DDT Induction Distance Measurements for Methane/hydrogen/oxygen

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1 Introduction

Following ignition at the closed-end of a tube, under the appropriate conditions, flame acceleration can lead to deflagration-to-detonation transition (DDT). Flame acceleration is initially governed by flame area growth due to the parabolic unburned gas axial-velocity profile and later by turbulent combustion in the boundary layer and adiabatic heating behind the compression waves [1]. DDT occurs after the flame reaches a velocity roughly equal to the speed of sound of the products. During the last phase of flame acceleration, a cone-shaped (or tulip) flame develops [1] that is preceded closely by a strong shock. This complex is commonly referred to as a fast-flame. In a smooth tube, the axial distance from the ignition wall to the point of DDT (run-up distance) can be very long, especially for fuel-air mixtures. The axial-distance from where the fast-flame forms (flame velocity reaches ½V_{CJ}) to where DDT occurs was called the "DDT induction distance" and was shown to be a function of the detonation cell size [2]. The flame acceleration process can be by-passed by generating a fast-flame following the interaction of a detonation wave with a perforated plate [3]. In tests performed in a square [4] and round [5] channel, it was demonstrated that for a perforated plate with uniformly distributed 6.3 mm holes (77% area blockage), the transverse shock waves generated downstream of the perforated plate play a significant role in the DDT process and therefore is not a good representation of the fast-flame conditions generated at the end of flame acceleration in a long smooth tube [1]. In a similar recent study performed in a 40 mm square channel and very small 3-mm diameter perforated plate holes, it was shown that the addition of methane to hydrogen-oxygen results in a shorter DDT run-up distance after the perforated plate. Furthermore, based on a limited data set they proposed a linear relationship between the DDT run-up distance and the detonation cell size for the different hydrogen/methane mixtures [6].

In this study, a perforated plate with small diameter holes, compared to [5], were used to reduce the strength of the transverse shock waves generated downstream of the plate. This prevents rapid DDT due to strong transverse wave collisions, allowing the fast-flame structure to develop as a result of viscous wall effects. This setup allows the direct measurement of the DDT induction length. The test fuel consists of methane and hydrogen because of its importance to power generation and its wide range in detonation cell structure regularity.

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2 Experimental

Experiments with different premixed stoichiometric hydrogen/methane/oxygen mixtures were performed in a 7.6 cm inner-diameter polycarbonate tube, see Fig. 1. Functionally there are DDT, stabilizing and test sections. A flame was ignited at the endplate using a standard automotive coil-on-plug spark system (BWD E1082) and/or glow plug. For most tests the glow plug was sufficient to ignite the mixture, for lower initial pressures the glow plug was heated for roughly 30 s and then the spark plug was activated. Flame acceleration and DDT was promoted by 5.3-cm inner-diameter orifice plates (50% blockage area) evenly spaced at the tube diameter in the first 1.4 m, see Fig.1. The next 0.74-m was free of orifice plates to stabilize the detonation wave before the perforated plate. Transition to detonation was observed in the obstruction-free 1.2-m long test section after the perforated plate. In later tests, the test section was increased to 2.4-m long.

Two synchronized high-speed cameras were used to capture the chemiluminescence from the fast-flame propagation and DDT in the test section. Filters were used to block out some of the light from the flame. A Photron SAZ with 50-mm lens was positioned to the side of the tube to measure the flame progression. The flame velocity and DDT run up distance were measured with the camera placed 3.15-m from the tube, for zoomed-in images the camera was located 1.50-m from the tube. A Photron SA5 was positioned co-linearly with the tube, roughly 0.65-m from the endplate window. The f-stop on the SA5-mm lens was set to 2.8 to limit the background light emitted from a debris cloud just after the perforated plate. Soot foils were used to capture the detonation cell structure. The foil, cut from 0.02-inch (0.5 mm) thick 3000 series aluminum sheet, was coated with soot by holding it above a kerosene lamp flame. Tests were performed with stoichiometric hydrogen/methane/oxygen, i.e., (1-x) H_2 + x CH_4+ 1/2(1+3x) O_2, where x = 0, 0.5, and 1 (or 100% hydrogen, 50/50 hydrogen-methane, and 100% methane fuel).

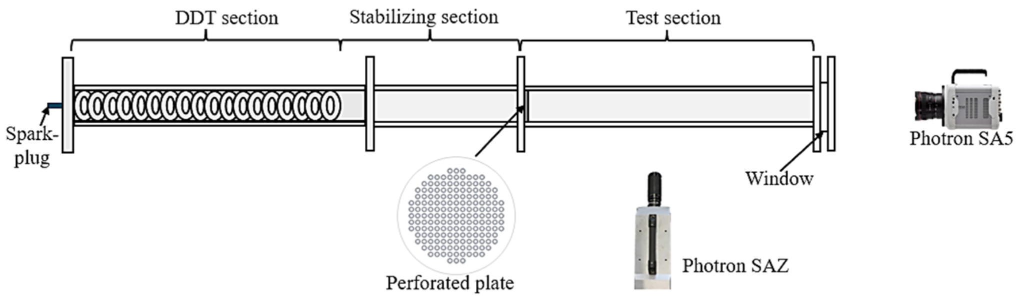
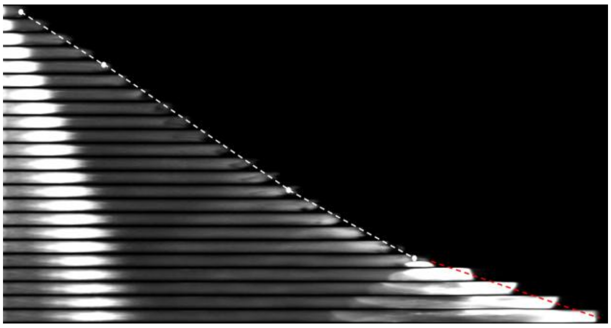


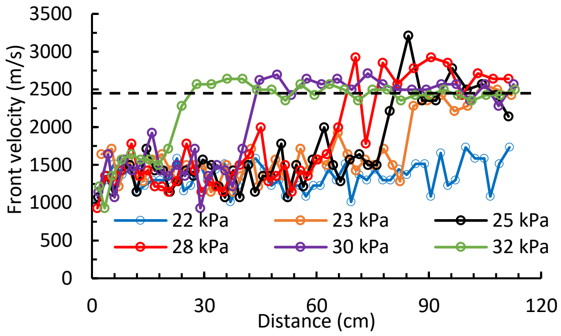
Figure 1: Experimental setup showing the polycarbonate tube equipped with orifice plates and camera field-of- views.

3 Results

3.1 Detonation Initiation in Stoichiometric Methane-hydrogen Mixtures

Experiments were carried out for each fuel mixture where the chemical reactivity was varied via the initial pressure. High-speed video captured in the full test section after the perforated plate for a 50/50 methane/hydrogen fuel at 28 kPa is provided in Fig. 2. The time between frames is 4.8 μs, the four dotted line segments (with average velocity indicated) break up the propagation into four stages. The last detonation propagation stage starts with the DDT event, highlighted by very bright light emission at the front that propagates around the CJ velocity. The bright light region just downstream from the perforated plate is from a hot fine-debris cloud. Although difficult to see in Fig. 2a, there is an oscillation in flame front velocity and changes in the front shape. The axial velocity of the leading edge of the primary flame as a function of the axial distance from the perforated plate for 50/50 fuel at different initial pressures is plotted in Fig. 2b. Prompt detonation initiation was not observed, i.e., within a couple of hole diameters after the perforated plate [4], for pressures up to 32 kPa. DDT is highlighted by a sudden increase in velocity. The average flame velocity measured from the perforated plate to the DDT location is between 1428 m/s, just above the speed of sound in the combustion products 1225.34 m/s. There is significant fluctuation in the flame velocity, some of it related to the measurement from the video images but much of it is real. Following DDT the average detonation velocity (for all tests) is 2572 m/s, slightly above the CJ velocity of 2412 m/s. This is due to a velocity overshoot typical of DDT. The DDT limit is 22 kPa, for which detonation may, or may not, occur from test to test.





(a) (b)

Figure 2: A series of images (4.8 μs between frames) showing the combustion front propagation for a 50/50 fuel mixture at 28 kPa where the camera field-of-view is 114.1 cm long and left-edge is 4.3 cm after the perforated plate (a) Velocity of the primary flame leading edge versus propagation distance from the perforated plate obtained from video images captured at 192 kfps for 50/50 mixture as a function of initial pressure (b). The average CJ velocity is 2412±10 m/s over the pressure range.

It is difficult to see the individual curves in Fig. 2b but the flame velocity oscillates before DDT. These oscillations correspond to a change in flame shape as can be seen in the sequence of zoomed-in images in Fig. 3 of every-other frame from Fig. 2. The flame shape is relatively planar when it emerges from the perforated plate (closely coupled to the leading shock that is not observed in self-illumination photography), as seen in image 1 where the flame has propagated roughly 6 cm from the perforated plate. In images 2-3 the flame jumps ahead at the centerline and then inverts symmetrically to form a "tulip flame," during this inversion the velocity decreases. The acceleration at the core is believed to be due to the quasi-symmetric convergence of a cylindrical compression wave that generates an explosion at the centerline. This shock implosion was observed in tests with larger 6 mm perforated plate holes for propane-oxygen; however, in those tests it resulted in detonation initiation [5]. Flame inversion happens when a flame is ignited at the closed end of a round tube where the inversion coincides with the loss of flame area when the finger flame skirt reaches the tube wall [1]. No such phenomenon occurs here, rather the inversion is most likely caused by the increase in burning velocity at the wall due to turbulence and viscous heating of the gas, this was observed in the final stages of flame acceleration before DDT in the flame acceleration study [1].

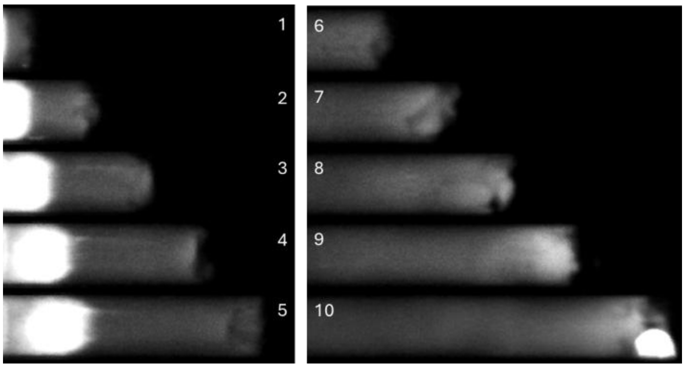
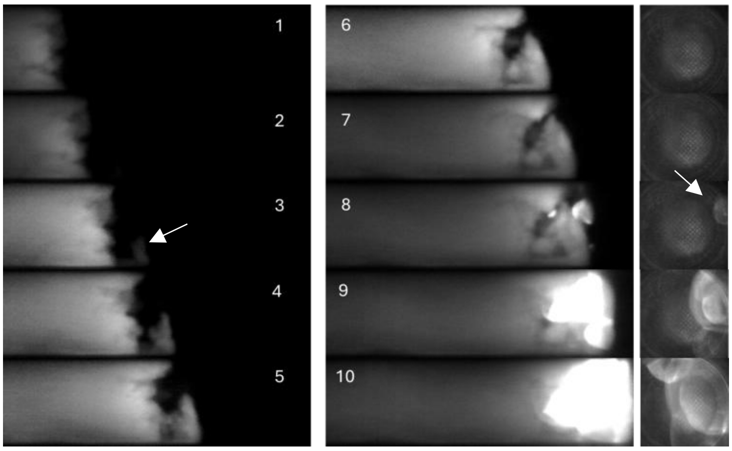


Figure 3: Every other image from Fig. 2a, the field-of-view for image 6-10 is shifted to follow the flame front.

Just before DDT there is a re-acceleration of the flame front in images 7-10. To study the DDT event more closely simultaneous side and end-view photography. Images from a different 50/50 fuel test performed at 26 kPa with a narrower field-of-view is shown in Fig. 4. Note the time between frames 7-10 is half the time between frames 1-7. The flame front cannot be observed in the end view images because of the light emitted from the hot debris cloud; however, detonation onset can be identified because of the significantly brighter light emitted. Since the flame cannot be observed the end view images 1-5 are not included, they are identical to the end view images 6 and 7 where the perforated plate can vaguely be seen through the product gas. The flame enters the field-of-view as a highly corrugated turbulent front propagating at roughly 1400 m/s, again, there is a shock present ahead that cannot be observed. In image 3 auto-ignition occurs ahead of the primary flame at the bottom of the tube (see arrow) presumably due to a combination of shock heating and viscous heating in the boundary layer. The flame kernel rapidly spreads upwards towards the tube center at an estimated velocity of 625.88 m/s and forms a relatively smooth leading front. This second flame front propagates forward at roughly the same axial velocity as the primary flame front, but the gap between them narrows in images 3-7 due to combustion in the gap. The smoothness of the flame could indicate coupling to the lead shock.



(a) (b)

Figure 4: Sequence video images for 50/50 methane/hydrogen at an initial pressure of 26 kPa. Only side-view images shown in (a), simultaneous side and end-view for (b). The time between frames for 1-6 is 7.1 μs and for 7-10 is 14.3 μs. The left side of the field-of-view corresponds to 68 cm downstream from the perforated plate.

Detonation initiation occurs in image 8 just ahead of the secondary flame, the end view image shows that the detonation originates at the back tube wall roughly at the 3 o'clock position (see arrow). Subsequent detonation initiation occurs at the tube wall at the 5 and 12 o'clock positions. In all experiments, detonation initiation occurred at the tube wall typically at a single hot spot (like that reported in [1]) following the generation of a secondary flame at the tube wall ahead of the primary flame. Most often, the detonation is initiated at the wall diametrically opposite where the secondary flame ignites; one can conclude that the reflection of the shock wave formed ahead of the secondary flame leads to detonation initiation at the wall.

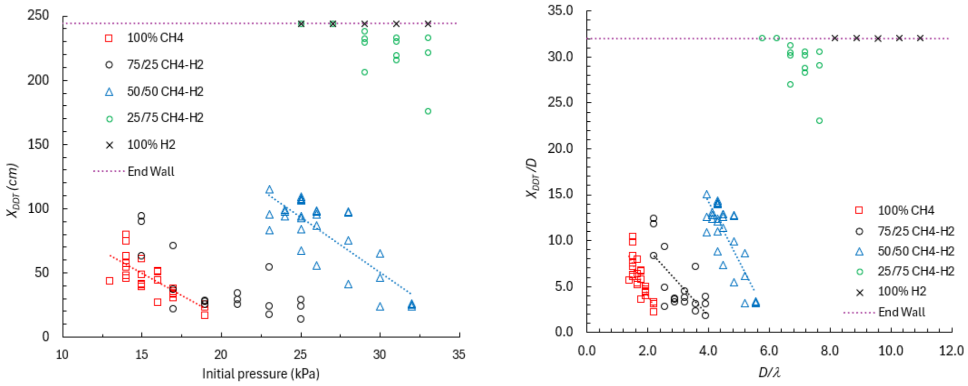


Figure 5: DDT distance from the perforated plate as a function of a) initial pressure, and b) scaled inverse cell size.

The axial distance from the perforated plate to the DDT location was measured from videos like that shown in Fig. 2a. The DDT distance versus initial pressure is provided in Fig. 5a for the methane-containing mixtures. The scatter in the data is significant, but in general there is an inverse dependence with initial pressure as reported in [5], a linear fit is shown for 100% methane and 50/50 methane-hydrogen. If higher pressures were tested the curve would asymptote to a value consistent with prompt initiation. Notably, the minimum initial pressure for initiation decreases with decreasing hydrogen content. The tube diameter scaled DDT distance as a function of the scaled inverse detonation cell size is given in Fig. 5b. For a given cell size (or reactivity) higher methane concentration leads to a shorter DDT distance. DDT was not observed for 0% methane ($2H_2+O_2$) up to 35 kPa, however detonation initiation was triggered at the end wall following shock reflection. This result is consistent with the sparse data from a much smaller 10-mm square channel [6]. For 100% methane, the DDT limit is close to the expected limit of $D/\lambda \approx 1$, whereas for 50% hydrogen the limit is significantly higher ($D/\lambda \approx 4$).

3.2 Fast-flame in Stoichiometric Hydrogen-oxygen

For hydrogen-oxygen a tulip flame-like structure develops in Fig. 6a image 2, like that observed in methane-containing mixtures (see Fig. 3 images 1-5). However, for hydrogen the tulip flame is sustained the full length of the tube. In Fig. 6b the images taken at the end of the tube at a 45 degree to the tube axis show the transformation of the tulip flame into a creased hollow cone, as observed in [1]. Images 3-4 show how the flame lateral edge propagates circumferentially over the top of the tube forming the crease on the front side of the tube. This crease is self-sustained as the flame continuously propagates circumferential along the tube wall as the front flame edge propagates axially forward next to the wall.

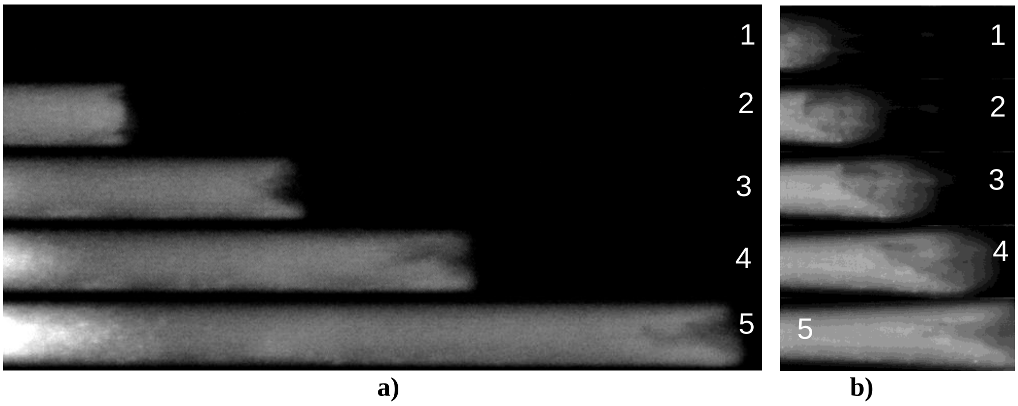


Figure 6: Sequence video images for 2H+O2 at 26 kPa, a) side view b) 45 deg angle view

For stoichiometric hydrogen-oxygen, the velocity oscillations observed in the methane-containing mixtures are also observed in Fig. 7, globally the flame initially decelerates after the perforated to 900-1100 m/s and then reaccelerates after the creased hollow cone develops. This late phase acceleration was observed in acetylene-oxygen mixtures in unobstructed tubes ultimately leading to DDT [1]. For higher pressures the flame velocity fully recovers but DDT was not observed, we expect in a longer tube DDT would have occurred. For the lowest pressure of 15 kPa, the velocity decelerates continuously down to 700 m/s and does not reaccelerate; actually, the reflected shock interacts with the flame before the end of the tube ceasing its forward motion.

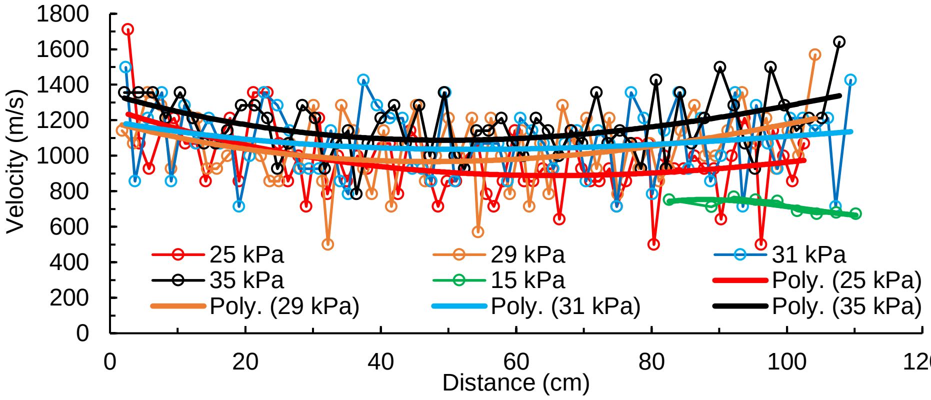


Figure 7: Flame velocity versus propagation distance from the perforated plate for stoichiometric hydrogen-oxygen for a 15 – 35 kPa initial pressure range. Data is fit with second order polynomial.

4 Conclusions

A fast-flame was generated following the interaction of a CJ detonation with a perforated plate. This approach to study DDT bypasses the complex flame dynamics associated with the flame acceleration process that is the dominant factor affecting the DDT run-up distance. In a study with 6-mm perforated plate holes and propane-oxygen we showed that transverse waves generated by the decoupling of the detonation wave govern transition to detonation within a few tube diameters [5]. In this study, with smaller 3-mm holes and hydrogen-addition to methane-oxygen, transition was delayed and autoignition due to flame acceleration governed the onset of detonation. Higher hydrogen fuel content resulted in longer DDT distances. For pure hydrogen, no DDT was observed, despite hydrogen having a significantly higher laminar burning velocity and smaller cell size, and a creased hollow cone flame accelerated over the second half of the tube.

References

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