (b)

Fig. 2. Sequential schlieren photograph showing (a) re-initiation process of detonation wave by the first shock-shock interaction (IFT = 2 μs, po = 40 kPa, w = 8 mm, x = 5 mm) and (b) re-initiation process of detonation wave by the second shock-shock interaction (IFT = 2 μs, po = 20 kPa, w = 5 mm, x = 10 mm)

3.2 The second shock-shock interaction (SSI2)

Figure 2(b) is sequential schlieren photograph of high-speed video camera showing local explosion due to shock-shock interaction which could not re-initiate detonation wave just behind the slit-plate. A frame interval and exposure time is same as Fig. 2(a), while slit-plate of $w = 5$ mm, $x = 10$ mm is used with initial pressure $p_0 = 20$ kPa. This condition corresponds to soot track record as shown in Fig. 3(a-III). The cell size of detonation wave for this condition is estimated as 9 mm, it means that cell number inside the slit is less than unity. Incident shock waves emerged from the slit are propagated with a velocity of 921 m/s. A local explosion shock wave (ES) is also generated in this case which could be observed at frame number 2 and 3 and propagated with a velocity of 2,177 m/s, lower than C-J velocity of 2,750 m/s. However detonation wave could not be re-initiated by this local explosion because of lower sensitivity of gas mixture and lower velocity of incident shock wave emerged from the slit compared with a case of with Fig. 2(a). The local explosion shock wave (ES) overtakes the incident shock wave (IS) and transits to a strong shock wave shown as black layer in frame number 8 to 10.

The phenomena after frame number of 10 could not be shown in this figure because of limitation of active coverage of camera. However by analyzing soot track record as shown as Fig. 3(a-III), it is confirmed that detonation wave is failed to re-initiate after that the coupled shock wave interact with surface of wall. Later, reflected shock waves generated by interaction of coupled shock wave with surface of wall and propagated transversally collide each other at the center of tube. This collision produces hot-spot region and strong Mach stem at center of tube, which is identified as white region at position of shock-shock interaction. An overdriven detonation wave is re-initiated at downstream of white region as shown as fine detonation cells. As shown in Fig. 3(a-III), the overdriven detonation wave is transited to stable detonation at downstream region, where cell size becomes relatively larger. This behavior of re-initiation process is classified as type SSI2 (re-initiated by second interaction of shock wave with shock wave).

3.3 Re-initiation observed by soot track record

Since coverage area of an image converter camera on the observation section is limited, the re-initiation generated at downstream position is understood by using soot track record.

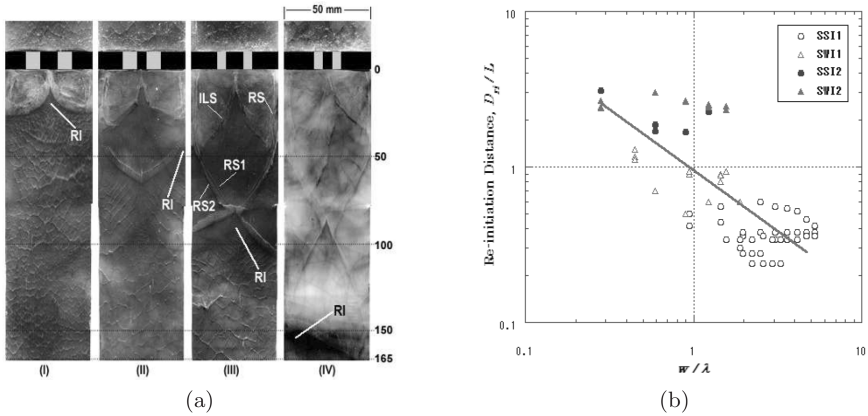


Fig. 3. (a) Soot track record of detonation wave, (I) SSI1, slit-plate 8-10-8, $p_0 = 40$ kPa, (II) SWI1, slit-plate 8-5-8, $p_0 = 20$ kPa, (III) SSI2, slit-plate 5-10-5, $p_0 = 20$ kPa, (IV) SWI2, slit-plate 5-5-5, $p_0 = 20$ kPa and (b) relationship of non-dimensional re-initiation distance D_{ri}/L and non-dimensional width of slit w/λ

Figure 3(a) shows the images of soot track record showing four types of re-initiation processes of detonation wave behind the slit-plate up to 165 mm.

Figure 3(a-I) is a case of the first shock-shock interaction, named as type SSI1 where detonation is re-initiated by direct interaction of diffracted shock waves at center of the tube. This interaction induces overdriven detonation wave at a region indicated as RI, where fine cellular pattern is observed. However the overdriven detonation wave is quickly attenuated to stable detonation wave, which is shown as relatively larger cell size of detonation wave at downstream of re-initiation point.

Figure 3(a-II) is soot track record obtained from a slit-plate of $w = 8$ mm, $x = 5$ mm and initial pressure of driven section of $p_0 = 20$ kPa. In this case, re-initiation of detonation wave is failed at position of shock-shock interaction, incident shock wave and local explosion shock wave are coupled to be strong shock wave and it will interact with surface of wall. The shock wave is reflected from the wall and temperature behind reflected shock wave becomes high value, where compressed unburned gas mixture and turbulent boundary layer have formed. If temperature is high enough, local explosion will be generated and will induce overdriven detonation wave near the surface of wall as indicated as RI in Fig 3(a-II). This type of re-initiation is characterized by type SWI1 (re-initiated by the first interaction of shock wave with surface of wall).

As explained in section 3.2, Fig. 3(a-III) is the case, detonation wave is re-initiation by the second interaction of two shock waves reflected from both wall and propagated transversally. This type of re-initiation would be occurred if re-initiation by both types SSI1 and SWI1 has failed and this type of re-initiation is characterized as SSI2.

Figure 3(a-IV) is a case where distance between the slit x is changed to 5 mm. The initial pressure of test gas is same as Fig. 3(a-III). In this case, interaction of incident shock wave, emerged from slits could not produce strong local explosion below the slit-plate. After four times of interaction, the diffracted shock wave is reflected from the wall secondly to re-initiate the detonation wave at position as indicated as RI in Fig. 3(a-IV). Same as previous re-initiation phenomena, overdriven detonation wave is also observed in this case. This type of re-initiation is named as SWI2 (re-initiated by the second interaction of shock wave with surface of wall).

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 gases p_0. The re-initiation distance of detonation wave D_{ri} might be correlated using width of slit w and cell size λ, which is inversely proportional to a reaction rate of the test gas mixture. Figure 3(b) shows a relationship between re-initiation distance and width of the slit, where vertical axis is re-initiation distance D_{ri} normalized by the width of square detonation tube L, horizontal is width of slit w normalized by cell size λ. Non-dimensional re-initiation distance is decrease as the w/λ is increased. Furthermore, most of the re-initiation type indicated SSI1 is occurred for the condition w/λ is greater than unity. Therefore, the detonation wave directly re-initiated by the first interaction of diffracted shock waves is found for experimental condition that at least one cell is emerged from the slit. When non-dimensional distance w/λ is less than unity, detonation wave has tendency to be re-initiated by the type SWI1, SSI2 or SWI2.

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 wave. When a detonation wave is propagated through the slit, it is consistent that the detonation wave is once failed to transmit, even though relatively high-initial pressure of test gas. Shock waves diffracted from the slit interact each other at center of the tube and local explosion is observed producing explosion shock waves. This explosion shock wave is enough to re-initiate the detonation wave for the case that w/λ is greater than unity. The detonation wave is re-initiated by shock-wall interaction for the case that w/λ is less than unity.

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