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Formation and Propagation of Single Pulse Detonation Wave

Abstract

An experimental study was conducted to investigate the effect of propane-oxygen mixtures composition on the DDT run-up distance in a smooth tube. Measurements of the combustion wave front and pressure wave were conducted to obtain the DDT run-up distance. The experimental results show two typical deflagration-to-detonation transition processes (DDT), which are induced by a localized explosion originating near the turbulent flame or by the precursor shock wave. Based on the criterion of self-initiation and autoignition limit, the critical turbulent flame burning velocity is estimated. Consequently, the amplification factor is obtained from this critical turbulent flame burning velocity and initial laminar flame burning velocity. This present study indicated that the DDT run-up distance based on the trajectories of the combustion and detonation waves is linearly dependent on the amplification factor, which only depends on the specified initial conditions of reactant mixtures. This implies that the DDT run-up distance can be predicted when the initial conditions of the reactant mixtures are known, which can be applied in the development of the PDE. This paper then discusses the amplification factor is associated with the comprehensive form of gasdynamic and the fluiddynamic feedback mechanism. The composition of the mixtures is only related to the gasdynamic feedback mechanism, and affects the DDT run-up distance. Since both critical turbulent flame burning velocity and initial laminar flame burning velocity are independent of the diameter of the tube, the DDT run-up distance might be proportional to the diameter of the tube at a given amplification factor.

Keywords: DDT run-up distance, criterion of self-initiation, amplification factor

Nomenclature:

- \( d \) = diameter of tube
- \( C_0 \) = sound speed ahead of the shock
- \( AS \) = amplified shock wave
- \( CW \) = combustion wave
- \( DW \) = detonation wave
- \( PS \) = precursor shock wave
- \( RW \) = retonation wave
- \( E_\alpha \) = overall error of the DDT run-up distance
- \( M_s \) = Mach number of precursor shock wave
- \( P_s \) = pressure of post-shock condition
- \( Q \) = specific chemical energy in the standard state
- \( Re_\lambda \) = turbulent Reynolds number
- \( T_s \) = temperature of post-shock condition
- \( U_s \) = velocity of post-shock condition
- \( U_f \) = critical turbulent flame propagation velocity
- \( u_t \) = critical turbulent flame burning velocity
- \( u_i \) = laminar flame burning velocity based on the
- \( u_i / u_t \) = amplification factor
- \( X_f \) = DDT run-up distance
- \( \Delta u_r \) = component error of retonation wave average
- \( \Delta \phi \) = component error of pressure transducer response
- \( \lambda \) = turbulent ratio of the reactant mixtures
- \( \gamma \) = specific heat ratio ahead of shock
- \( Q' \) = turbulent microscale length
- \( u_i^* \) = \( u_i / C_0 \)
- \( u_t^* \) = laminar burning velocity based on the properties
- \( u^* \) = root mean square value of the turbulent velocity
- \( X^* \) = nondimensional length
- \( X_f^* \) = nondimensional DDT run-up distance

1. Introduction

The pulse detonation engine (PDE) offers the high performance in propulsion and compact structure compared to the current propulsion devices. It has attracted more attention recently. One of the key issues in the development of the PDE is the transition of
deflagration-to-detonation process (DDT), in which shorter DDT run-up distance could reduce the weight of the PDE and might operate at a higher frequency [1]. It is noted that the DDT run-up distance is dependent on the tube geometry, the wall roughness, the boundary condition at the ends of the tube, the energy and location of the igniter, and the initial conditions of reactant mixtures (temperature, pressure and composition) [2, 3].

Based on the photographic observation of the DDT process [2,4,5], there are three distinguishable stages: (1) the acceleration of the initial laminar flame to the turbulence flame; (2) creation of the critical autoignition condition for the formation of localized explosion; (3) amplification of the blast waves from the localized explosion to detonation wave. Taylor and Tankin [6] pointed out that the critical autoignition condition is achieved via the adiabatic compression of the shock wave generated by the turbulent flame at the critical turbulent flame speed. For the most of hydrocarbon-oxygen mixtures, the post-shock temperature (T_s) required for the autoignition limit is about 1100 K. This gives the minimum precursor shock strength of M_s ≈ 4. Nevertheless, the occurrence of a localized explosion does not necessarily result in the onset of the detonation wave. For the amplification of a localized explosion into the detonation wave, the chemical energy release by an explosion must make a positive contribution to the shock wave produced by the chemical energy released prior to this explosion. This is known as the Shock Wave Amplification through Coherent Energy Release (SWACER) [5].

The present study investigates the composition of propane-oxygen mixtures on the DDT run-up distance. Measurements of the combustion wave front and pressure wave were conducted. The numerical calculation by CEC89 code and CHEMKIN III were also performed to evaluate the effects of the critical turbulent flame burning velocity and the laminar flame burning velocity on the DDT run-up distance.

2. Experiment

2.1 Facility and instrumentation

The experiments were performed in a smooth detonation test tube with SUS316 stainless steel as shown in Fig. 1. The tube is 914.4 mm long and 152.4 mm in internal diameter. A weak electric spark at the closed end of the tube was used as the ignition source. Five PCB piezoelectric pressure transducers (Model 112A) were mounted along the streamwise direction of the tube. The average velocity of the pressure wave is determined by the time of flight between the pressure transducers. An additional pressure transducer was positioned on the closed end surface. Further, the combustion wave front was detected by five HAMAMATSU photodiode (Model S6468-10 with spectral response from 320 to 1000 nm).

The NI SCXI system and the LeCroy (Model 6810) waveform recorders were used for the present experiments. The test conditions were controlled by the NI SCXI system, and the signals of the pressure transducers and photodiodes were stored in the LeCroy system. The typical sampling period is 2 µs (500 kHz). It is noted that the response time of the PCB pressure transducers is 2 µs as quoted by the manufacturer. The uncertainty of the pressure wave average velocity is estimated to be 1.7-5.5 %. For the photodiode, the response time of is 3.5 ns. The uncertainty of the combustion wave front is negligible compared with the measurement of pressure wave.

2.2 Experimental methods

Tests were conducted with the propane-oxygen mixtures. Prior to all the experiments, the tube is evacuated to less than 0.05 kg/cm² with a thin diaphragm sealing the open end. The mixtures were filled based on the partial pressure method to control the concentrations of propane and oxygen, which corresponds to the different equivalence ratio φ of the reactant mixtures. The initial pressure and temperature of the mixtures for all the tests were at 1 atm and room temperature, respectively.

DDT run-up distance X_c corresponds to formation of the detonation wave when the velocity of the pressure wave or the combustion wave front is greater than the Chapman-Jouguet velocity (CJ velocity). In general, the CJ velocity could be estimated by the pressure transducer measurements [3, 7] or the ionization probe monitor [8-10]. Another method employed the measurement of the flame emission [11]. It is also known that the essential feature of the onset of detonation is the formation of a localized explosion in the vicinity of the turbulent flame brush [12]. The blast wave propagates into the unburned gases to induce a detonation wave and also backs into the burned gases to form a retonation wave. In other word, the retonation wave is coupled with the formation of the detonation wave. Thus DDT run-up distance obtained from the trajectories of the combustion wave and retonation wave would be more realistic for the physical phenomena.

2.3 Criterion for Self-Initiation

Lee [2] has proposed a criterion to predict the critical state for the onset of detonation in DDT process with the known initial conditions. The model assumed that the energy release rate in the turbulent flame is linked directly to the rate of work done by the piston that maintains the required shock strength. Thus, for the energy release rate per unit area of the shock may be written:

\[ \rho_s Q u_t = P_t U_t \]  \hspace{1cm} (1)

where \( P_t \) and \( U_t \) denote the pressure and velocity of the post-shock condition. \( \rho_s \), \( Q \), and \( u_t \) represent the density of the unburned gas in front of the turbulent flame, the specific chemical energy in the standard state, and the critical turbulent flame burning velocity, respectively. For a given strength of shock (\( M_s \)) that is computed from the adiabatic shock relation based on temperature of post-shock condition (\( T_0 \)) equal to 1100 K, the Rankine-Hugoniot equations give state variables across the shock. Substituting into Eq. 1 leads to

\[ u_t^* = 4(\gamma - 1) \rho_s M_s^3 [(\gamma + 1)Q^*] \]  \hspace{1cm} (2)

Where \( u_t^* = u_t/C_0 \) and \( Q^* = Q/C_0^2 \). In the present study, \( \gamma \) and \( Q \) for a given equivalence ratio of the reactant mixtures (\( \phi \)) is calculated from the chemical
equilibrium program CEC89 [13]. A sketch diagram of the flame acceleration process at the beginning stage and the critical turbulent flame speed are shown in Fig. 2a and Fig. 2b, respectively. It is also noted that the turbulent flame burning velocity is defined by \( u_t = U_f - U_r \), where \( U_f \) is critical turbulent flame propagation velocity.

Lee [2] further indicated that the DDT run-up distance has some bearing on the amplification factor, \( u_t / U_f \), where \( u_t \) is initial laminar flame burning velocity. It is the characteristic property of a given reactant mixtures and depends only on the temperature, pressure and composition of the unburned mixtures. The CHEMKIN III numerical code for the simulation of a freely propagating, one-dimensional, adiabatic premixed flame [14] was used to calculate \( u_t \).

Figure 3a shows the variations of \( u_t \) and \( U_f \) with \( \phi \). For a given \( T_r \), the decreasing \( \gamma \) and increasing \( M_0 \) (or \( U_r \)) is associated with higher value of \( \phi \). This leads to the increase in \( U_f \). For the critical turbulent flame burning velocity, there exhibits a minimum near the stoichiometric condition ( \( \phi = 1 \)). A sharp increase toward the lean fuel and gradually rises for rich condition are also observed. The amplification factor in Fig. 3b shows a similar trend with the critical turbulent flame burning velocity. The U-shaped curve corresponds to the influence of the equivalence ratio on the specific chemical energy. For more sensitive reactant mixtures, there shows smaller amplification factor. This implies less increase in the flame velocity for the onset of detonation.

3. Results and Discussion

3.1 Deflagration-to-Detonation Transition

A typical result of DDT process at \( \phi = 1.028 \) is presented in Fig. 4. Six pressure transducers are positioned at \( X^* = 0, 1.25, 2.33, 2.5, 3.5, 4.75 \), and five photodiodes are positioned at \( X^* = 1.5, 1.75, 2.33, 2.5, 3.5 \). The pressure signals and photodiode signals are shown as solid lines and light-solid lines, respectively. Three kinds of trajectories, the combustion wave front (CW), detonation wave (RW) and deflagration wave (DW) are illustrated as shot-dash line, dash-dot line and long-dash line, respectively. It can be seen that the average CW velocity increases downstream. When the average CW velocity exceeds the critical turbulent flame propagation velocity (1129 m/s), a nearly constant volume combustion or a localized explosion is supposed to be formed between \( X^* = 2.5 \) and 3.5. Here a RW moves from this constant volume combustion region back to the ignition source. Thus the DDT position is evaluated from intersection of the CW and RW trajectories, i.e. \( X^*_D = 2.91 \). Further downstream, the DW propagates at 2976 m/s, which is higher than the CJ velocity (2373 m/s) calculated from CEC89. Brinkley and Lewis [12] indicated that the acceleration of the deflagration wave prior to the DDT results in compression or shock wave ahead of the deflagration wave. The unburned mixtures is pre-compressed and pre-heated, which may change the initial condition, and lead to increase the ideal CJ velocity.

To further understand the transitional process, the wave diagram at \( \phi = 1.028 \) is re-plotted in Fig. 5. A small pressure jump at 8.34 ms near the location of the DDT (\( X^* = 2.33 \)), which is considered as the precursor shock wave ahead of the CW, is not amplified. The CW front is detected at 8.372 ms (\( X^* = 2.5 \)) and at 8.388 ms (\( X^* = 2.33 \)). At 8.406 ms, the photodiodes detect the CW fronts almost simultaneously between \( X^* = 2.5 \) and \( X^* = 3.5 \). This intensive combustion, which is related the localized explosion, would generate strong pressure pulse. Further downstream, peak pressure is observed at \( X^* = 3.5 \). This amplification of the shock wave is due to the time sequence of chemical energy release from combustion wave, and is consistent with the study of Lee and Moen [5].

Another typical result of DDT process is shown in Fig. 6. The acceleration of the CW front, simultaneous combustion (localized explosion) and the RW are also observed. However, a strong shock wave occurs ahead of the localized explosion, and the CW accelerates behind the shock wave. When the CW is undergoing the constant volume combustion, it gradually overtakes with the shock wave and a DW is formed. In other word, the DDT is due to the strength of the shock wave generated ahead of the turbulent flame. This strong shock wave induces the occurrence of the localized explosion and the transition to a DW. It is also noted that the DDT by a localized explosion originating near the turbulent flame is found in most of the present test. No explanation is given at this moment.

3.2 DDT run-up distance

The DDT run-up distance \( X^*_D \) is estimated by three methods in the present study, which include the average velocity of the pressure wave or the CW greater than the CJ velocity, and the intersection of the CW and RW trajectories. For the average velocity method, the uncertainty is related to the distance between the two transducers (pressure transducer or photodiode) and the data sampling period. The uncertainty of \( X^*_D \) is estimated to be \( \pm 0.625 \). For the trajectory method, estimation of \( X^*_D \) is mainly associated with the response time of pressure transducer \( (\Delta \tau) \), and the average velocity of RW \( (\Delta u_r) \). The overall error \( (E_a) \) could be computed using Eq. 3 [15]. The calculation results of \( E_a \) are approximately 0.28-4 %.

\[
E_a = \Delta u_r \frac{\partial X^*_D}{\partial u_r} + \Delta \frac{\partial X^*_D}{\partial t} \quad (3)
\]

Further, the dependence of the DDT run-up distance on the equivalence ratio \( \phi \) is shown in Fig. 7. Based on the average velocity method by pressure transducers, it can be seen that the \( X^*_D \) ranges between 3.5 and 4.75. This may imply \( X^*_D \) is not dependent on \( \phi \). However, small spacing of the pressure transducers would be required to detect the actual position of the DDT. For the average velocity method by photodiodes, the minimum \( X^*_D \) appears near \( \phi = 1 \) and \( X^*_D \) increases toward the lean side or rich side. However, the spacing of the photodiodes also limits the resolution of \( X^*_D \). For the present study, the trajectory method is considered to be more adequate for the estimation of \( X^*_D \). The minimum \( X^*_D \) occurs at
stochiometric ratio ($\phi = 1$), and no DDT is observed for $\phi > 1.6$ and $\phi < 0.58$ within the present 914.4 mm long tube. This trend is similar to the observation by the average velocity method through photodiodes. However, the relationship between $X_t^*$ and $\phi$ is clearer.

It is known that the DDT run-up distance is related to the amplification factor [2]. The variations of the DDT run-up distance and amplification factor with the equivalence ratio are shown in Fig. 8. It can be seen that the $X_t^*$ and $u_t / u_i$ with $\phi$ show the similar trend, e.g. U-shaped curve. This implies the similar effect of the equivalence ratio on the amplification factor and the DDT run-up distance. It is also interesting to note that the relationship between $X_t^*$ and $u_t / u_i$ could be written as follow:

$$X_t^* \approx 0.5 \frac{u_t}{u_i}$$  \hspace{1cm} (4)

The above equation indicates the linear dependence of DDT run-up distance on the amplification factor. For smaller amplification factor, there shows smaller DDT run-up distance. Further, it is noted that $u_t$ and $u_i$ are obtained using the Eq. 2 and the CHEMKIN III code, respectively. Those are only based on the specified initial conditions of reactant mixtures (temperature, pressure, and composition). This may imply that the DDT run-up distance can be predicted when the initial conditions of the reactant mixtures are known. It is significant achievement in the DDT fundamental studies and can be applied in the development of the PDE.

3.3 Amplification factor

As mentioned above, amplification factor plays an important role on the DDT run-up distance. In the flame acceleration of the DDT process, the laminar flame burning velocity depends on the reaction rate, which is related to temperature and pressure. The turbulent flame burning velocity depends on the turbulence intensity of unburned mixtures in front of the flame. Various physical effects could cause the flame acceleration from the laminar flame to the critical turbulent flame, which are known as the gasdynamic and fluiddynamic feedback mechanism [16]. In gasdynamic feedback mechanism, compression wave or shock wave ahead of flame front generated by the acceleration of the deflagration wave will preheat the unburned mixtures and lead to an increase in burning velocity. In fluiddynamic feedback mechanism, an increase in burning velocity increases the expansion flow with an associated increase in the turbulence intensity in front of the flame which in turn increases the burning velocity and further increases the expansion flow. Andrews et al. [17] proposed a correlation for $u_t / u_i^*$ as function of the turbulent Reynolds number ($\text{Re}_t$). The correlation form [18] is as follows:

$$\frac{u_t}{u_i^*} = 1 + 0.022(\text{Re}_t)^{1.12}$$  \hspace{1cm} (5)

where $\text{Re}_t = u' \lambda / \nu$ and $u_i^*$ is the laminar burning velocity based on the properties of unburned mixtures ahead of flame. Substituting Eq. 5 into Eq. 4 leads to the relation:

$$X_t^* \approx 0.5 \frac{u_t}{u_i} \left[1 + 0.022(\text{Re}_t)^{1.12}\right]$$  \hspace{1cm} (6)

The first term, $u_t / u_i$, indicates the increase of the laminar burning velocity due to gasdynamics feedback mechanism, which is related to the initial temperature, pressure, mixtures composition and precursor shock strength. The second term, $[1 + 0.022(\text{Re}_t)^{1.12}]$, indicates the increase of the burning velocity due to the turbulent Reynolds number $\text{Re}_t$ or the turbulence intensity $u'$ in fluiddynamic feedback mechanism. When the process has no turbulent effect ($u'=0$ and $\text{Re}_t=0$), the gasdynamic feedback mechanism dominates the flame acceleration process. On the other hand, if $\text{Re}_t$ increases to a sufficient level, the turbulent flow will play a significant role in flame propagation.

Andrews et al. [17] further pointed out that $\text{Re}_t$ is independent of mixtures composition. Therefore, the composition of the mixtures is only related to the gasdynamic feedback mechanism, and affects the DDT run-up distance.

The present study indicates that the DDT run-up distance is coupled with the amplification factor. However, both $u_t$ and $u_i$ are independent of the diameter of the tube. For a given amplification factor, the DDT run-up distance might be proportional to the diameter of the tube ($X_t \propto d$). This agrees with the experimental results of Nettleton [19] for $d > 102$ mm. However, the present study is only limited to a fixed diameter of tube ($d = 152.4$ mm). Further study is required to characterize the combined effect of amplification factor and diameter of a tube on the DDT run-up distance.

4. Conclusions

The present investigation examines the effect of the equivalent ratio of reactant mixtures on the DDT run-up distance in a smooth tube. The results of this study are summarized as follows:

1. Two typical transition processes are observed, including DDT by a localized explosion originating near the turbulent flame and due to the precursor shock waves.
2. The DDT run-up distance based on the intersection of CW and RW trajectories wave is considered to be more suitable than the average velocity methods.
3. The minimum DDT run-up distance occurs at $\phi = 1$ and increases with increasing or decreasing $\phi$. No DDT is observed for $\phi > 1.6$ and $\phi < 0.58$ within the 914.4 mm long tube.
4. The DDT run-up distance is linearly dependent on the amplification factor for the present test condition.

5. References

Project Evaluation
The experimental tasks in the project have been carried out and compared with the theoretical computes in the present study. The measurement technique in observing detonation phenomena with pressure transducers and photodiodes is also established. Some results have been presented in “2003 International Symposium on Combustion Work-In-Progress Posters” and “30th International Conference on Combustion”. The results of this study are important to design PDE practically. To gain the achievement of PDE, further and deeper investigations will be performed by the authors.

Figures
Figure 4. Wave diagram at \( \phi = 1.028 \). Solid lines are pressure transducer signals time histories. Light-solid lines are photodiode signals time histories.

Figure 5. Wave diagram at \( \phi = 1.028 \) at increase time and spatial resolution. DDT is by a localized explosion originating near the turbulent flame.

Figure 6. Wave diagram at \( \phi = 1.0 \). DDT is due to the precursor shock wave.

Figure 7. Equivalence ratio on the DDT run-up distance. \( X_i \) are estimated by the average velocity of the pressure wave greater than the CJ velocity (□), and the average velocity of the CW greater than the CJ velocity (□), and the intersection of the CW and RW trajectories (□). The uncertainty of \( X_i \) is shown as I.
Figure 8. DDT run-up distance with amplification factor. (□) amplification factor. (□) DDT run-up distance are estimated by the intersection of the CW and RW trajectories.