Re-initiation in Diffraction of Detonation Propagating in A Thin Channel

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1 Introduction

When a detonation wave propagates into unconfined space, a sudden expansion of the cross-sectional area causes the detonation wave to diffract, resulting in attenuation of the shock wave that comprises the detonation front. In the case of circular tubes, detonations are known to propagate successfully in unconfined space if the inner diameter of the tube is at least 13 times larger than the detonation cell width λ [1]. Lee studied the effects of the detonation cell regularity on detonation diffraction and the following re-initiation mechanism [2]. Pintgen and Shepherd proposed that the differences in detonation failure between regular highly argon-diluted H_2–O_2 mixtures and highly irregular H_2–N_2O mixtures were associated with the difference in effective activation energy [3]. They also reported the detonation re-initiation is due to local fluctuations at random locations within the region between the leading shock and reaction front. Radulescu et al proposed the model for critical detonation diffraction in two-dimensional channels, using a weakly supported shock model [4] and predicted the critical diffraction of irregular detonations using the relation between the detonation speed and the detonation frontal curvature [5]. Although these researches successfully explain the detonation diffraction structure and well predict the critical condition, quantitative information on the condition of the re-initiation point, which is closely related to onset of detonation, remains insufficient up to the present.

In the present study, a thin channel in which a two-dimensional detonation can be regarded is constructed so that the re-initiation position can be determined by visualization from one direction. Re-initiation process of detonation in the sudden expansion of the cross-section has been experimentally studied for mixtures with irregular and regular cellular structures, focusing on the behavior of transverse waves that have not been fully analyzed in the detonation diffraction issues.

2 Experimental Apparatus

A schematic of the experimental apparatus used in the present study is shown in Fig. 1. It consists of a pre-detonator tube, a guide section, a test section, and a damping section. As shown in Fig. 1(b), the cross-section of the guide section is 2 mm × 15 mm, while in the test section, the flow path, which is 2 mm × 60 mm, is expanded downward. The aspect ratio of the cross-section W/H, which is the ratio of the channel height H to the channel width W, is kept 0.13 to achieve two-dimensional detonation.

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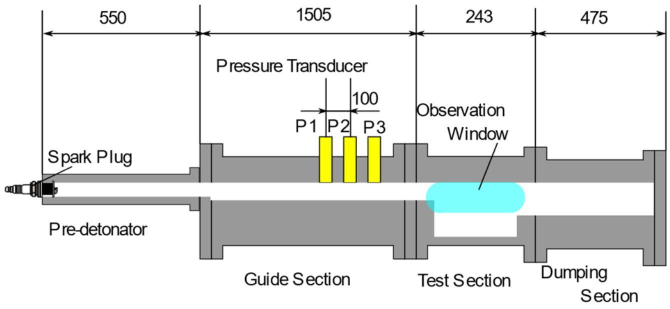
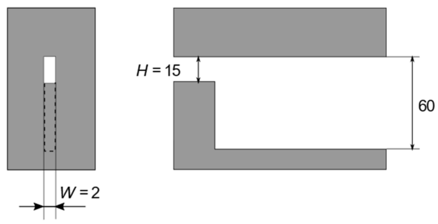


(a) Overview



(b) Detail of test section

Figure 1: Schematics of experimental apparatus for diffraction and re-initiation of detonation.

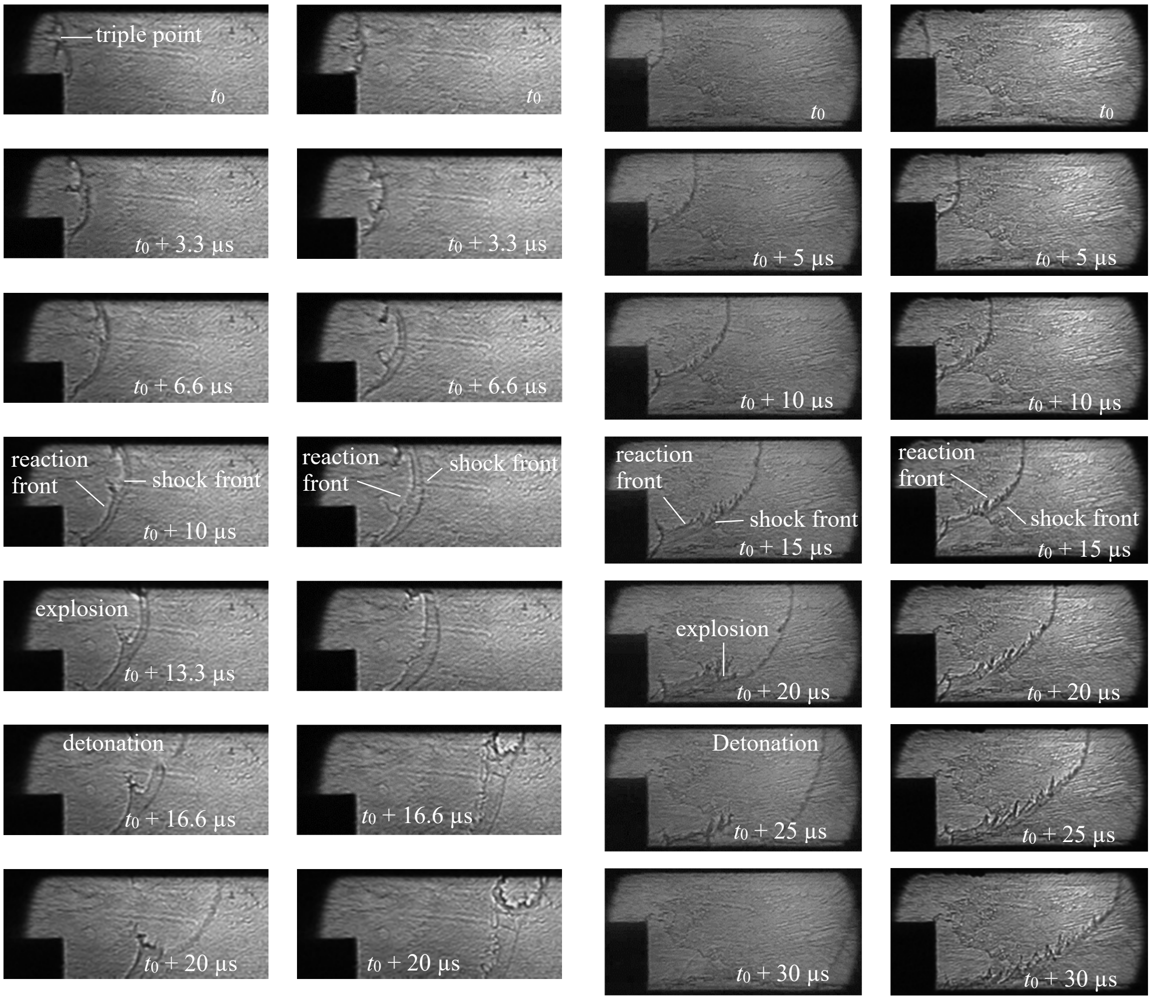
The test gas was $C_2H_4 + 3O_2 + \beta Ar$, where Ar dilution ratio of β was 0 or 4. The whole detonation tube was filled with the test gas at an initial pressure of p_0 ranging from 17.5 kPa to 40 kPa for $\beta = 0$ and from 45 kPa to 80 kPa for $\beta = 4$. The test gas was ignited with a conventional spark plug fixed to the end of the pre-detonator tube, and after deflagration to detonation transition process a steady detonation propagates in the guide section. Propagation velocity of the detonation entering the test section was measured using three pressure transducers (PCB Piezotronics, 113B26) placed at 100 mm intervals in the guide section, as shown in Fig. 1. A pair of quartz windows for shadowgraph photography was installed in the test section.

3 Experimental Results

Figure 2 shows typical shadowgraph images of the detonation transmission process taken by a high-speed camera for $\beta = 0$ and $\beta = 4$. Fig. 2(a) shows the case of successful transmission for $\beta = 0$ and $p_0 =$ 20 kPa. The triple point is clearly visible on the detonation front just before entering the sudden expansion area. Afterward, the triple point moves upward and downward and at the same time, a lower part of the detonation front is decoupled into a shock and a reaction front. When the upward-moving triple point reaches the upper wall of the test section, an explosion occurs, which triggers detonation re-initiation. Figure 2(b) shows the case of failed transmission at the same initial pressure as Fig. 2 (a). Even in the failed transmission, when the upward-moving triple point arrives at the upper wall, the explosion is generated, however, this does not contribute to detonation re-initiation.

Figure 2 (c) shows the case of successful transmission for $\beta = 4$ and $p_0 = 50$ kPa. While the decoupling of the detonation front gradually proceeds after entering the sudden expansion area, the detonation front adjacent to the upper wall continues to propagate without decoupling. Subsequently, an explosion occurs near the boundary between the detonation front and the unburnt mixture pocket due to the decoupling, and then a new curved detonation front is generated from this explosion point. In Fig. (d), which shows the case of failed transmission for $\beta = 4$, the decoupling proceeds without explosion and the entire wave front is curved, resulting in further deceleration of the shock front.

As shown in Fig. 2, a new detonation front is generated by the explosion in the marginal condition, regardless of the mixture type. However, the re-initiation mechanism is dependent on the mixture type. For the detonation with irregular cellular structure, namely for $\beta = 0$, the explosion originates from the reflection of the triple point at the upper wall, which is partially weakened by the expansion waves. This coincides with the fact that the transverse wave plays an important role in the propagation mechanism of detonation with irregular cellular structure. In contrast, no explosion occurs by the triple point reflection at the upper wall for the detonation with regular cellular structure, namely for $\beta = 4$. In this case, the explosion point lies near the interface between the unburnt pocket and the transverse wave, judging from the curvature of the newly generated detonation front. Because the slip line, which tends to give rapid mixing of gases on both sides of the line, exists near the transverse wave, this type of re-initiation mechanism is relevant to rapid mixing of the unburnt and burnt mixture in jet initiation [6].



(a) $\beta = 0$, success (b) $\beta = 0$, failure (c) $\beta = 4$, success (d) $\beta = 4$, failure

Figure 2: High-speed shadowgraph images of detonation diffraction for $C_2H_4 + 3O_2 + \beta Ar$.
$\beta = 0$ and p_0 = 20kPa for (a) and (b), $\beta = 4$ and p_0 = 50 kPa for (c) and (d).

The present experimental results are summarized in Table 1, which shows the classification of the propagation behavior at each initial pressure. Because the channel is enlarged only on the lower side, the success or failure of detonation transmission was evaluated using $2H/\lambda$ with consideration of the mirror symmetry of the upper wall. The cell widths were estimated in a different experiment for $\beta = 0$ and were extrapolated from the cell width in Ref. 5 for $\beta = 0$.

Table 1 Summary of detonation transmission of $C_2H_4 + 3O_2 + \beta Ar$.

<table>
<tr><th>β</th><th>p_0 [kPa]</th><th>$2H/\lambda$ [7]</th><th colspan="2">Transmission behavior</th></tr>
<tr><td rowspan="6">0</td><td>17.5</td><td>11</td><td colspan="2">Failure</td></tr>
<tr><td>20</td><td>12</td><td>Marginal</td><td rowspan="3">Explosion at the upper wall</td></tr>
<tr><td>25</td><td>16</td><td rowspan="4">Successful transmission</td></tr>
<tr><td>30</td><td>19</td></tr>
<tr><td>35</td><td>23</td><td rowspan="2">Without explosion</td></tr>
<tr><td>40</td><td>26</td></tr>
<tr><td rowspan="8">4</td><td>45</td><td>17</td><td colspan="2">Failure</td></tr>
<tr><td>50</td><td>19</td><td rowspan="2">Marginal</td><td rowspan="7">Explosion at the unburnt pocket near the detonation front</td></tr>
<tr><td>55</td><td>20</td></tr>
<tr><td>60</td><td>22</td><td rowspan="5">Successful transmission</td></tr>
<tr><td>65</td><td>24</td></tr>
<tr><td>70</td><td>25</td></tr>
<tr><td>75</td><td>27</td></tr>
<tr><td>80</td><td>29</td></tr>
</table>

4 Discussion

To obtain the condition under which the explosion causing the re-initiation occurs, the transverse wave movement was analyzed for $\beta = 0$. Figure 3 shows the coordinate system, whose origin is the lower wall giving the sudden expansion of the channel. The initial position of the triple point entering the expansion section is (x_t, y_t).

The velocity of the upward-moving transverse wave calculated from the obtained shadowgraph images is shown in Fig. 4 (a). The vertical axis is the transverse wave velocity V_{TR}, non-dimensionalized by the CJ velocity V_{CJ} and the horizontal axis indicates the initial vertical location of the triple point y_t. It is obviously found that in all the tests, the detonation transmission succeeds for $V_{TR}/V_{CJ} > 0.31$ and $y_t > H/3$. In the present configuration, the upward-moving transverse wave is fairly weakened by the expansion wave, indicating that a downward flow is generated. Thus V_{TR} is not an actual velocity of the propagating shock wave, but an apparent velocity in the experimental coordinate. Nevertheless, $V_{TR}/V_{CJ} > 0.31$ can be treated as the criterion of strength of the transverse wave causing the re-initiation of detonation. Because the initial vertical position of the triple point randomly changes from test to test, the transverse wave, which lies initially on the lower side of the channel, is more affected by the expansion waves, resulting in failed transmission in the marginal condition in which both success and failure of the detonation transmission occur.

For $\beta = 4$, the velocity of the quenched detonation wave affected by the expansion waves is estimated from the shadowgraph images, instead of the transverse wave movement as shown in Fig. 4 (b), where V denotes the velocity normal to the wavefront just before onset of the explosion. The horizontal axis is the initial triple point location moving afterward to the explosion position, which is estimated from the curvature of the newly generated detonation front. In the failure case, the quenched detonation velocity at the positions where the re-initiation occurs in the successful case with the same initial condition is

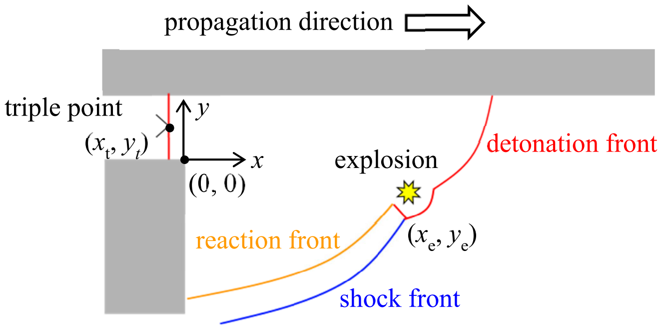
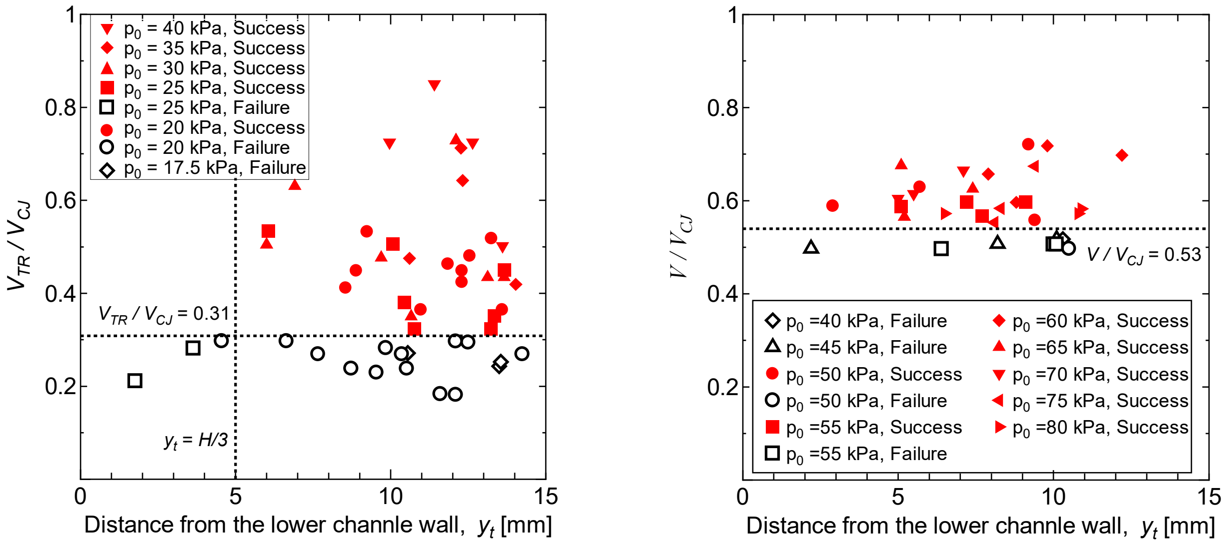


Figure 3: Coordinate system to analyze detonation diffration. Depicted waves show the case of detonation re-initiation for $\beta = 4$.

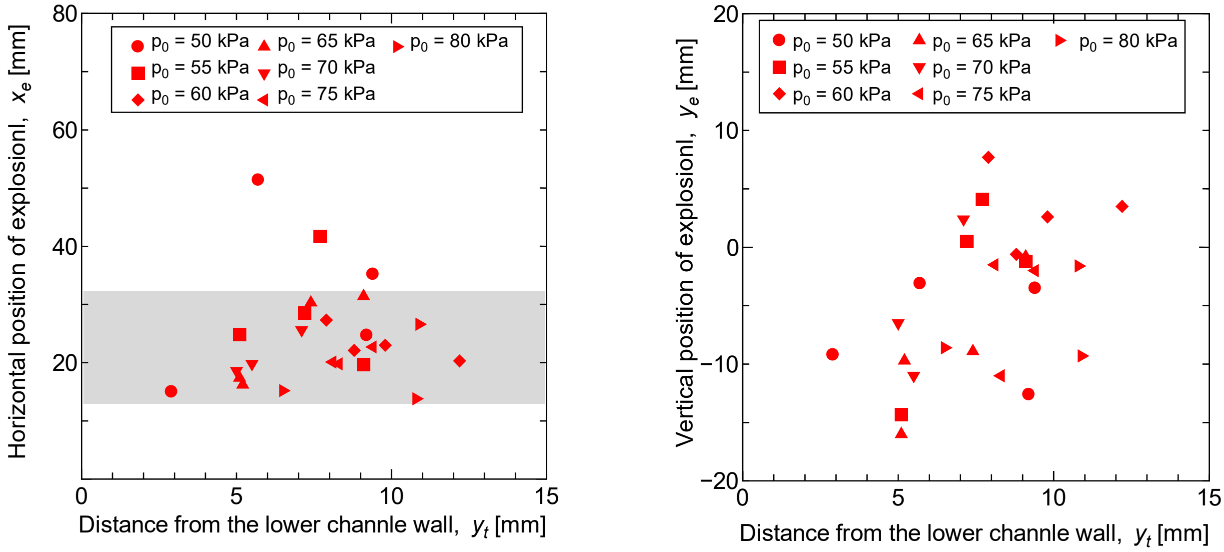


(a) $\beta = 0$ (b) $\beta = 4$

Figure 4: Wave velocities in detonation diffraction for $C_2H_4 + 3O_2 + \beta Ar$. V_{TR}: velocity of transvers wave, V: velocity of quenched detonation wave just before onset of explosion.

plotted in Fig. 4 (b). The criterion of successful detonation transmission is found to be $V/V_{CJ} > 0.53$ and the initial position of the triple point is not related to the success or failure of transmission.

Figure 5 shows the relationship between the explosion position and the initial triple point position for $\beta = 4$, where (x_e, y_e) is the coordinates of the explosion as shown in Fig. 3. Although it is found that there is almost no correlation between x_e and y_t as shown in Fig. 5(a), Fig. 5 (b) indicates that the vertical explosion position y_e has a simple linear regression with y_t. This suggests that the re-initiation occurs when the decoupling of the detonation proceeds to the triple point position behind the expansion waves.



(a) horizontal position (b) vertical position

Figure 5: Relationship between explosion location (x_e, y_e) and triple point positon from the lower channel wall y_t in detonation diffraction for $C_2H_4 + 3O_2 + 4Ar$.

5 Conclusion

Transmission of detonations propagating through a sudden increase in flow cross-sectional area has been experimentally studied for mixtures with irregular and regular cellular structures. Diffraction and re-initiation of detonations in a thin rectangular channel were observed using high-speed shadowgraph photography. As the result, for the mixture with irregular cellular structure $C_2H_4 + 3O_2$, the re-initiation occurs at the upper wall because of transverse wave reflection and the success criterion of the transverse wave velocity is $V_{TR}/V_{CJ} > 0.31$. For the mixture with regular cellular structure $C_2H_4 + 3O_2 + 4Ar$, the re-initiation originates from the boundary between the quenched detonation and the unburnt mixture pocket. The success criterion is that the quenched detonation velocity V/V_{CJ} is larger than 0.53.

References

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