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燃震波的形成及特性之實驗研究

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Abstract
The present study shows experimental results of the transmission of the overdriven detonation across a mixture in the tube of diameter near the detonability limits. The strength of the incident overdriven detonation play an important role in the wave transmission process. A transmitted overdriven detonation wave takes place instantaneously when a strong incident overdriven detonation wave is used. The near CJ state of the incident wave leads to a transmitted shock wave, and then the transition to the overdriven detonation occurs downstream. Whatever the transmitted overdriven detonation wave is attained instantaneously or by transition, the process of the transmitted overdriven detonation wave attenuating to near CJ detonation state occurs in all tests. In most tests, there is an unstable detonation wave observed after the attenuation process approaching to near CJ. This may be attributed to that the increase of the cell width in the attenuation process lies outside the detonability limits.

Keywords: deflagration-to-detonation, tube diameter, overdriven detonation wave

Introduction
The phenomenon of the transmission of detonation from one mixture to another of different sensitivity is of interest for the development of pulse detonation engines (PDE). To ensure the success of a PDE, a predetonator concept is adopted. A detonation wave can then be generated in the predetonator and transmitted into the larger diameter, main combustor filled with a hydrocarbon-air mixture to produce the required engine thrust. Critical parameters for the predetonator were investigated in various mixture compositions recently [1-3]. From a practical perspective, the use of liquid fuel that has been approved by the aviation industry such as JP-10 or Jet-A is considered for the main combustor. Because the cell size of JP-10/air and Jet-A/air is close to that of propane/air, propane is a suitable gaseous surrogate for JP-10 and Jet-A [4]. However, a previous study on detonation diffraction through different mixture compositions [3] indicated that the detonation wave in a tube of \( d = 33 \text{ mm} \) with a \( \text{C}_3\text{H}_8 + 5\text{O}_2 \) mixture failed to transmit into the main combustor with \( d = 165 \text{ mm} \), filled with a \( \text{C}_3\text{H}_8 + 5(\text{O}_2 + \beta\text{N}_2) \) mixture (\( \beta \geq 0.76 \)). The studies of Desbordes and Lannoy [5] showed that a CJ detonation wave propagating into a less sensitive mixture can result in an overdriven detonation condition, in which the cell size decreases with a higher degree of overdrive \( D^* = U / U_{CJ} \) and in turn a decrease in the diffraction critical diameter. Here the overdriven detonation wave (or called strong detonation wave) is defined as the detonation wave velocity \( U \) higher than theoretical CJ detonation velocity \( U_{CJ} \). They suggested a method to enhance a successful transmission of detonation waves into a larger tube, which is to move the interface between different mixture compositions prior to the location of area change. This method can be applied to carry out the predetonator concept. Furthermore, an overdriven detonation wave was observed in the Deflagration-Detonation-Transition DDT process [6]. It was expected that the overdriven detonation wave propagating into a mixture change will result in a higher degree of overdrive than that of the CJ detonation wave.

Transmission of detonation waves across
a mixture change has been studied from the 1950s [7-12]. Most studies used a detonation wave from a donor propagating into a buffer section to generate shock waves. They observed shock-induced ignition process in an acceptor mixture [7-9]. Effects of mixtures properties, shock strength, gradients of mixture compositions and initiator lengths were examined in these studies. Otherwise, some studies used a donor with long enough length to obtain a CJ detonation wave rather than a shock wave propagating into the acceptor [5, 10-12]. Comparing to these previous studies, the transmission of an overdriven detonation has not been studied in detail. For such reasons the present work performed experimental study on the transmission of the overdriven detonation between a C3H8/O2 mixture and a C3H8/air mixture. The understanding of this transmission process will provide significant information to design the predetonator of PDEs.

Results and discussion

Attenuation of the overdriven detonation in DDT

According to the results of the preliminary test, the degree of overdrive $D^*$ with different tube diameters is shown in Fig. 1. The equivalence ratio is near 1.1 for all tests. The decay of $D^*$ is correlated with $X / X_{ddt}$. This is because that the attenuation of the overdriven detonation wave is related to the rarefaction. And the strength of the rarefaction can be connected with $X_{ddt}$. Referred to Eq. (1), the decreasing rate of the particle velocity of the burned products just behind the overdriven detonation front due to the rarefaction is inverse proportioned to the distance from the closed end. It implies that a longer $X_{ddt}$ corresponds to a lower strength of the rarefaction.

$$\frac{du_r}{dt} = -2[(\gamma + 1)](U_r^2 / X)$$

(1)

Fig. 1 shows that the highest $D^*$ in all four tube diameters appears immediately behind the DDT transition location ($X / X_{ddt} \approx 1$). This is associated with the formation of a localized explosion in a DDT process [6]. Among all tube diameters, there is the highest $D^*$ in tube of $d = 152.4$ mm. We can find that $D^*$ decreases with increasing $X / X_{ddt}$, and the length of attenuation of the overdriven detonation wave approaching to the CJ detonation is estimated about $2X / X_{ddt}$. In order to obtain a high $D^*$ of incident overdriven detonation wave, the interface of mixture change should be placed close to DDT location. In the experiment of the transmission of an overdriven detonation wave, the tube diameter of 50.8 mm was used. We set the diaphragm locations as 152.4, 203.2 and 254 mm, which are all within $2X / X_{ddt}$ (300 mm). The difference in the diaphragm locations will cause not only different strength of the incident overdriven detonation wave but also different strength of the rarefaction.

Transmission of overdriven detonation wave across a mixture change

The measured $D_i^*$ of the incident overdriven detonation wave prior and next to the diaphragm at three diaphragm locations is shown in Fig. 2. For $L_D = 152.4, 203.2$, there is a dramatic variation in $D_i^*$ among these tests although their mixture concentration are unchanged ($\phi_i = 1$). For $L_D = 254.2$, $D_i^*$ has a slight variation and
lie on the range from 1~1.1. This phenomenon is probably attributed to the inherent non-universal way for DDT to occur [6] and the existence of the diaphragm across a mixture change. In the DDT process, a number of compression waves accompanying the flame acceleration run ahead of the flame and reflect from the diaphragm. Not far away enough of the transition location from the diaphragm, the reflected compression waves will further precompress non-reacted mixture and cause higher $D_i^*$ than that without precompressing in the preliminary test. With different strength of the reflected compression wave due to that flame acceleration process differs in various ways for DDT, the variation in $D_i^*$ naturally occur. Whereas increasing $L_D$ decreases the strength of the reflected compression wave from the diaphragm because more compression waves will be caught up by the established detonation wave in DDT process. Fig. 3 shows the measured $D_i^*$ of the transmitted wave behind and next to the diaphragm. With different mixture compositions $\phi_i$, $D_i^*$ for $L_D = 254$ is closely comparable and near to CJ detonation state. But $D_i^*$ for $L_D = 152.4, 203.2$ represents a wide variation. It is consistent with the distribution of $D_i^*$ shown in Fig. 2.

These results show that $D_i^*$ mainly depends on $D_i^*$ rather than $\phi_i$. It indicates that the observation of the transmitted wave behind the diaphragm for each test must concern its specific degree of overdrive of the incident overdriven detonation wave even the diaphragm location is the same. Moreover, the results shows that $D_i^* = 0.95$ as $D_i^* = 1.07$ with $\phi_i = 1$ and $\phi_i = 1$. This sub-CJ state of the transmitted wave is more close to $D_i^*(I_3)$, which is the degree of overdrive of the transmitted shock wave. It shows that a transmitted shock wave is obtained as a slight degree of overdrive of detonation wave impacts the mixture change interface.

After the overdriven detonation wave impacting the diaphragm, the velocity of the transmitted wave falls abruptly shown in all tests. It is due to the presence of the concentration discontinuity and the diaphragm [10]. This study showed that the transmission of detonation wave to a weaker mixture was as effective with the diaphragm as without. In addition, Berets et al. [7] indicated that the diaphragm can cause the time delays in the transmission of the waves. In the present study, no attempt to measure this time delay since it is difficult to estimate the time delay with an unstable incident overdriven detonation wave. Consequently, the mean speed across the diaphragm is not included in our analysis and discussion below.

According to all experimental results, the wave transmission can be classified into three types behind the diaphragm:

A. Decay to overdriven state and no transition.
B. Decay to overdriven state and transition.
C. Decay to sub-CJ state and transition.

Typical diagram of the degree of overdrive varying with the distance from the closed is shown in Fig. 4. For the type A, there are two distinct modes observed. The displacement-time diagram for mode (A1) is shown in Fig. 5. The high overdriven detonation wave decays abruptly at the diaphragm and then maintains an overdriven
state \( D^*_i = 1.43 \) between \( A_5 \) and \( A_6 \). This overdriven detonation wave gradually attenuate to near CJ state \( D^*_i = 0.9 \) between \( A_7 \) and \( A_8 \). Subsequently, the mean speed measured at the rear of the test tube is \( 0.8 D_{CJ} \). The pressure profile measured at \( A_0 \) represents no detonation wave to occur, see Fig. 7 (a). In this mode, the transmitted overdriven detonation wave is obtained because of high \( D^*_i \). The rarefaction leads to the attenuation of the transmitted overdriven detonation wave. Because the cell width \( \lambda \) depends on the degree of overdrive [5], the attenuation process will increase \( \lambda \). Once \( \lambda \) becomes so large to lie outside the detonability limits \( d \geq \lambda \), the detonation wave starts to fail. For \( \phi_i = 0.94, \lambda \approx 60 \) mm at CJ detonation state, which is larger than the tube diameter \( d = 50.8 \) mm. This is most likely interpretation that not a detonation wave is found as the attenuation of the transmitted overdriven detonation wave approaching CJ detonation state. This mode of wave transmission is only obtained at \( L_D = 203.2 \) mm for \( \phi_i = 1.1, 1.0 \) when a drastic incident overdriven detonation wave \( (D^*_i > 2.64) \) is found.

Fig. 6 shows the displacement-time diagram for mode (A2). The transmitted overdriven detonation wave is obtained \( (D^*_i = 1.32) \) after diaphragm ruptures and gradually decays to near CJ state \( (D^*_i = 0.99 \) between \( A_5 \) and \( A_6 \) ). Then an overdriven detonation wave \( (D^*_i = 1.17) \) is found between \( A_7 \) and \( A_8 \). Further downstream between \( A_8 \) and \( A_9 \), the overdriven detonation again decay to near CJ state \( (D^*_i = 0.93) \). Over the rear of the test tube, this wave propagating at \( 0.98 D_{CJ} \). Near to the open end, a detonation wave is observed, see Fig. 7 (b). Similarly, the process of the transmitted overdriven detonation wave attenuating to CJ detonation state occurs. But the distances of this process for mode (A1) and (A2) are 153.65 mm and 73.5 mm, respectively. The difference strength of the incident overdriven detonation wave between mode (A1) and mode (A2) may cause this result. Where \( D^*_i = 5.29 \) for mode (A1) and \( D^*_i = 2.12 \) for mode (A2), see Fig. 4 and 5. In addition, the stronger rarefaction due to the shorter \( L_D \) in the mode (A2) also results in the faster decay.

Because of the weaker \( D^*_i \) and stronger rarefaction, the pressure rise after the diaphragm mode (A2) shows not as steep as that of mode (A1), see Fig. 5 and 6. In must be noted that the transition to an overdriven detonation wave is observed after the attenuation process between \( A_7 \) and \( A_8 \), and then it decays to near CJ state again. This repeated process of the attenuation, transition, and attenuation was also observed and regarded as an unstable detonation wave in the Ref [10]. However, this unstable detonation wave is not found in mode (A1). The question is discussed later. For this mode, it is seen for all tests at \( L_D = 152.4 \) mm for \( \phi_i = 1.1, 1.0 \).

It must be noted that for the similar strength incident overdriven detonation wave and test condition, mode (A1) only happens at \( L_D = 203.2 \) mm. This implies that the rarefaction at \( L_D = 152.4 \) mm have more significant effect on the wave transmission process to result in mode (A2) rather than (A1) to occur. In
addition, mode (A2) also frequently happens at \( L_D = 203.2 \) mm with intermediate strength of the incident overdriven detonation wave \( (D_i^* = 1.06 - 2.12)\).

In Mode (B), the overdriven state \( (D_i^* = 1.07)\) is obtained after diaphragm ruptures between \( A_5 \) and \( A_6 \). However, a gradually acceleration process takes place and develop a higher degree of overdrive \( (D_i^* = 1.25)\) between \( A_7 \) and \( A_8 \). Then the overdriven detonation wave decay to near CJ state \( (D_i^* = 0.93)\) between \( A_8 \) and \( A_9 \) as modes (A1) and (A2). The propagation speed measured at the rear of the test tube is \( 0.81D_{CJ} \). And not a detonation wave is found near to the open end. For the acceleration process rather than attenuation process after diaphragm ruptures, it is considered that a transmitted shock wave is formed. Because of less reactivate mixtures in this case \( (\phi_i = 0.76)\), the induction time to react is too long to result in no detonation wave initiated instantaneously. In this case, the overdriven state after the diaphragm corresponds to a high strength of shock wave. The transmitted shock wave preheats the mixture and results in reaction. Small pressure disturbance from the reaction accelerates the transmitted shock wave and transition to overdriven detonation wave. The detailed transition mechanism has been observed by Edwards et al. [8, 9]. The unstable detonation wave is also not found in this mode. This mode is a special case in all tests. We found it at \( L_D = 203.2 \) mm for \( \phi_i = 1.0 \) with \( D_i^* = 4.04 \). This mode may occur when a drastic incident overdriven detonation wave and low reactivate mixtures is used.

In mode (C), a sub-CJ state \( (D_i^* = 0.77)\) is observed after diaphragm ruptures between \( A_3 \) and \( A_4 \). The strength of the incident overdriven detonation wave of this mode \( (D_i^* = 1.08)\) is apparently lower than the other modes. It leads to form a transmitted shock wave as shown in section 3.2. Fig. 8 shows the displacement-time diagram for this mode. The transition to an overdriven detonation wave takes place between \( A_4 \) and \( A_5 \). From Fig. 4, the attenuate of new overdriven detonation wave to near CJ state without transition downstream is found. However, based on Fig. 8, there is another transition to overdriven detonation wave between \( A_7 \) and \( A_8 \). Then it decays again downstream. This reveals the occurrence of the unstable detonation wave. The propagation speed measured at the rear of the test tube is \( 0.92D_{CJ} \). Near to the near open end, a detonation wave is still observed. This mode is found at \( L_D = 152.4 \) mm for \( \phi_i = 0.9 \). It is due to the DDT run-up distance for this mixture is longer than \( 152.4 \) mm [13]. A high speed turbulent flame is used to impact the mixture change interface and results in the formation of the transmitted shock wave. In addition, this mode also frequently appears at \( L_D = 254 \) mm for \( \phi_i = 0.9, 1.0, 1.1 \). In these tests, \( D_i^* = 0.9 - 1.07 \), they are reasonably regarded as using an incident CJ detonation wave in the wave transmission.

Among these modes, an unstable detonation wave appears in mode (A2) and (C), which is mostly found in all tests. The experiments by Mooradian and Gordon [10, 22] have shown similar results. They noted the
unstable detonation wave near the detonability limits as the overdriven detonation wave decays approaching the CJ state. This unstable detonation wave would be a spinning detonation or a galloping detonation depending on how far the test condition from the detonability limits, e.g. according to the cell width and the tube diameter [19, 23]. Generally, the unstable detonation wave would be characterized by the measured longitudinal pulsations, defined as pitch. The pitch of the spinning detonation and galloping detonation is about $3d$ and more than $100d$, respectively [23]. Gordon et al. further pointed that the pitch for the spinning detonation in hydrogen-oxygen mixture with diluted gas could be two to six times the tube diameter [22]. In this study, the tube diameter $d = 50.8$ mm is near and outside the detonability limits. Employing the repeating transition phenomenon as the unstable detonation wave present, the pitch is estimated to be 86.5-150 mm, see Fig. 8. It points out that the unstable detonation wave in this study may be a spinning detonation. In the modes (A1) and (B), the unstable detonation wave is not present in our observation. The possible explanation for it is not adequate transducer locations to measure it or no this phenomenon in fact in these modes. It is not clear at this moment.

Otherwise, we should notice that there is no detonation wave near the open end in some modes. Fig. 9 shows the failure or not of the detonation wave near the open end for all tests. It shows that the survival of the detonation wave is mainly related to the mixture compositions and propagating velocity. It is independent of what mode of wave transmission is. The critical condition is $\phi_i \geq 0.87$ and $D_i^* \geq 0.82$. Both of these parameters are directly connected to the cell width. It implies that the detonability limits is dominant factor in the propagation of the detonation wave after the process of wave transmission.

Summarizing these experimental results, mode (A1), (A2) and (B) is suitable to apply in the predetonator to enhance a successful transmission of detonation waves into a larger tube. This is because that there is high degree of overdrive of transmitted overdriven detonation after the mixture change interface. However, the strength of the incident overdriven detonation is highly overestimated in this study due to the presence of the diaphragm at the mixture change interface. For instance, in the same test condition, $D_i^*$ for $d = 50.8$ mm in the preliminary test is about 1.3 just behind DDT, see Fig. 1. And $D_i^*$ with diaphragm at 152.4 mm (near DDT location) is 1.41 – 4.24, see Fig. 2. Further, an extreme strong incident overdriven detonation wave is required to attain mode (A1) and (B); these are $D_i^* > 2.64$ for mode (A1) and $D_i^* = 4.04$ for mode (B). This indicates that we can not attain the mode (A1) and (B) in practice. Fortunately, mode (A2) can be obtained because only an intermediate strength of the incident overdriven detonation wave is required. To meet it, the mixture change interface should be placed between slight behind DDT location and one diameter from DDT location.

Conclusions

The present study shows experimental results of the transmission of the overdriven detonation across a mixture in the tube of diameter near the detonability limits. The results are summarized as follows:

1. The rarefaction from the end wall can
weaken the transmitted overdriven detonation wave in the wave transmission process.

2. The detonation wave is observed near the open end if $\phi_i \geq 0.87$ and $D^o_i \geq 0.82$, which is independent of what kind of the wave transmission is. The propagation of the detonation wave after the wave transmission process of wave directly connects with detonation limits.

3. For application in the predetonator, it is suggested that the mixture change interface should be placed between slight behind DDT location and one diameter from DDT location.

References.


Predicting Chemical Kinetic Behavior behind Incident and Reflected shocks, SAND82-8205, 1982.


Figure 1 Degree of overdrive with different tube diameters

![Figure 1](image1)

Figure 2 Measured $D_i^*$ of the incident overdriven detonation wave for $\phi_i = 1$

![Figure 2](image2)

Figure 3 Measured $D_t^*$ of the transmitted overdriven detonation wave

![Figure 3](image3)

Figure 4 Typical diagram of the degree of overdrive varying with the distance from the closed

![Figure 4](image4)

Figure 5 The displacement-time diagram for mode (A1), $A_3$ is scaled by 4; $A_4$ and $A_5$ are scaled by 2

![Figure 5](image5)
Figure 6 The displacement-time diagram for mode (A2), $A_3$ is scaled by 2

Figure 7 Typical pressure measured near the open end at $A_{ij}$ (a) shock wave (b) detonation wave

Figure 8 The displacement-time diagram for mode (C)

Figure 9 The wave behavior near the open end for all tests