An experimental study on the detonation transmission behaviours in acetylene-oxygen-argon mixtures

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Abstract
Accidental explosions/detonations prevention and control are practical as well as scientific issues. Although numerous research have been carried out to examine the combustion characteristics in acetylene mixtures, very limited studies focused on detonation transmission behaviours in a finite expansion space, which is of vital importance for the explosion safety assessment. This paper reports the detonation transmission behaviours through a confined sudden expansion in stoichiometric acetylene-oxygen mixtures diluted with varying amount of argon. Detonation velocity measurement and soot visualization were used to characterize the detonation behaviour. The experimental results indicate that the initial over-driven degree of re-initiated detonation decreases with the increase of argon dilution in the expanded tube. Two transmission modes with distinct detonation cellular structures are experimentally observed. For the large expansion ratio, localized explosions followed by fine-scale detonation structures are observed in the expanded tube. As the initial pressure approaches the limiting transmission pressure, the re-initiation distance remarkably increases. For the small expansion, the near-limit detonation waves are observed to transmit to the expanded tube successfully without detonation re-initiation. A dimensionless cell size \( \lambda \) is introduced to correlate with the re-initiation distance of transmitted detonation in acetylene-oxygen-argon mixtures, and a unified curve can be obtained.

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1. Introduction

Acetylene (C\(_2\)H\(_2\)) is a colourless explosive gas with garlic smell produced from hydrolysis of calcium carbide or innovatively converted from coal under thermal plasma condition [1]. The triple bond in acetylene makes itself thermodynamically unstable, and thus acetylene possesses wide applications, such as in welding industry and used as an alternative fuel or additive for internal combustion engines to reduce NO\(_x\) emissions [2,3]. However, compared with other fuels, acetylene exhibits some hazardous aspects, such as wide flammability range in air (2.5–81% by volume), low ignition energy (the minimum ignition energy 0.019 mJ) and fast chemical energy release rate [4]. As a result, released acetylene during the production, transportation and storage stage might cause explosions/detonations, endangering personal and property safety. Thus, the study of detonations with acetylene mixtures in confined space has great significance.

The detonation is a supersonic combustion wave, in which a shock wave is propagated ahead sustained by a reaction zone with rapid heat release process. Across the detonation front, thermodynamic states such as pressure and temperature grow sharply. With the objective to getting a deeper insight into the phenomenon and mechanism of detonation, detonation propagation and transmission has received considerable attention. Detonation transmission to unconfined space has been extensively investigated by numerous researchers [5–12]. It is not only a topic from fundamental perspective but also applied to a more practical problem when the detonation transmits to a confined expansion with a physical boundary downstream. Only when insights to the detonation transmission mechanism are understood, can devices like detonation arresters effectively work to prevent the destructive hazards of detonations in tunnels or pipes.

The outcome of detonation transmission to unconfined space is divided into three parts: super-critical, critical and sub-critical outcome [10]. For most gaseous hydrocarbon/oxygen mixtures, a correlation was scaled between the critical tube diameter \( d_c \) and detonation characteristic lengthscale cell size \( \lambda \): \( d_c = 13\lambda \) [13]. These mixtures are referred as unstable mixtures, where highly irregular transverse wave patterns with substructures are observed.
As argued by Lee [17], for an unstable detonation the inability to develop new transverse waves at the detonation front during the transmission process leads to the failure. However, the failure mechanism for a stable detonation is due to the excessive front curvature, whereas the cellular instability seems not to play a prominent role for detonation transmission. Influence of cellular instability on sustaining the detonation propagation is widely discussed [18–24]. In particular, it is interesting not only to look at the performance of detonation transmission for mixtures with two distinct propagation mechanisms (i.e., $C_2H_2 + 2.5O_2$ and $C_2H_2 + 2.5O_2 + 70\%Ar$), but also to systematically study the transmission behaviours for $C_2H_2 + 2.5O_2$ mixtures with varying amount of argon dilution.

For sub-critical cases, detonation could be re-initiated in the expanded space via shock-wall interaction or deflagration-to-detonation transition (DDT). Detonation transmission behaviours in the confined space depend on the mixture sensitivity, initial condition, and geometry parameters of the channel [25–31]. Sornin et al. [30] investigated the detonation transmission in different diameter step configurations with various hydrocarbon mixtures. They proposed a dimensionless parameter that below a critical value the detonation re-initiation distance increases rapidly. Lv and Ihme [31] studied the effect of mixture sensitivity and the evolution of diffracted wave front on the detonation re-initiation when the detonation diffracts from a backward facing step. The results indicated that the ignition kernels behind the regular shock reflection and wave-wave interaction behind Mach reflection lead to the detonation re-initiation. Refs. [18,32] observed that in a high aspect ratio channel, the cellular structure at the detonation front is much smaller than the height of the channel, suggesting that the detonation structures remain three-dimensional when the detonation cell size is comparable to the channel height. The out-of-plane transverse waves will interact with the triple-points which propagate in the vertical direction.

In the present study, the investigation is focused on the detonation transmission in stoichiometric acetylene-oxygen mixtures diluted with varying amount of argon at various initial pressures. Three expansion ratios of 1.34, 2 and 4 are introduced to observe the phenomenon of detonation transmission, re-initiation and failure. Photodiodes and smoked foil techniques are applied to acquire the velocity data and detonation structures. In this paper, experiments are carried out in round tubes so that the side-wall effects are eliminated.

### 2. Experimental details

In the present study, a 3 m long transparent polycarbonate tube of inner diameter $D = 50.8 \, \text{mm}$ was used as the test section. A 1 m long polycarbonate tube of outer diameter 50.8 mm was inserted into the test section as an initiator tube to produce a sudden expansion. By varying the inner diameter of the initiator tube $d$ as 12.7 mm, 25.4 mm and 38 mm, three expansion ratios $D/d$ of 4, 2 and 1.34 were obtained. The schematic of the experimental system is shown in Fig. 1.

A 1 m long steel tube was mounted upstream of the test section as a driver section. To minimize the influence of detonation initiation in the driver section on the detonation propagating state in the initiator tube, the tube was located a few hundred millimeters away from the driver section. A small volume of a more detonable gas mixture (e.g., stoichiometric $C_2H_2 - O_2$) was filled in the driver section to facilitate the initiation of detonations here. A high energy spark and a short length of Shchelkin spiral in the driver section also ensured the successful detonation transmission to less detonable test mixture.

Stoichiometric $C_2H_2$--$O_2$ mixtures without and with 25%, 50% and 70% Ar dilution were investigated. By varying the initial pressure $p_0$, the characteristic length-scale (i.e., cell size $\lambda$) was determined. These explosive mixtures were prepared using the partial pressure method and allowed to mix by diffusion for at least 24 h in order to ensure homogeneity prior to being used. An Omega pressure transducer (PX309-015AI) and an Omega digital meter (DP24-E) were used to monitor the pressures of the experiments. The measurement gave a total error of 0.1%. For each shot, the detonation tube system was evacuated to 0.1 kPa before the mixtures being fed into the tube.

The optical fibers were fixed at the outer wall of the large tube and spaced periodically along the section. Three optical fibers were mounted along the initiator tube to verify the self-sustained state of the detonation wave here, while others were registered at the re-cep- tor tube. Since the detonation wave is a shock-reaction zone complex, self-luminescence of detonation front can be captured by optical fibers. Then, light signals were converted to electrical sig- nals by the photodiodes and transmitted to the oscilloscope. With recording the time-of-arrival of the detonation at neighbouring position, the local detonation velocity was determined. Typical output from the oscilloscope is indicated in Fig. 2 to show a suc- cessful detonation transmission. The detonation structure behav- iour was visualized by smoked mylar foils. The smoked foil was made of a thin (0.2 mm) mylar sheet covered with uniform soot and carefully bent and inserted downstream of the expansion.

### 3. Results and discussions

#### 3.1. Detonation propagation state in the initiator tube

In order to evaluate the influence of initiator tube on the deto- nation behaviour, cellular structures are recorded on the smoked foil along the initiator tube, as shown in Fig. 3. The detonation propagation direction is from left to right. For both cases, main triple-point trajectories are quite distinct on the smoked foil, forming fairly regular diamond shape cells. Cell sizes $\lambda$ are observed to be about 4 mm in both tubes. Ref. [27] also argued that the insert tube has little influence on the detonation wave. Thus, it indicates from cellular structure that the detonation propagates in a self- sustaining state, and the average velocity in the initiator tube can be obtained.

Fig. 4 shows the average velocity and the standard deviation, as error bars, in the initiator tube with acetylene-oxygen-argon mix- tures. The curve of theoretical Champan-Jouguet (CJ) detonation velocity is also indicated in the figure. Fig. 4a shows that in each initiator tube, the average detonation velocity is observed to approach the theoretical CJ velocity when the initial pressure $p_0$ is relatively high, and it gradually deviates from CJ value with the decrease of $p_0$. Subsequently, the velocity deficit becomes larger when $p_0$ drops further, due to the heat and momentum losses by boundary effects [25,33–35]. It also indicates that the velocity deficit is larger at the same $p_0$ when the tube diameter $D$ reduces. For other three mixtures, similar findings of velocity deficits can be found when the experimental error is considered, as shown in Fig. 4b–d. The increase of velocity deficit in a smaller tube can be explained by Fay’s model [33]. Near the detonation limit, the ve- locity deficit is observed to be about 10% for low argon diluted mixtures, while it reaches 20% for high argon diluted mixtures. The velocity deficit is due to heat and momentum loss from tube wall as well as the interference of boundary with the detonation instability.
For low argon diluted acetylene-oxygen mixtures, the cellular instabilities play a prominent role in the detonation propagation, and the influence of the boundary effects is slight. Hence the detonation velocity deficit is small. With the increase of argon dilution in acetylene-oxygen mixtures, the cellular instabilities of the detonation front are suppressed, leading to more energy loss with boundary effects, and thus the velocity deviation from CJ value becomes larger.

3.2. Velocity characterization

Typical velocity trajectories of successful and failed detonation transmissions at the expansion ratio of 2 are shown in Fig. 5 for the \( \text{C}_2\text{H}_2 + 2.5\text{O}_2 + 70\% \text{Ar} \) mixture. It shows that the successful detonation transmission represents an initial pressure of \( p_0 = 24.9 \text{ kPa} \); whereas the failed transmission corresponds to \( p_0 = 15.0 \text{ kPa} \). The incident detonation velocity in the initiator tube is approximately 1750 m/s and 1710 m/s for \( p_0 = 24.9 \text{ kPa} \) and 15.0 kPa, respectively, which is quite close to the theoretical CJ value of 1776 m/s and 1741 m/s, indicating that the detonation is well within the detonation limits and free from boundary effects.

For the case of \( p_0 = 24.9 \text{ kPa} \), when the detonation diffracts through the sudden expansion, the velocity drops to 70% of CJ value initially and re-accelerates back to CJ value at the second symbol downstream of the expansion. A self-sustained propagating detonation wave of about 1750 m/s is observed in the expanded tube and thus the detonation re-establishes itself after the transmission. However, at a lower initial pressure of \( p_0 = 15.0 \text{ kPa} \), the incident detonation de-accelerates rapidly in the receptor tube. By the end of the tube, the velocity decreases to about 500 m/s.

Fig. 6 shows the velocity trajectories of detonation transmission at the expansion ratio of 2 with \( \text{C}_2\text{H}_2 + 2.5\text{O}_2 \) and

![Figure 1](image1.png)

Fig. 1. The schematic of the experimental system.

![Figure 2](image2.png)

Fig. 2. Sample signals of the oscilloscope.

![Figure 3](image3.png)

Fig. 3. Cellular structures for \( \text{C}_2\text{H}_2 + 2.5\text{O}_2 + 70\% \text{Ar} \) mixture at \( p_0 = 5 \text{ kPa} \) in the (a) \( d = 25.4 \text{ mm} \) and (b) \( d = 38 \text{ mm} \) tube.
C$_2$H$_2$ + 2.5O$_2$ + 50%Ar. Ref. [20] indicated that the cellular instabilities of two mixtures are distinct by comparing the critical tube diameter and critical initiation energy. As shown in Fig. 6a, for the unstable C$_2$H$_2$ + 2.5O$_2$ mixture, the velocity approaches the CJ value in the initiator tube. At relatively high initial pressure $p_0$, when the detonation transmits to the receptor tube, the local velocity drops slightly and recovers quickly back to CJ value, indicating the detonation re-initiates in a short distance. Then it fluctuates ranging from 0.9 to 1.1 CJ velocity for some distance of travel until the detonation reaches the self-sustaining state. At $p_0 = 1.7$ kPa, the velocity of the diffracted wave approaches 0.6 $V_{CJ}$ before it jumps to the over-driven value at the location of the third symbol downstream of the expansion, indicating the detonation re-initiation distance is lengthened. When $p_0$ is decreased further to 1.3 kPa, the velocity drops to about 0.5 $V_{CJ}$ and maintains this value till the end, thus the detonation transmission fails at this condition. For the more stable mixture of C$_2$H$_2$ + 2.5O$_2$ + 70%Ar, above 6.0 kPa, the detonation can transmit to the receptor tube successfully, whereas below 5.0 kPa, the detonation decays and fails to transmit to the receptor tube. The velocity trajectories indicates that in the receptor tube the over-driven degree of the re-initiated detonation is less than the unstable mixture, and the velocity fluctuation is slighter as the over-driven detonation decays to the self-sustained detonation.

3.3. Cellular structures of transmitted detonation waves

Fig. 7 shows the cellular structure evolution in the receptor tube with the C$_2$H$_2$ + 2.5O$_2$ mixture at the expansion of 2. The left side of the foil represents the location of sudden expansion. It can be seen from Figs. 6 and 7 that at the end of the smoked foil velocity fluctuations and variations of the detonation cellular structures are

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**Fig. 4.** The average velocity and its standard deviation as error bars in the initiator tube.

**Fig. 5.** Typical trajectories of successful and failed detonation transmission with the 25.4 mm diameter initiator tube with C$_2$H$_2$ + 2.5O$_2$ + 70%Ar mixture.
small, thus the detonation wave propagates at a relatively steady state. Cell sizes are measured at the end of the foil and summarized in Table 1.

As shown in Fig. 7a, for the super-critical condition \( \frac{d}{\lambda} > 13 \), the detonation does not quench in the expanded tube. Cellular structures are observed to re-appear in quite a short distance from the expansion. Several semi-circular explosion regions followed by small cells can be observed on the smoked foil, indicating that the detonation implodes before the diffracted detonation front reaches the tube wall. Pintgen and Shepherd \[10\] observed that for super-critical outcome, transverse detonations are generated to ignite compressed but unreacted gas mixtures behind the leading shock front. Thus, in the super-critical regime, when a detonation diffracts from a circular tube, transverse detonations are generated at the shock front, leading to localized explosions.

Fig. 7b shows the detonation transmission under a sub-critical condition at \( p_0 = 3.5 \text{ kPa} \). Cell patterns diminish initially in the expanded tube and an extinction region is clearly observed. Subsequently, the detonation re-initiates when a cone-shaped boundary line followed by fine-scaled cells is shown on the smoked foil. From this locus, the re-initiated detonation propagates both along the tube axis and transversely into the unreacted gas mixture. Cells gradually grow as the detonation propagates, and the over-driven detonation decays to a self-sustained propagating detonation. It indicates that when the decoupled shock reaches the tube wall, the shock-wall interaction generates the Mach reflected wave, which triggers the detonation re-initiation.

At \( p_0 = 2.5 \text{ kPa} \), the re-initiation spot is observed to be about 100 mm downstream of the expansion. The diffracted detonation is initially quenched again, when some decayed triple-point trajectories are indicated on the smoked foil. Near the boundary line, more than one re-initiation points can be clearly observed on the smoked foil, indicating that shock-wall interaction generates several local explosions near the tube wall. The re-initiation process in the circular tube is somehow different from the detonation re-initiation in the two-dimensional rectangular channel \[26\], where the re-initiation position is unique and near top or bottom wall.

As \( p_0 \) is decreased further to 1.5 kPa, the re-initiation distance is significantly increased to 550 mm. A boundary line is observed to separate no cell region and fine cells region. The evolution of cell pattern is similar to the above photos. When the diffracted detonation travels about 500 mm distance, the decoupled shock may be too weak that shock-wall interaction cannot trigger the Mach reflection. Thus, it suggests that detonation re-initiation is triggered by DDT process as the initial condition approaches the detonation transmission limit \( p_{\text{lim}} \).

For the expansion ratio of 4, similar phenomenon of the cellular structure evolution can be observed in the receptor tube, as shown in Fig. 8. Ahead of the boundary line, no cells are indicated on the smoked foil. With the decrease of the initial pressure \( p_0 \), the re-initiation distance is progressively increased.

Detonation transmission behaviours at the expansion ratio of 1.34 are more interesting. Fig. 9 shows the cellular structures with the unstable \( \text{C}_2\text{H}_2 + 2.5\text{O}_2 \) mixture and the stable \( \text{C}_2\text{H}_2 + 2.5\text{O}_2 + 70\%\text{Ar} \) mixture. As shown in Fig. 9a, a single-headed spinning detonation with well-defined triple-point trajectory is observed in the initiator tube. When the spinning detonation wave transmits to the expanded tube, it keeps propagating downstream as the spin mode. The evidence of the triple-point trajectory can be seen along the foil. Fig. 9b shows that a single-cell detonation is formed in the initiator tube. When it transmits to the receptor tube, at the very beginning only a spin mode is left. It becomes wavy as the wave propagates. After about 700 mm distance of travel, the single-cell structure recovers from the expansion. The results indicate that when the expansion ratio \( D/d \sim a1 \), the incident detonation wave can transmit to the expanded tube successfully when the detonation is near the limits.

### 3.4. Re-initiation distance

By measuring the distance between the sudden expansion and the re-initiation spot, the re-initiation distance can be determined. Figs. 7 and 8 indicate that the re-initiation distance is relied on the mixture sensitivity, or the detonation cell size \( \lambda \). Here, A non-dimensionalized characteristic length-scale \( A \) is employed to correlate with re-initiation distance \[25\], which is defined as:

\[
A = \frac{d/\lambda}{k_c}
\]

where \( k_c \) is the critical diffraction ratio. Thus, \( A < 1 \) represents a sub-critical detonation transmission case. The values of \( k_c \) for acetylene-oxygen-argon mixtures are obtained from Ref. [20].

Fig. 10 gives the variance of re-initiation distance with non-dimensionalized cell size \( A \). Data of reinitiation distances with stoichiometric acetylene-oxygen-argon mixtures from Ref. [30] is also plotted for comparison. The figure shows that the present data.
points are in accord with the results of Sorin et al. [30], regardless of dilution ratios of argon. A critical value of $L$ is also found. When $L > 0.4$, the re-initiation distance remains relatively short (less than 100 mm), and it gradually grows with the reduction of $L$. Subsequently, the distance increases sharply with the further decrease of

### Table 1

<table>
<thead>
<tr>
<th>$p_0$ (kPa)</th>
<th>8.6</th>
<th>3.5</th>
<th>2.5</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$ (mm)</td>
<td>0.91</td>
<td>2.93</td>
<td>4.53</td>
<td>10.01</td>
</tr>
<tr>
<td>$d/\lambda$</td>
<td>27.9</td>
<td>8.7</td>
<td>5.6</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Fig. 7.** Smoked foil records in the expanded tube at the expansion ratio of 2 for $\text{C}_2\text{H}_2 + 2.5\text{O}_2$ mixture: $p_0 = (a) 8.6$ kPa; (b) 3.5 kPa; (c) 2.5 kPa; and (d) 1.5 kPa.

**Fig. 8.** Smoked foil records in the expanded tube at the expansion ratio of 4 for $\text{C}_2\text{H}_2 + 2.5\text{O}_2$ mixture: $p_0 = (a) 12$ kPa; (b) 5.5 kPa; (c) 4 kPa; and (d) 3 kPa.
\( \Lambda \) until it reaches about 500 mm as \( \Lambda \) approaches 0.2.

In order to generalize correlation between the re-initiation distance and the cell size for different expansion ratios, another characteristic length-scale \( D_h \) is employed to non-dimensionalize the re-initiation distance. For 3D expansion cases, \( D_h \) is the difference of the radii of initiator tube and receptor tube:

\[
D_h = \frac{D - d}{2} \tag{2}
\]

Wu and Kuo [25] investigated the detonation transmission behaviour in two-dimensional expansion channels with the stoichiometric ethylene-oxygen-nitrogen mixtures. For 2D expansion cases, \( D_h \) is the step height:

\[
D_h = \frac{H - h}{2} \tag{3}
\]

The evolution of dimensionless re-initiation distance as a function of dimensionless cell size is plotted in Fig. 11. As shown in the figure, the experimental data obtained from Ref. [30] and this study fall on a unified curve. It is also observed that most of data plots fall on the region where the dimensionless re-initiation distance is less than 50, while the other group of data is substantially larger. The reason lies in the fact that the detonation propagation states are different in the initiator tube. In our study, the detonation propagates as the multi-head cellular detonation mode before it transmits to the receptor tube. However, for lower values of \( \Lambda \), single-head spinning detonations propagate in the initiator tube [25]. It should note that the spinning detonation does not correspond to a unique initial condition. There is a range of conditions in which spinning detonations persist after its first appearance. As the lowest fundamental propagating mode, spinning detonations are not steady as they propagate, accompanied by the large fluctuation both in the velocity and cell patterns [36,37]. Under this condition, the detonation re-initiation is due to shock-flame instability, and the re-initiation distance can be hundreds of tube diameters long [36]. Therefore, detonation propagation modes in the initiator tube will apparently affect the detonation transmission behaviours, leading to the two distinct re-initiation distance regions.

4. Concluding remarks

In this study, detonation transmissions through finite expansions in round tubes are investigated for the stoichiometric acetylene-oxygen mixture with varying amount of argon dilution. The sudden expansion ratio is changed by varying the diameter of the initiator tube. The influence of both argon dilution and expansion ratio on the detonation transmission behaviours are examined. The results indicate that the initiator tube has little influence on the detonation wave. The influence of both argon dilution and expansion ratio on the detonation transmission behaviours are examined. The results indicate that the initiator tube has little influence on the detonation wave. In the initiator tube, within the detonation limit the detonation velocity reduces gradually as the initial pressure is progressively decreased, while the velocity decreases rapidly as the initial pressure approaches the limit. In the expanded tube, the over-driven degree of re-initiated detonation is observed to be higher for mixtures with low argon dilution.

For large expansion ratios of 2 and 4, localized explosions are shown on the smoked foil when the detonation re-initiated in the expanded tube at sub-critical regime. As the initial pressure approaches the limiting transmission pressure, the re-initiation distance is remarkably lengthened. At this condition, the detonation
re-initiation is probably ascribed to the DDT mechanism. The detonation transmission behaviours at the expansion of 1.34 are more interesting. The near-limit detonations are observed to transmit to the receptor tube successfully for mixtures with argon dilution up to 70%. The cellular structures can recover from the sudden expansion.

The re-initiation distance of the diffracted detonation is measured. A dimensionless cell size \( \lambda \) is introduced to correlate with the re-initiation distance. When \( \lambda \) is below a critical value, the re-initiation distance is significantly increased. Regardless of amount of argon dilution, a unified curve for \( \mathrm{C}_2\mathrm{H}_2/\mathrm{O}_2/\mathrm{Ar} \) mixtures is obtained. In conclusion, the experimental results provide applications in explosion safety assessment and in developing new devices to prevent explosions and detonations.

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**References**


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