Tube Diameter Effect on Deflagration-to-Detonation Transition of Propane-Oxygen Mixtures

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Introduction

A pulse detonation engine (PDE) with compact structure can offer better performance compared to current propulsion devices. To ensure the success of a PDE, a predetonator can be used to generate a detonation wave by the deflagration-to-detonation transition (DDT) process. This detonation wave is then transmitted into a larger diameter tube (detonation diffraction) with fuel-air mixture. The decrease in impulse is also associated with the need of extra oxygen with a predetonator [1]. To minimize the volume of a predetonator, the composition of mixtures and the tube diameter are of great concerns. Previous experimental studies with stoichiometric fuel/oxidizer mixtures indicated that DDT run-up distance X_{ddt} is shorter with smaller diameter tubes [2, 3, 4]. However, the effect of tube diameter with non-stoichiometric mixtures on X_{ddt} is less known.

In the present study, single shot experiments were carried out with the propane-oxygen mixtures in a smooth tube. X_{ddt} is determined with varying equivalence ratio ϕ in four tube diameters (25.4, 50.8, 101.6, 152.4 mm). The overdriven state of the detonation is evaluated, which is the key parameter for successful detonation diffraction [5]. The dependence of the degree of overdriven detonation on the distance from the transition location through DDT process was also addressed.

Experiments

The smooth, aluminum 6061-T6 tubes are 457.2, 914.4 mm long and 25.4, 50.8, 101.6, 152.4 mm in internal diameters. A weak electric spark at the closed end was used as the ignition source. The maximum effective discharge energy is estimated to be 0.47 J. PCB piezoelectric pressure transducers were mounted along the streamwise direction to evaluate the average propagation speed of the pressure wave. At the center of the closed end, a Hamamatsu photodiode was installed to define the onset of detonation.

Prior to each run, the tube with a thin diaphragm sealing the open end was evacuated to 20~30 Pa. Propane and oxygen were injected into the tube, and the equivalence ratio of the mixtures at one atmospheric pressure was determined by the partial pressure method. A circulation pump was also used for about 5~10 minutes to ensure the homogeneity of mixtures. In addition, the concentration of propane-oxygen mixtures is calibrated by gas chromatography for each run.

Signals from the pressure transducers and photodiodes were digitized and stored in LeCroy Model 6810 high-speed modules. The typical sampling rate was 500 ksamples/sec. Estimation of X_{ddt} was based on the time of the onset of detonation by the emission of visible light and the trajectory of pressure wave. The nonstationary cross-correlation technique (NCCF) [6] is adopted to evaluate its uncertainty.

Results and Discussion

Examples of the dependence of X_{ddt} on ϕ are shown in Fig. 1. It can be seen that the variation of X_{ddt} shows a similar trend for all four tube diameters, namely a U-shaped curve. The minimum X_{ddt} deceases with smaller tube diameter. For $d =$ 152.4 mm, X_{ddt} is minimized at $\phi \approx$ 1.1 and increases with leaner or richer mixtures. The increase of X_{ddt} with richer mixtures ($\phi \geq 0.95$) is less pronounced with smaller tuber diameter. For the diaphragm effect at the tube end, the reflection of the pressure waves may influence the flame acceleration through the DDT process [7]. The tubes with 457.2, 914.4 mm in length were adopted, Fig. 1. It can be seen that the tube length has no significant influence on X_{ddt} for $d =$ 25.4, 50.8, 101.6 mm. But for $d =$ 152.4 mm, X_{ddt} at $L =$ 457.2 mm is slightly shorter than that at $L =$ 914.4 mm, especially for richer and leaner mixtures. It is considered that the location of DDT process for $d =$ 152.4 mm is closer to the diaphragm at $L =$ 457.2 mm. The diaphragm influence is expected to be more significant.

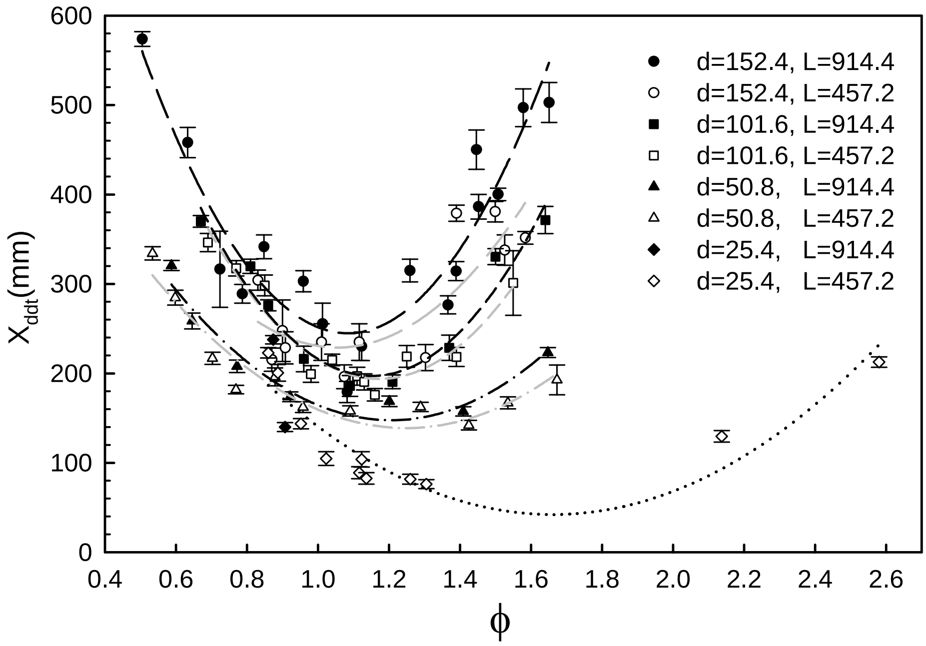

Figure 1 Effect of equivalence ratio on X_{ddt}

For a smooth tube, Nettleton indicated that X_{ddt} is associated with the tube diameter, in which $X_{ddt} = Kd^{a}$ and K is a constant. X_{ddt} decreases with decreasing in tube diameter. For a stoichiometric mixture of town gas-air in tubes $d =$ 12.7, 25.4, 50.8, 101.6 mm, a is equal to 0.44 [4]; for a stoichiometric mixture of hydrogen-oxygen in tubes $d =$ 3, 6, 19, 25, 25, 51 mm, a is equal to 0.5 [3]. The numerical simulation of DDT process based on the hydraulic resistance also showed similar dependence of X_{ddt} on tube diameter [8]. The present study reports the dependence of X_{ddt} on tube diameter $d =$ 25.4, 50.8, 101.6, 152.4 mm with fixed ϕ of propane-oxygen mixture. Fig. 2 shows the relationship between X_{ddt} and tube diameter. For ϕ = 1.0, 1.1, 1.25 (stoichiometric and slightly fuel rich mixtures), the values of a are 0.41, 0.47, 0.46, respectively. This shows a similar trend with the results of Baumann et al. [3] However, as ϕ increases (richer fuel mixtures, e.g. ϕ = 1.65), the value of a rises and closes to 1.0. For the fuel lean mixtures (e.g. $\phi = 0.96$, 0.85), X_{ddt} still decreases with decreasing in tube diameter from $d =$ 152.4~50.8. But X_{ddt} in $d =$ 50.8 mm is not longer than that in $d =$ 25.4 mm. This implies the effect of tube diameter with non-stoichiometric mixtures on X_{ddt} is unlike that at stoichiometric mixtures. It is considered that the dependence of the run-up distance on tube diameter may presumably be not only related to hydraulic resistance but also to heat losses and some parameters associated to the mixture compositions.

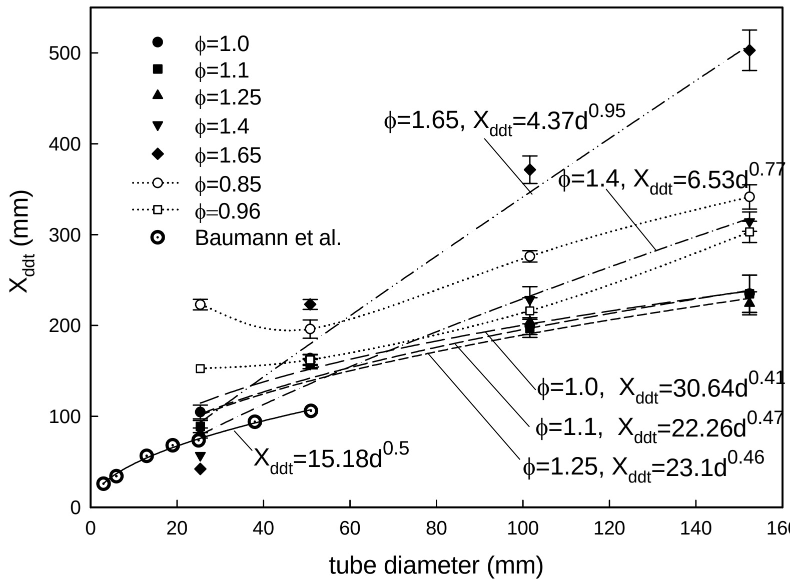

Figure 2 Dependence of X_{ddt} on tube diameter with fixed ϕ

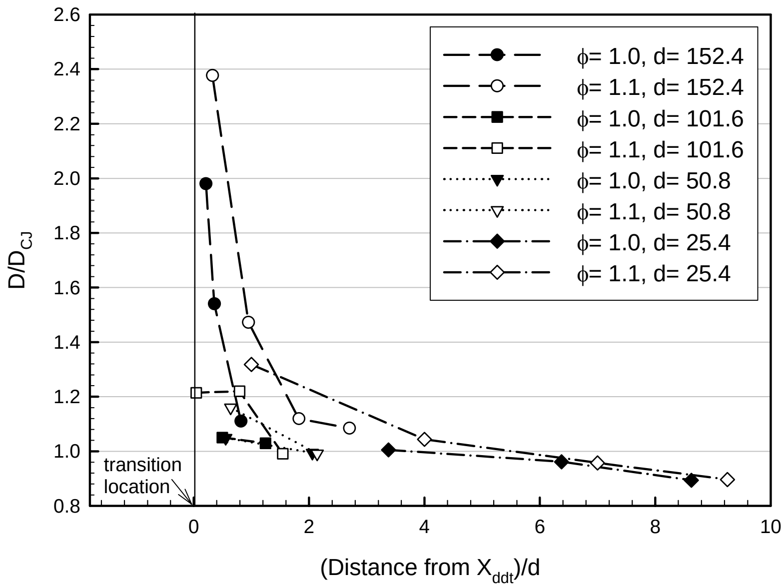

Figure 3 tube diameter effect on the degree of overdriven detonation through DDT process

It is known that overdriven detonation appears through the DDT process [8, 9], which has attracted more attention in the development of PDE [5]. The present study reports the tube diameter effect on the degree of overdriven detonation as DDT occurs, as shown in Fig. 3.

D/D_{CJ} is the degree of overdriven detonation wave defined as the ratio of the mean value of the propagating detonation wave speed based on TOF (time-of-flight) method to the theoretical C-J detonation speed. ϕ is fixed at 1.0 and 1.1, which are frequently used in the application of a PDE. It can be found that D/D_{CJ} increases with decreasing in the distance from the transition location. D/D_{CJ} with $\phi =$ 1.1 is higher than that with $\phi =$ 1.0 for all four tube diameters. D/D_{CJ} in $d =$ 152.4 mm is higher than that in smaller diameter tubes. The maximum D/D_{CJ} is 2.4 with $\phi =$ 1.1. Nevertheless, the small tube diameters are interesting due to their shorter X_{ddt} for practical PDE. At one tube diameter of the distance from the transition location, D/D_{CJ} with $\phi =$ 1.1 in $d =$ 25.4 and 50.8 mm are 1.3 and 1.12, respectively. Overdriven detonation wave decays back to C-J state in approximately 4 tube diameters for $d =$ 25.4 mm and 2 tube diameters for $d =$ 50.8 mm, respectively. Their physical dimensions are the same about 100 mm. It can be concluded that the use of slight fuel rich mixture can attain higher degree of overdriven detonation wave. The predetonator length must be longer than run-up distance and as possible as close to it in order to obtain high degree of overdriven detonation wave.

Conclusions

The present study shows that the effect of tube diameter on the run-up distance depends on the mixture compositions. For stoichiometric and slightly fuel rich mixture ($\phi = 1.0 \sim 1.25$), the run-up distance decreases with decreasing in tube diameter. $X_{ddt} = Kd^a$, where $a = 0.41 \sim 0.47$. This is consistent with the previous studies for a stoichiometric mixture. For richer mixture, the value of a rises and closes to 1. For leaner mixture, X_{ddt} don't decrease with the decreasing of tube diameter as $d \le 50.8$ mm. The tube diameter effect on X_{ddt} need to be further addressed in small tube. In addition, overdriven detonation is observed for all four tube diameters. The results show the degree of overdriven detonation wave increases with decreasing in the distance from the transition location. Overdriven detonation wave decays back to C-J state in approximately 100 mm for $d = 25.4$, 50.8 mm. This indicates the predetonator length must be longer than run-up distance and as possible as close to it.

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