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ORIGINAL ARTICLE

Reinitiation process of detonation wave behind a slit-plate

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Abstract The propagation phenomenon of a detonation wave is particularly interesting, because the detonation wave is composed of a 3D shock wave system accompanied by a reaction front. Thus, the passage of a detonation wave draws cellular patterns on a soot-covered plate. The pressure and temperature behind the detonation wave are extremely high and may cause serious damages around the wave. Therefore, it is of great significance from a safety-engineering point of view to decay the detonation wave with a short distance from the origin. In the present study, experiments using high-speed schlieren photography are conducted in order to investigate the behaviors of the detonation wave diffracting from two slits. The detonation wave produced in a stoichiometric mixture of hydrogen and oxygen is propagated through the slits, and the behaviors behind the slit-plate are investigated experimentally. When a detonation wave diffracts from the slits, a shock wave is decoupled with a reaction front. Since the two shock waves propagate from the slits interact with each other at the center behind the plate, the detonation wave is reinitiated by generating a hot-spot sufficient to cause local explosions. Furthermore, it is clarified that the shock wave reflected from a tube-wall is also capable of reinitiating the detonation wave. The reinitiation distance of the detonation wave from the slit-plate is correlated using a number of cells emerged from each slit.

Keywords Detonation wave · Shock wave · Diffraction · Reflection · Reinitiation

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1 Introduction

The pressure and temperature behind a detonation wave is so high that the detonation wave is characterized by a hazardous wave that causes serious damage in the vicinity of the wave. Therefore, initiation processes, propagation features, and quenching mechanisms of the detonation wave are significant from the standpoint of safety and in developing a detonation arrestor technique. Furthermore, the detonation wave is known to be generated by the transition from the deflagration wave called the deflagration to detonation transition (DDT) process [1–4]. The propagation mechanisms of the detonation wave are due to the structure of the detonation wave, namely the detonation wave is constructed from a shock wave system such as an incident shock wave, a reflected shock wave, or a Mach stem, as well as the reaction front. Moreover, the detonation wave possesses a triple point, which is the intersection point of these three shock waves. Explosions generated at this triple point and the reaction front create another compression wave and continuously reinforce the preceding shock wave system. In short, the detonation wave is self-sustained by constructing a feedback system from the shock wave and the reaction front with a compression wave supporting the preceding shock wave. When the detonation wave propagates on a soot-covered plate, cellular patterns are recorded on the plate. This is known as a triple point trace, as mentioned above. Therefore, no steady detonation wave can propagate in a premixed gas without possessing triple points and cellular structures.

In order to eliminate the propagation of the detonation wave from a safety point of view, the cellular structure must be disintegrated by either increasing the detonation cell size beyond the diameter of the tube or propagating the detonation wave into a tube that has a diameter smaller than the cell size. Since the former method is accomplished by decreasing the pressure or changing the equivalence ratio of premixed gas, implementing this method is not easy considering practical applications, where the pressure and concentration of premixed gas is already fixed. In contrast, the latter method, which is actualized by inserting a plate equipped with holes smaller than the detonation cell size into the supply pipe of premixed gases, is relatively easier to implement. When a detonation wave propagating in the pipe is diffracted from the hole, the detonation wave is predicted to be quenched by expansion waves originating from the corner of a hole.

A great deal of effort has been made to investigate the diffraction phenomena of the detonation wave [5–13]. Mitrofanov and Soloukhin [5] obtained schlieren photographs of the diffraction of the detonation wave and demonstrated that the diffracted detonation wave was self-sustained under the conditions in which the number of cells before diffraction was greater than thirteen, which is known as the critical tube diameter, $d_c \simeq 13\,\lambda$. Several important effects of the orifice-geometry on a critical value were reported [14,15]. Specifically, they reported that the diffracted detonation wave might be continuously propagated without failure if the number of cells inside the orifice are greater than the critical value, which is defined as the hydraulic diameter corresponding to the orifice-geometry. Teodorczyk et al. [16] reported that the reinitiation mechanism is a result of the reflection of a shock wave from the wall and that a shear layer wall jet is generated by the Mach stem near the wall. Jones et al. [7] conducted a numerical simulation to elucidate the reinitiation of the detonation wave by the reflection of a shock wave from the wall and reported the significance of the interaction of the shock wave and the contact surface and the interaction of the shock wave along the slip-line of the Mach reflection. Pantow et al. [8] presented a detailed schlieren photograph illustrating the behavior of diffraction of a detonation wave, including the reflection process of the shock wave, and reported that decoupled shock waves did not, by themselves, cause the reinitiation of detonation after a sudden expansion. Rather, Mach reflection generating transverse waves were responsible for detonation reinitiation. Ciccarelli and Boccio [17] investigated diffraction of detonation under a condition of elevated temperature and clarified that the critical tube diameter obtained at room temperature, $d_c \simeq 13\,\lambda$, was not applicable under elevated temperature conditions. Khasainov et al. [10] and Sorin et al. [12] investigated the behavior of a detonation wave diffracted from circular tubes by varying the divergence angle and reported the threshold angle to reinitiate the detonation wave. Chao et al. [18] conducted experiments by inserting a perforated plate equipped with a circular hole inside a detonation tube and concluded that the importance of the turbulence scale in the downstream mixing zone, in which reinitiation was controlled by varying the hole dimensions of the perforated plate.

Most studies focused on the diffraction of the detonation wave in order to investigate the limit of self-sustained detonation and the critical tube diameters. However, the phenomenon of detonation reinitiation by the interaction of a diffracted shock wave or the reflection of the shock wave from the wall is open to question, because these phenomena occur with extremely short duration on the order of a few microseconds and are localized.

In the present study, a plate equipped with two rectangular slits (called a slit-plate) is inserted into an observation section of the detonation tube and the behavior of detonation wave diffraction from the slit is visualized using a high-speed video camera with a schlieren optical system [2,19]. The pressure histories and soot track records are acquired behind the slit-plate in order to understand the reinitiation distance of the detonation wave from the end of the slit-plate. Experimental conditions to distinguish whether the detonation wave is reinitiated behind the slit-plate are also reported using the cell size of the detonation wave.

2 Experimental

Figure 1 shows a schematic diagram of the vertical detonation tube used in this experiment [20]. The vertical detonation tube has a cross–section of 50 × 50 mm and a total length of 4,100 mm. The tube is constructed from a driver tube of 1,000 mm, a driven tube of 2,000 mm, an observation section of 700 mm, and a dump tank of 400 mm. An ignition plug intended for use in an automobile engine is installed at the top of the driver tube. A Schelkin spiral coil of 500 mm in length, 50 mm in outer diameter, and 38 mm in pitch is also inserted inside the driver tube with the aim of decreasing the detonation induction length. A detonation wave generated inside the driver tube is propagated through the driven tube so as to transit to the Chapman–Jouguet (for short C–J) detonation wave. Pressure measuring stations are equipped in the driven tube, named P1 to P11 with 100 mm intervals. Pressure transducers (PCB Piezotronics, 113A24, response time: 1 μs) are installed at measuring stations P4, P5, P7 and P8 with an ionization probe to detect ionized gas following the detonation wave. This probe is equipped with two electrical needles with a separation gap of approximately

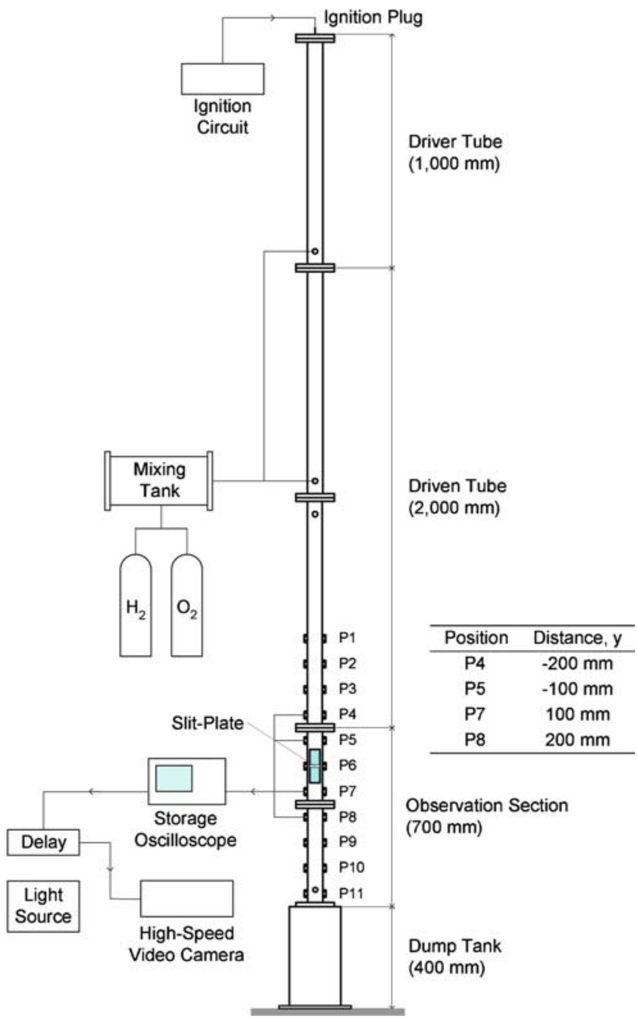

Fig. 1 Schematic diagram of vertical detonation tube (total length: 4,100 mm, cross section: 50 × 50 mm); P1 ∼ P11 are measuring stations of pressure transducer and ionization probe; slit-plate is mounted at position P6 and detonation wave propagates downward

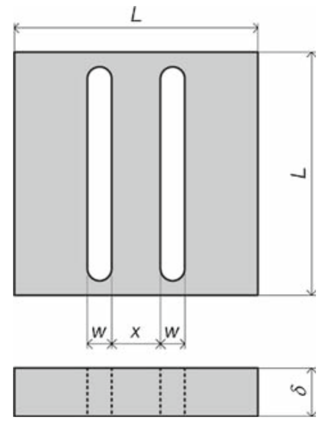

Fig. 2 Schematic diagram of slit-plate inserted at observation section P6 of detonation tube as shown in Fig. 1

Table 1 Configuration of slit-plate

Parameter of slit	Dimension
Length, L (mm)	50
Thickness, δ (mm)	10
Width of slit, w (mm)	3, 5, 8
Distance between slit, x (mm)	2, 5, 10

Table 2 Experimental parameters of driver and driven gas

Parameter of gases	Driver	Driven
Fuel	H_2	H_2
Oxidizer	O_2	O_2
Equivalence ratio, ϕ	1.0	1.0
Initial pressure, p_0 (kPa)	100	10–100

1 mm is mounted opposite the pressure transducers. The distance between pressure transducers mounted in this experiment from the slit-plate is designated as table in the figure. The propagation of a detonation wave can be confirmed on the grounds that the rise time of pressure transducers and ionization probes are simultaneous. A signal from pressure transducers and ionization probes are recorded using a digital storage oscilloscope (Yokogawa, Co. Ltd, ScopeCorder DL–750, 10 MS s^{-1}).

A slit-plate is inserted at measurement station P6, as shown in Fig. 1. Figure 2 shows a schematic diagram of a slit-plate, and the configuration of the slit-plate is shown in Table 1. The length of and thickness of slit-plate are $L = 50$ mm and $\delta = 10$ mm, respectively. The width of each slit w is varied as 3, 5, and 8 mm, and the distance between slit x is varied as 2, 5, and 10 mm. Accordingly, slit–plates with nine combinations by varying w and x are tested with an initial pressure of test gas p_0. A Mylar film of thickness 50 µm is inserted between the driver tube and the driven tube and between the observation tube and the dump tube, beforehand. The experimental conditions are listed in Table 2. A driver gas is used to generate the detonation wave, and a test gas is a stoichiometric premixed gas of hydrogen and oxygen. The pressure of the driver gas is constant at 100 kPa, while the test gas pressure p_0 is varied in the range of 10–100 kPa. The gas is premixed using a mixing tank and is stored for at least 12 h.

Figure 3 shows the schlieren optical system. A metal–haloid light (Sumita Optical Glass Inc., LS-M350, 350 W) is used as a light source and is guided by an optical fiber. A high-speed video camera (Shimadzu Corp., Hyper Vision, HPV–1) is applied to visualize the reinitiation behavior of the detonation wave behind the slit–plate with an interframe time of 1 µs and an exposure time of 500 ns for each frame. This video camera is used to capture high-speed sequences of a total of 100 frames. The video camera is triggered by

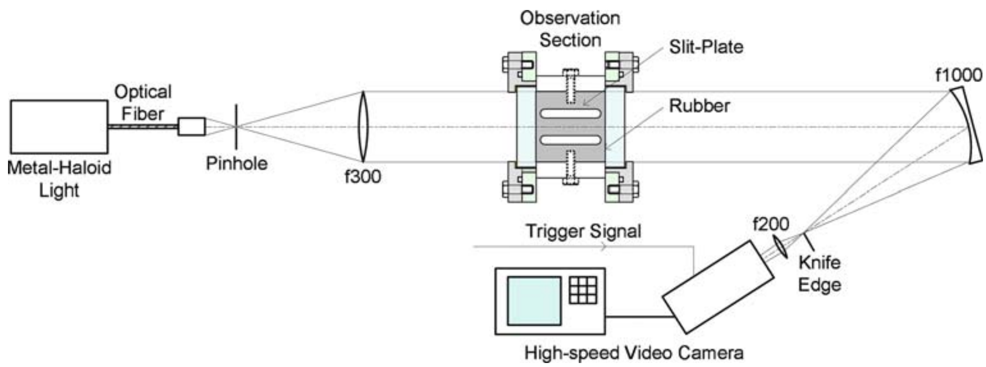

Fig. 3 Schematic diagram showing top view of schlieren optical system having a high-speed video camera; detonation wave propagates to a depth direction through a slit-plate

an output signal from pressure transducers mounted at position P5 via a pulse delay generator (Hadland Photonics, Ltd, Model 103). A rectangular area having a width of approximately 50 mm and a height of 60 mm behind the slit-plate is visualized, including the diffraction of the detonation wave and reinitiation processes.

3 Results

Observation of a diffraction phenomena of a detonation wave from the slit reveals three types of behavior. (1) A detonation wave is reinitiated via a local explosion through the interaction of two diffracted shock waves. (2) A detonation wave is reinitiated by the reflection of a shock wave from the wall. (3) A detonation wave is quenched, and a shock wave propagates, separating from the reaction front in the observation region. In this section, these three behaviors are discussed.

3.1 Behavior of detonation wave reinitiated by the interaction of diffracted shock waves

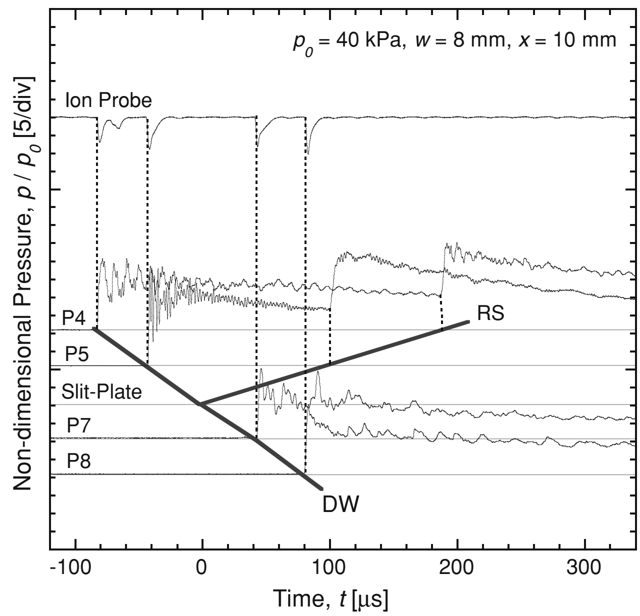

Fig. 4 Profile of ionization current (*upper*) and pressure (*lower*) measured at P4, P5, P7 and P8 ($2H_2 + O_2$, $p_0 = 40$ kPa, slit-plate: $w = 8$ mm, $x = 10$ mm)

Figure 4 shows the output record from the ionization probe (upper) and the pressure (lower three histories) measured at positions P4, P5, P7, and P8, as shown in Fig. 1. The vertical axis indicates the non-dimensional pressure normalized by initial pressure p/p_0, and the horizontal axis indicates the elapsed time t from the detonation wave propagation at the slit-plate. Measuring stations P7 and P8 are located below the slit-plate. The test gas is a stoichiometric mixture of hydrogen and oxygen with an initial pressure of $p_0 = 40$ kPa. A slit-plate of width $w = 8$ mm and a distance between slits of $x = 10$ mm is used. The pressure is increased by the propagation of the detonation wave in the order of P4 and P5, thus a shock wave is reflected on the top surface of the slit-plate. The reflected shock wave propagates P5 and P4 without the output from ionization probes. The fact that the rise time of the pressure and the ionization probe are simultaneous at positions P7 and P8 suggests that the detonation wave is already reinitiated at position P7, which is 100 mm below the slit-plate.

Figure 5 shows a sequential schlieren photograph of the reinitiation process of a detonation wave behind the slit-plate. The experimental conditions are the same as in Fig. 4. The frame interval is 1 µs with an exposure time of 500 ns for each frame. A slit-plate of $w = 8$ mm and $x = 10$ mm is indicated at the top of each frame. A C–J detonation wave propagating downward is diffracted from two slits.

Figure 6 shows the velocity variation of a preceding wave propagating along the central axis of the slit-plate (indicated as axis y in the first frame of Fig. 5), where the horizontal axis t indicates the elapsed time from the onset of detonation diffraction. The velocity before interaction of two

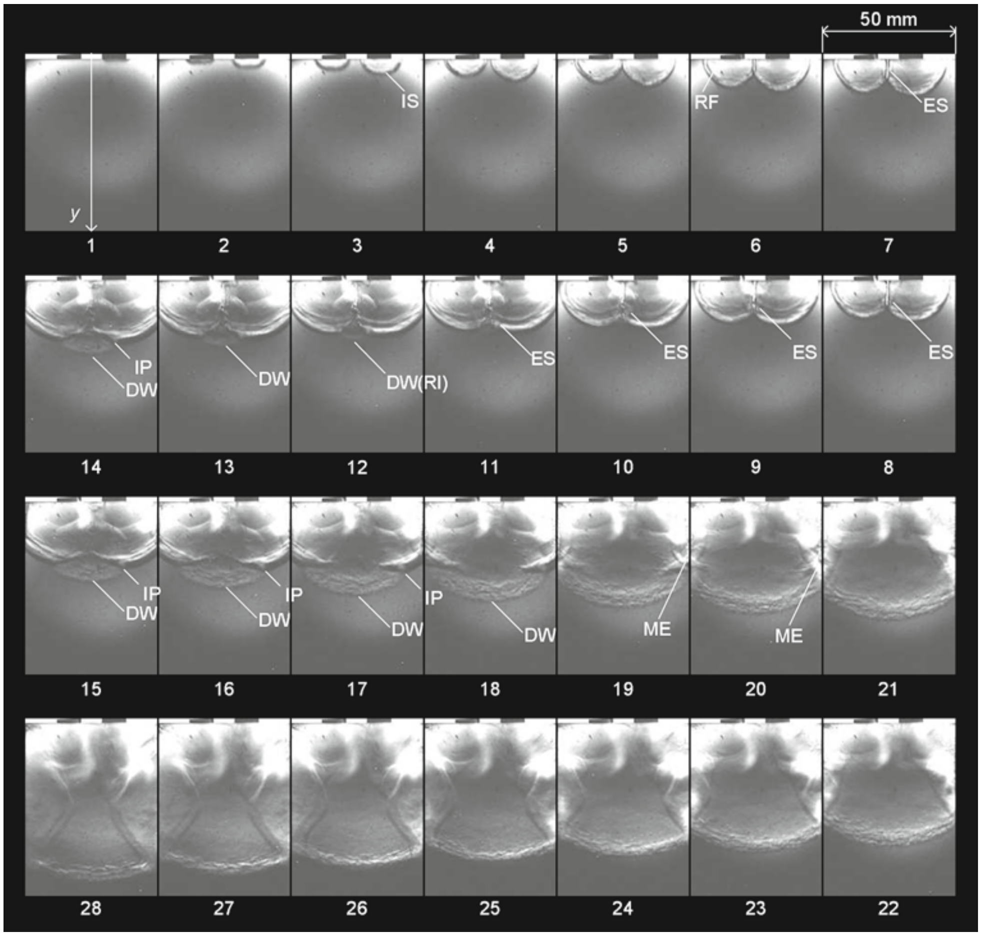

Fig. 5 Sequential schlieren photograph showing re-initiation process from center below slit-plate; *DW* detonation wave, *ES* explosion shock, *IP* intersection, point of IS and ES, *IS* incident shock, *ME* mild explosion, *RF* reaction front, *RI* detonation re-initiation point observed by soot track record as shown in Fig. 7, ($2H_2 + O_2$, $p_0 = 40$ kPa, slit-plate : $w = 8$ mm, $x = 10$ mm, frame interval : 1 µs, exposure time : 500 ns)

shock waves on y axis is evaluated from a position of shock front, which is diffracted from two slits. This figure also shows the C–J detonation velocity of $V_{CJ} = 2.79\,\mathrm{km\,s^{-1}}$ for this condition.

In the second frame of Fig. 5, two detonation waves marked IS are starting to diffract from the slit. The detonation wave changes to a convex shape by expansion waves generated at each corner of the slit. The temperature of the reaction zone constituting the detonation wave is decreased by these expansion waves. The velocity of the diffracted detonation wave at the central axis is estimated to be approximately $V_{max} \simeq 3.2\,\mathrm{km\,s^{-1}}$ as demonstrated by Fig. 6, which exceeds the C–J velocity of $V_{CJ} = 2.79\,\mathrm{km\,s^{-1}}$. This is because of the reflection of the detonation wave at the top surface of the slit-plate, which produces extremely high–pressure, as shown in Fig. 4. In the sixth frame, a shock wave is decoupled with the reaction front and the structure of the preceding wave is observed as a double structure. Two shock waves diffracted from the slit interact at the central position of the slit in the seventh frame. Accordingly, a local explosion is induced to generate an elliptical shock wave, ES, from the center of the explosion. The propagation velocity of the local explosion shock wave, ES, increases steeply to $V_{max} = 3.0\,\mathrm{km\,s^{-1}}$, until this shock wave overtakes the diffracted shock waves in the 11 frame. It is not sufficient to state that this explosion shock wave is followed by a reaction front and that the detonation wave is reinitiated at this stage from this schlieren photograph; however, the detonation wave, DW, reinitiates at the 12 frame via the local explosion caused by the interaction of diffracted shock waves on the grounds that the propagation velocity of the explosion shock wave exceeds the C–J detonation velocity in $t = 10$ µs, and the soot track record described later indicates that cellular patterns emerge from a point, RI, as depicted in Fig. 5. Since the detonation front is visualized widely and reveals a complicated shape, this may corresponds to the cell structure of detonation front. When an intersection point of a diffracted shock wave and the explosion shock wave, IP, reflect from both sides of the tube–wall, a mild explosion, ME, is generated near the wall, and this is coupled with detonation wave traveling downward.

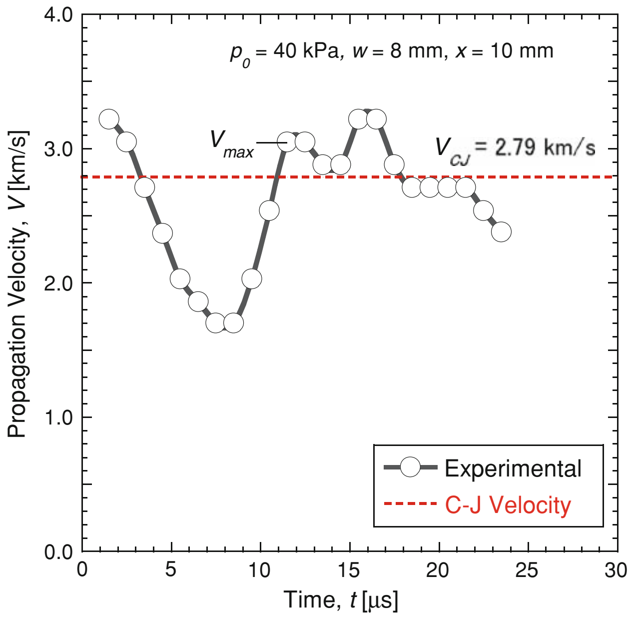

Fig. 6 Profile of propagation velocity at central axis of Fig. 5 ($2H_2 + O_2$, $p_0 = 40$ kPa, slit-plate: $w = 8$ mm, $x = 10$ mm)

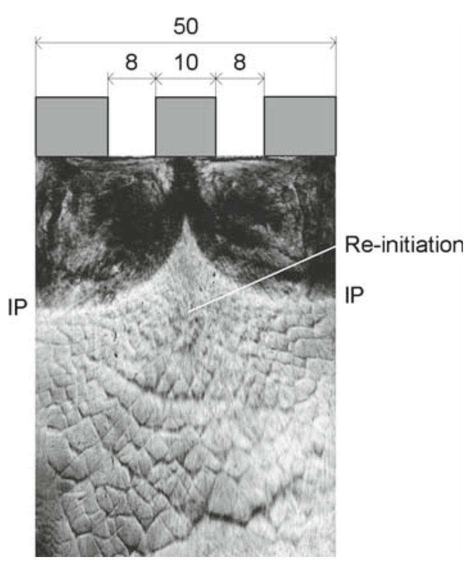

Fig. 7 Soot track record behind slit–plate corresponding to Fig. 5, *IP* intersection point of IS and ES ($2H_2 + O_2$, $p_0 = 40$ kPa, slit-plate: $w = 8$ mm, $x = 10$ mm)

Figure 7 shows the soot track record behind the slit-plate obtained under the same experimental conditions as used in Figs. 5 and 6. Two circular shapes originated from the center of the slit remained on the soot track, indicated as IP. The contour of this locus is identical to the intersection point of the diffracted shock wave, IS, and the explosion shock, ES, as shown in Fig. 5. Since a cellular structure is not visible inside these two sectors, the detonation wave is not reinitiated in these regions. Fine cellular patterns originated from the center below these two sectors, indicating that the detonation wave is reinitiated from the point at which the local explosion is caused by the interaction of two diffracted shock waves, as shown in Fig. 5.

Based on high-speed schlieren photographs, as shown in Fig. 5, and the soot track record behind the slit-plate, as shown in Fig. 7, the detonation wave is reinitiated when two diffracted shock waves interact with each other at the center of the slit-plate and producing a high-temperature sufficient to cause local explosion.

3.2 Behavior of a detonation wave reinitiated by the interaction of a shock wave with the wall

Figure 8 shows the high-speed schlieren photograph obtained under an initial pressure of $p_0 = 30$ kPa, a width of slit of $w = 8$ mm, and a distance of slit of $x = 5$ mm. The frame interval is 1 μs, and the exposure time is 500 ns. Figure 9 also shows the variation of the velocity of preceding wave front propagating along the central axis of the slit-plate. In addition, Fig. 10 is soot track record obtained under the same conditions as in Figs. 8 and 9.

Two detonation waves, IS, are diffracted from the second frame of Fig. 8 and interact at the center, which is similar to Fig. 5. The shock waves are decoupled from the reaction front by the overtaking of the expansion waves generated at the corner of the slit. The propagation velocity along the central axis decreases rapidly until $t = 5$ μs and reaches $V \simeq 2.4\,\mathrm{km\,s^{-1}}$. As the two shock waves interact at the center of the slit–plate, a local explosion is observed in the sixth frame of Fig. 8. A DW is reinitiated by this local explosion because the propagation velocity of the wave reaches $V_{max} \simeq 3.4\,\mathrm{km\,s^{-1}}$ in $t = 7$ μs and because of the observation of soot track record, as shown in Fig. 10, where the cellular patterns occur at the center of the plate, marked as ES_1. The fact that the cell size increases underneath this point indicates that once reinitiated, the detonation wave is once again separated into a shock wave and a reaction front. Furthermore, an intersection point of the diffracted shock wave, IS, and the ES, marked as IP, is propagated to both walls and reflects from approximately the 18 frame of Fig. 8. When this intersection point, IP, is reflected from the wall, the detonation wave is observed to be reinitiated, which is clearly visible from the 19 frame. In this stage, the occurrence of a local explosion at both walls triggers a detonation wave, which propagates toward the central axis of the plate. A close look at the narrow band from right and left walls toward the center, marked as DS, reveals that there are tiny cells inside this band region. This behavior indicates that this reinitiated detonation wave is propagating in the region of high-pressure and high-temperature behind the diffracted shock wave. Therefore, Fig. 10 shows that the cell size of the narrow band, marked as DS, started from both sides is particularly small. Based on the observation of both the schlieren photograph in Fig. 8 and the soot track record

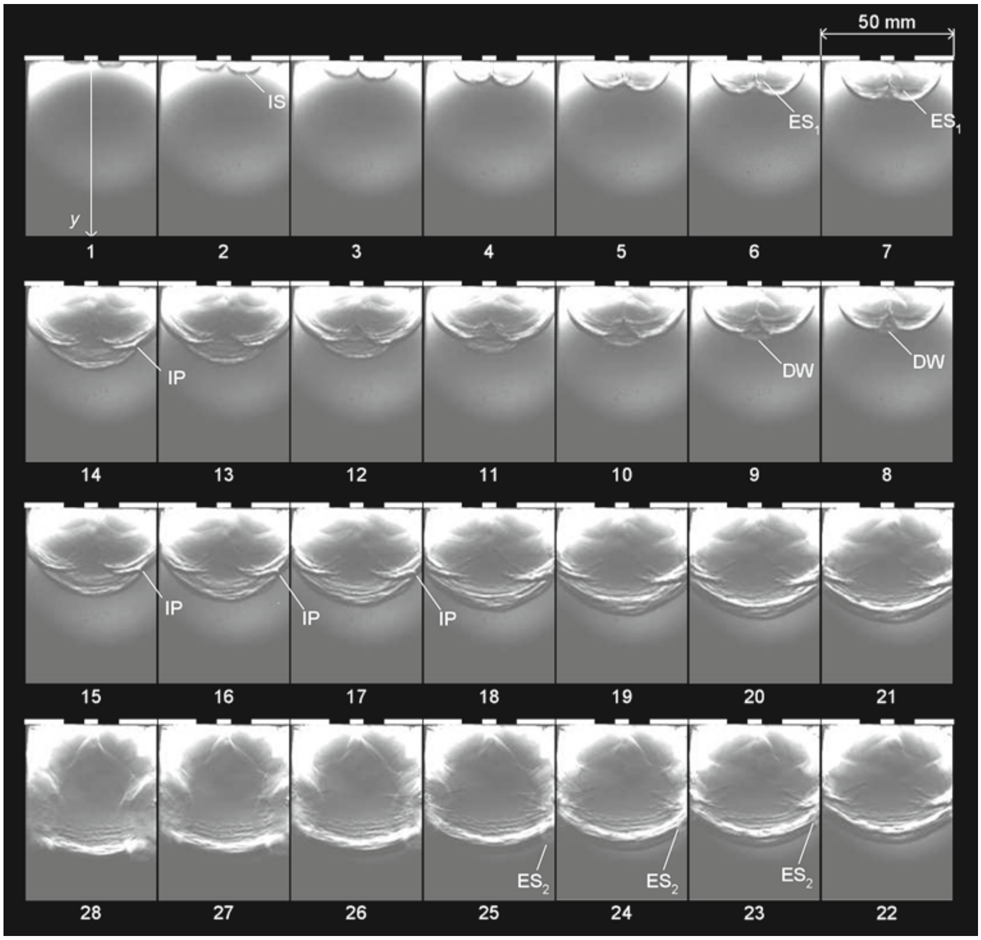

Fig. 8 Sequential schlieren photograph showing re-initiation process from wall of detonation tube, *DW* detonation wave, ES_1 first explosion shock, ES_2 secondary explosion shock, *IP* intersection point of IS and ES_1, *IS* incident shock ($2H_2 + O_2$, $p_0 = 30$ kPa, slit-plate : $w = 8$ mm, $x = 5$ mm, frame interval : 1 µs, exposure time : 500 ns)

in Fig. 10, the detonation wave is reinitiated once by the interaction of two diffracted shock waves at the center. The detonation wave is not self-sustained and is quenched but is then reinitiated by the reflection of the intersection point, IP, from the tube-wall.

3.3 Behavior of detonation wave quenching

Figure 11 shows a high-speed schlieren photograph obtained for an initial pressure of $p_0 = 40$ kPa, a width of slit of $w = 5$ mm, and a distance of slit of $x = 10$ mm. In this figure, the frame interval is changed to 2 µs while maintaining the exposure time as 500 ns. Figure 12 is the variation of the propagation velocity of the wave proceeding along the central axis of the slit-plate. Moreover, Fig. 13 is a soot track record obtained under the same condition as Figs. 11 and 12.

The diffracted shock wave, IS, is separated from the reaction front, RF, in the fourth frame, and the separation distance between IS and RF increases with time. This schlieren photograph also illustrates that the interaction of two diffracted shock wave causes a local explosion, as shown in the fifth frame, and generates an explosion shock wave, ES. The propagation velocity of explosion shock wave, ES, has a high $V_{\max} \simeq 2.2\,\mathrm{km\,s^{-1}}$ compared with that of the diffracted shock wave, $V \simeq 1.5\,\mathrm{km\,s^{-1}}$. However, the ES is not followed by a reaction front, as shown in the ninth frame. This is because the width of the slit is decreased to $w = 5$ mm and the distance of the slit is increased to $x = 10$ mm. Thus, expansion waves produced at the corner of the slits decrease the temperature of the reaction front. The trace of intersection point IP is clearly identified on the soot track, as shown in Fig. 13. The diffracted shock wave, IS, and the explosion shock wave, ES, are coupled in the seventeenth frame and generate a coupled shock wave, CS. When this coupled shock wave, CS, is reflected from the wall, a mild explosion, ME, occurs, as shown in the nineteenth frame. However, this explosion does not trigger the detonation wave because the

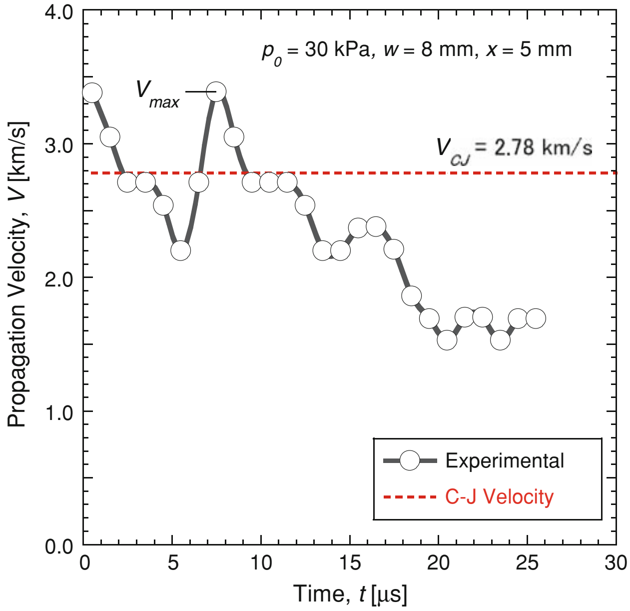

Fig. 9 Profile of propagation velocity at central axis of Fig. 8 ($2H_2 + O_2$, $p_0 = 30$ kPa, slit-plate: $w = 8$ mm, $x = 5$ mm)

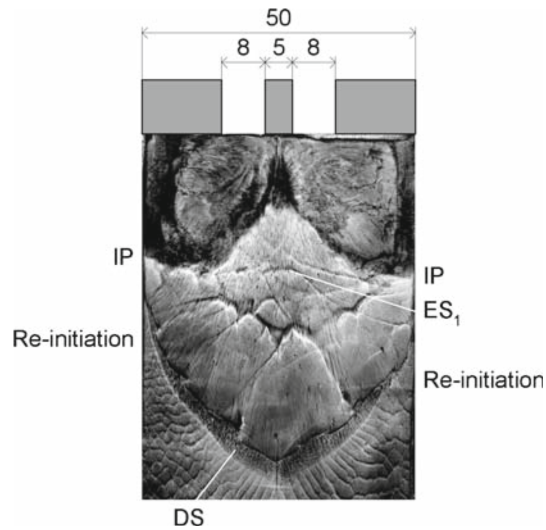

Fig. 10 Soot track record behind slit-plate corresponding to Fig. 8, ES_1 trace of explosion shock, *DS* interaction region of detonation with shock wave, *IP* intersection pcoint of IS and ES ($2H_2 + O_2$, $p_0 = 30$ kPa, slit-plate: $w = 8$ mm, $x = 5$ mm)

cellular structure is not visible on a soot track record, as shown in Fig. 13. On the soot track record, only the trace and reflection of the IP can be seen. The propagation velocity of the wave front along the central axis gradually decreases after the local explosion, ES, is induced at $t = 10$ μs, as shown in Fig. 12.

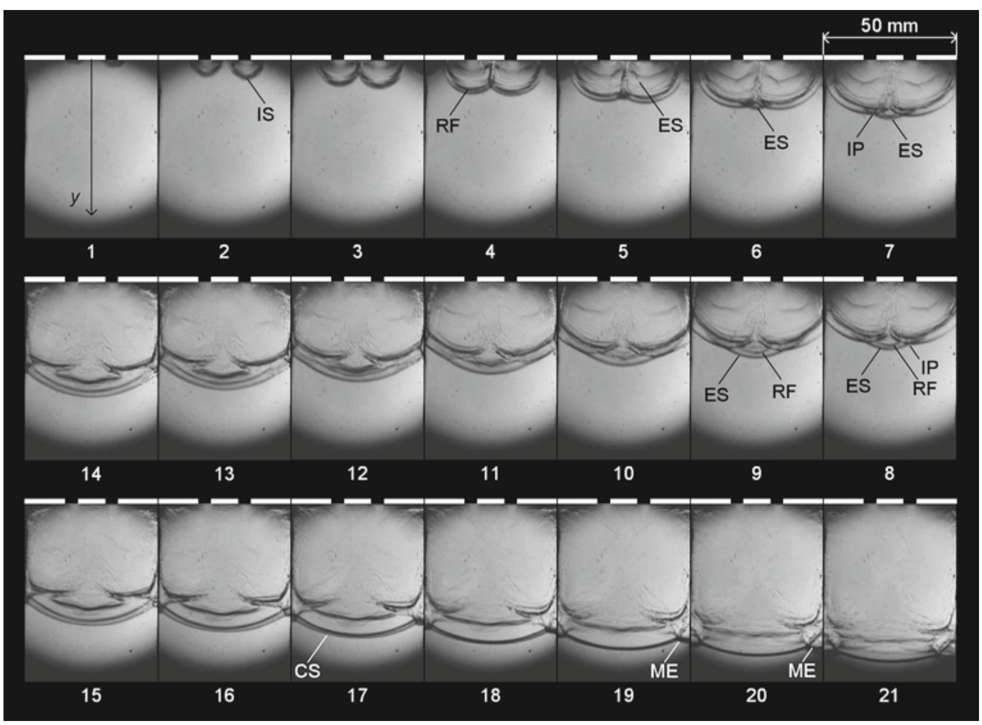

Fig. 11 Sequential schlieren photograph showing quenching process of detonation wave below slit-plate, *CS* coupled shock of IS and ES, *ES* explosion shock, *IP* intersection point of IS and ES, *IS* incident shock, *ME* mild explosion, *RF* reaction front ($2H_2 + O_2$, $p_0 = 40$ kPa, slit–plate: $w = 5$ mm, $x = 10$ mm, frame interval: 2 μs, exposure time: 500 ns)

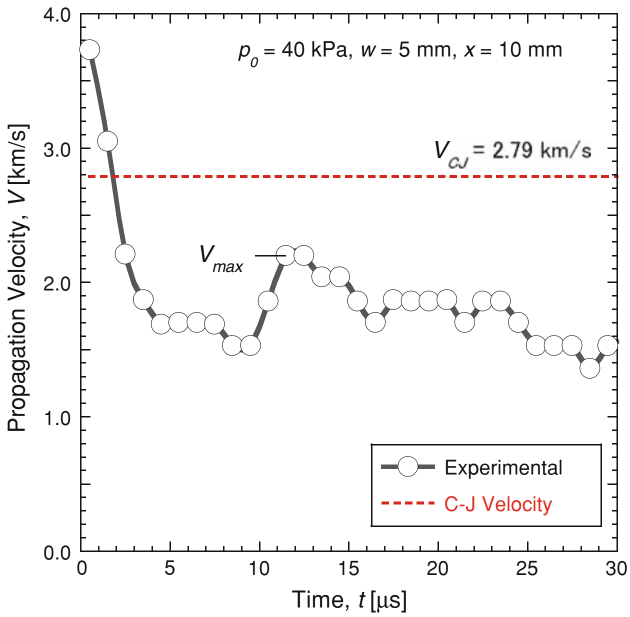

Fig. 12 Profile of propagation velocity at central axis of Fig. 11 ($2H_2+O_2$, $p_0 = 40$ kPa, slit-plate : $w = 5$ mm, $x = 10$ mm)

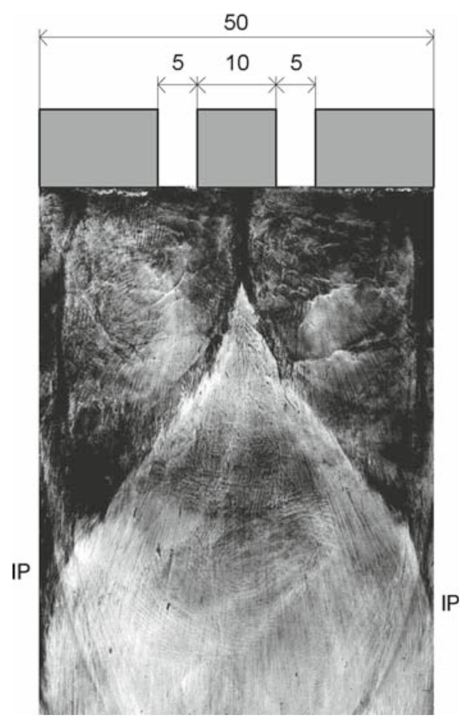

Fig. 13 Soot track record behind slit-plate corresponding to Fig. 11, *IP* : intersection point of IS and ES ($2H_2 + O_2$, $p_0 = 40$ kPa, slit-plate : $w = 5$ mm, $x = 10$ mm)

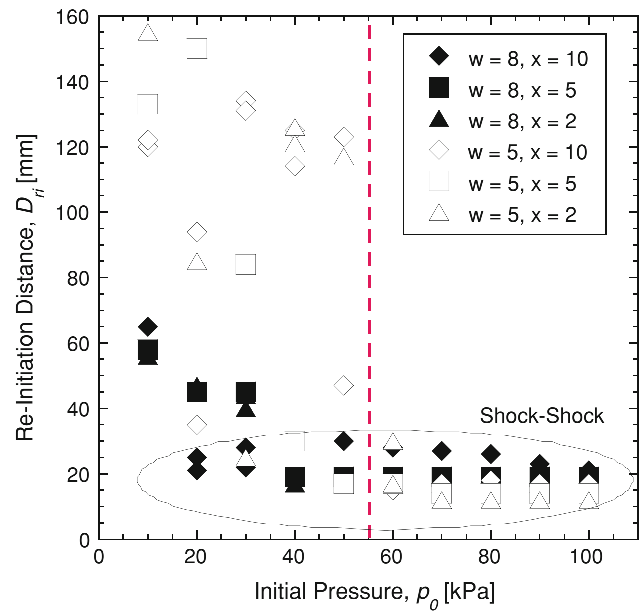

Fig. 14 Relationship between detonation re-initiation distance from the end of slit-pate D_{ri} and initial pressure of test gas p_0 when changing slit-plate ($2H_2 + O_2$)

4 Discussion

It is useful to clarify the experimental conditions as to whether the detonation wave is reinitiated or quenched from the standpoint of safety or designing a detonation arrestor, which is accomplished by inserting several plates having slits inside the tube. Consider the effect of the width of slit w and the distance of slit x on the behavior of detonation reinitiation.

Figure 14 shows the relationship between the reinitiation distance from the lower end of slit-plate D_{ri} and the initial pressure of test gas p_0 by changing the width of slit w and the distance between slit x, where solid symbols indicate data points for $w = 8$ mm and open symbols indicate data points for $w = 5$ mm. In this graph, reinitiation caused by the interaction of two diffracted shock waves as revealed in Fig. 5 is distinguished by a line labeled "shock–shock". This diagram tells us that the reinitiation distance is increased by decreasing the initial pressure of the test gas. In the case of the initial pressure being greater than 60 kPa, a detonation wave is immediately reinitiated by shock–shock interactions and the reinitiation distance is less than the dimension of the tube, i.e., $D_{ri}/L < 1$. This behavior is independent of w and x. On the other hand, for an initial pressure of less than 50 kPa, the reinitiation distance increases and is strongly dependent on the width of slit w, that is to say the reinitiation distance for the case of $w = 5$ mm is greater than the case of $w = 8$ mm. In particular, most of the data point obtained for $w = 5$ mm shows that the detonation is not immediately reinitiated by the interaction of diffracted shock waves means that detonation is not reinitiated without the wall in the observation region.

Figure 15 depicts the relationship between the maximum propagation velocity of local explosion shock wave V_{max} and the width of slit w. The vertical axis indicates the

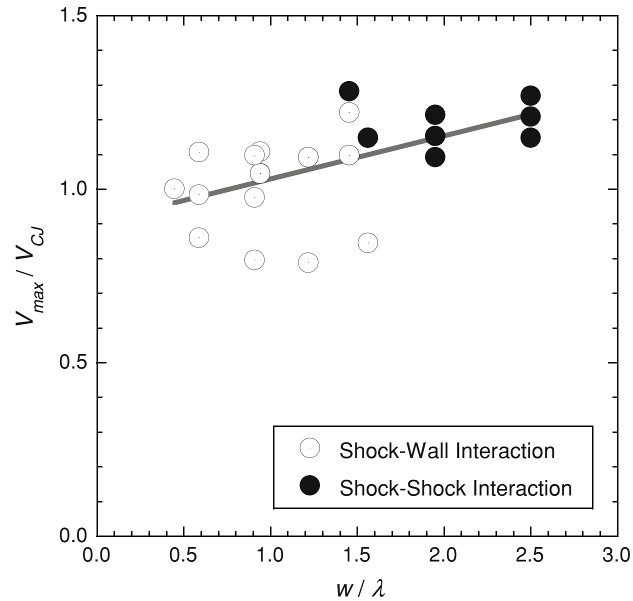

Fig. 15 Relationship between non-dimensional maximum velocity of detonation wave V_{max}/V_{CJ} and non-dimensional slit width w/λ ($2H_2 + O_2$)

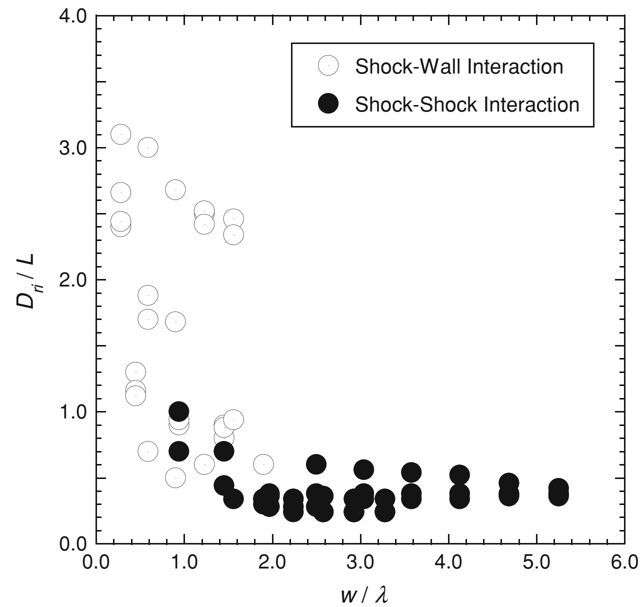

Fig. 16 Relationship between non-dimensional re-initiation distance D_{ri}/L and non-dimensional slit width w/λ ($2H_2 + O_2$)

non-dimensional maximum velocity normalized by the C–J detonation velocity of the test gas V_{max}/V_{CJ}, and the horizontal axis indicates the non-dimensional width of slit w/λ, where λ is the cell size of the C–J detonation wave and is obtained from a detonation database [21]. For a premixed gas of hydrogen and oxygen, the cell size λ is inversely proportional to a power of 1.1 for the initial pressure of test gas p_0, i.e., $\lambda \propto p_0^{-1.1}$. The solid circle symbol indicates that the detonation wave is reinitiated via local explosion caused by the interaction of diffracted shock waves, and the open circle symbol indicates that the detonation wave is not reinitiated without the wall, that is to say the detonation wave is reinitiated by the interaction of the shock wave with the wall. This diagram indicates that the maximum propagation velocity of a shock wave caused by a local explosion increases with the increase in the number of cells emitted from the slit. Furthermore, the reinitiation of the detonation wave triggered by the local explosion via the interaction of the diffracted shock wave is due to the generation of the overdriven detonation wave. In total, this indicates that the detonation wave is likely reinitiated for a sensitive gas via a local explosion caused by the interaction of the diffracted shock wave.

Figure 16 shows the relationship between the reinitiation distance of the detonation wave from the slit-plate D_{ri} and the width of slit w. The vertical axis indicates the non-dimensional reinitiation distance normalized by the width of the detonation tube D_{ri}/L, and the horizontal axis shows w/λ. The reinitiation distance is decreased as the non-dimensional width of slit w/λ is increased. Furthermore, reinitiation caused by the interaction of two diffracted shock waves occurred under the condition of $w/\lambda > 1$. For the experimental condition of $w/\lambda < 1$, the detonation wave propagated in the slit must be separated into a shock wave and a reaction front. In this case, the detonation wave is not immediately reinitiated by the interaction of two diffracted shock waves, because the shock wave diffracted from the slit is attenuated by expansion waves generated at the corner of the slit. Furthermore, the reinitiation of the detonation wave occurs immediately within the length of the tube dimension as a result of the interaction of diffracted shock waves under the condition of $w/\lambda < 1$. This result agrees with the results reported by Chao et al. [18], in which similar experiments were conducted using a perforated plate with circular holes. They also reported the importance of turbulence scale in the downstream mixing zone. In contrast, based on the schlieren photograph shown in Figs. 5 and 8, the detonation wave appears to be reinitiated by gas dynamic effects, such as the reflection of the diffracted shock wave or reflections of the intersection of the diffracted shock wave and the explosion shock wave. These reflections are likely critical for reinitiation of the detonation wave.

5 Conclusions

Experiments were carried out to investigate the reinitiation processes of the detonation wave behind the slit-plate using high-speed schlieren photography, the soot track record, and pressure measurements. In the experiments, the pressure of the test gas, the width of slit, and the distance between slits are varied. Based on the results of the experiments, the following conclusions were obtained.

The reinitiation processes of the detonation wave after the diffraction from two slits were visualized using a high-speed video camera. By varying the experimental conditions, the diffracted detonation wave shows the following three types of phenomena.

(1) The detonation wave is immediately reinitiated via a local explosion caused by the interaction of two diffracted shock waves.
(2) The detonation wave is not immediately reinitiated by the above mentioned local explosion, but is reinitiated when the intersection points of the diffracted shock wave and the local explosion shock wave were reflected from the wall.
(3) The detonation wave is not reinitiated in the region of observation, and the shock wave propagates by separation from the reaction front.

When a detonation wave is reinitiated by a mechanism (2), since the detonation wave generated at the wall propagates in a region of high-pressure and high-temperature behind the preceding shock wave, extremely fine cells are produced in the region.

A detonation wave was immediately reinitiated by a local explosion under the conditions that the width of each slit is less than the detonation cell size, i.e., $w/\lambda < 1$. In this case, an overdriven detonation wave having a propagation velocity that exceeds the C–J detonation velocity is generated. Therefore, this results in the generation of self-sustained detonation waves in a distance less than the width of the tube.

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