Experimental study of DDT in hydrogen-air behind a single obstacle

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1 Introduction

This paper reports an experimental study of detonation deflagration transition in a square channel. The gas mixtures used were hydrogen and air with varying concentrations. The channel had one obstacle with adjustable blockage ratio. A jet was formed behind the obstacle as the flame expanded and pushed the reactants ahead of itself. After the flame propagated through the obstacle it detonated in some experiments. A sketch of the setup is given in figure 1. This study investigate where the detonation started. We also report which hydrogen concentrations and blockage ratios that resulted in DDT.

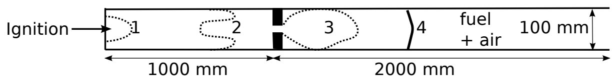

Figure 1: A sketch of the experimental setup. The principle of the flame propagation is drawn with dotted lines (1 to 3) as it burn from left to right. The detonation (4) is drawn with a thick line.

2 Background and motivation

Urtiew and Oppenheim [1] showed in 1966 the transition from deflagration to detonation in a channel. They showed that DDT could occur at the turbulent flame brush, behind a precursor shock wave or at the contact surface behind a shock wave. Oppenheim also introduced the term *”an explosion within the explosion”*, as pointed out by Lee [2]. Meyer *et. al.* [3] showed that an explosion could occur in a layer of unburned mixture behind the leading edge of a turbulent flame. Lee [2] pointed out that a detonation could originate from the explosion, but there must be an amplification mechanism between the reaction zone and the shock wave. Oran *et. al.* [4] showed that DDT could occur in a funnel of unburned mixture between two flames, and also noted the gradient mechanism as a detonation developed from a hot spot.

Knystautas *et. al.* [5] investigated how a jet of hot combustion products could initiate a detonation. They pointed out three requirements for DDT by turbulent mixing mechanism. The first is the generation of large scale energetic turbulent eddies, while sufficient small scale eddies to promote mixing is the second criteria. The last requirement is the generation of induction time gradients. Moen *et.al.* [6] did large scale version of similar experiments. They showed that DDT occurred at the top wall as a deflagration propagated out of a steel tube into a plastic bag. Thomas and Jones [7] investigated jet initiation of detonation as a deflagration followed a shock wave and emerged from a $50mm$ shock tube into a steel vessel. They wrote that in their experiments there were high reaction rates caused by the intense shear in the flame front. This lead to a transition to detonation via a hot spot as it developed in a induction time gradient. Thomas and Jones stated that it was more likely that the small scale (order of reaction front thickness) turbulence caused the DDT than an larger external eddy.

Vaagsaether [8] investigated numerically the onset of a detonation in a circular pipe with one obstacle (i.e. orifice plate). The simulation showed that there was a transition from deflagration to detonation after the flame passed the obstacle. DDT occurred between the flame and the pipe wall where the shear stress and local burning rates were high. Knudsen [9] showed experimentally that DDT could occur as a deflagration propagate through an obstacle. This experimental work is motivated by the work of Vaagsaether and Knudsen but also the experiment reported by Moen *et. al.* We will investigate the onset of a detonation as a deflagration propagate through a single obstacle. The main focus is to report DDT and events that lead up to the onset of detonation. The method of investigation is high speed film and pressure records. The experimental results are compared to similar numerical simulations to better the understanding.

3 Experimental setup

The experimental setup was a $3000mm$ long 100 by $100mm^2$ square channel. The channel was closed in one end and open to the atmosphere in the other. The channel side walls were transparent so the flame could be filmed, while the top and bottom walls were smooth, painted steel. An obstacle was placed $1000mm$ from the closed end, and it was $4mm$ thick and had a variable blockage ratio. In the experiments it ranged from $BR = 0.5$ to $BR = 0.9$. The obstacle opening was a rectangular slit in the middle of the channel. A sketch of the experimental setup is shown in figure 1. The gas mixtures used in the experiments were hydrogen and air, and the concentrations varied from 15% hydrogen to 35%. At the closed end of the channel, a $10kV$ spark was used to ignite the mixture. Three Kistler 603b pressure transducers were placed $200mm$, $600mm$ and $1000mm$ behind the obstacle. The experiments were filmed with a Photron SA1 high speed camera recording at $30000fps$. This was done to capture the slow deflagration and the fast detonation.

4 Results and discussion

The gas mixtures were ignited at the closed end, and the flame propagated the first meter of the experiment before reaching the obstacle. Details of this propagation was investigated earlier by the authors [10]. As the flame propagated it changed shape several times, but started as a convex (towards the reactants) flame. As the flame reached the obstacle it was concave often referred to as tulip shaped. Although the referred work only presented results from stoichiometric hydrogen-air, the same flame behaviour was seen for lean and rich flames as well. The following experimental results investigated DDT after a tulip flame propagated through the obstacle.

DDT was observed in several experiments, with different concentration and blockage ratio. Figure 2 summarise the experiments and show that we observed DDT when the blockage ratio was $BR = 0.75$, $BR = 0.84$ and $BR = 0.90$. The lowest observed concentration where the mixture detonated was 28% hydrogen in air. In general the distance from obstacle to DDT position decreased with increasing

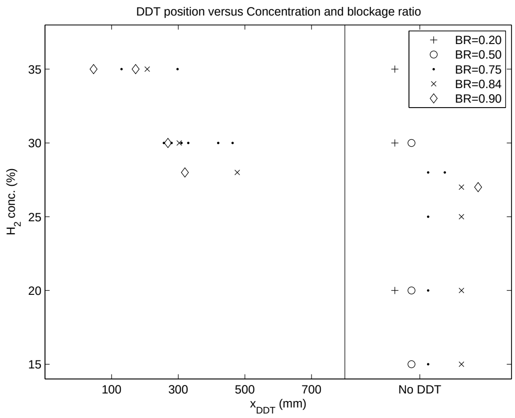

Figure 2: The distance behind the obstacle where DDT was observed for varying concentration and blockage ratios. Experiment marked at the right side of the vertical line did not detonate.

hydrogen concentration. DDT were observed first at the top wall of the channel in all but one experiment. DDT was observed at the bottom wall in one experiment with 30% hydrogen concentration and $BR = 0.75$. The distance from obstacle to the position where DDT was observed varied, but a similar series of events were observed in all experiments before it detonated.

Figure 3 shows high speed film pictures from one experiment (30% H_2 and $BR = 0.84$) which was representative for most of the experiments where the fuel-air mixture detonated. The figure also show a sketch where frames from the high-speed camera are described. The pressure records of the same experiment are shown in figure 4, where the vertical lines correspond to the frames of figure 3. As the flame propagated through the obstacle, seen in the first frame from the top, it stretched as a result of high horizontal flow velocity compared to the vertical burning velocity. This was due to the jet generated through the obstacle as the flame expanded in the first meter of the setup. The flame shape was not symmetric. There were relatively large pockets of unburned gas left in the corner at the obstacle and along the top/bottom walls. This is visible in frames 1 to 3. The next events were a series of subsequent local explosions near or at the walls. Frame 3 and 4 shows the explosions. It was not possible to determine where along the depth axis of the photo these explosions originated. The explosions caused pressure waves to propagate in the channel, see frame 4 to 6. Theses pressure waves were recorded at the pressure transducers, and a pressure plot is given in figure 4. In frame 7 there is a bright light appearing at the top of the channel. This bright light develops into a detonation which was recorded at pressure transducers further down the channel.

The local explosions were likely to originate from a thin layer of fuel-air mixture between the flame and the wall. As the flame burned towards the wall it compressed the reactants. It also heated the unburned mixture due to heat conduction and convection in the turbulent flow field. This preheated layer could have auto ignited or burned very fast. Some of these local explosions died out, probably because they burned in pockets of fresh gas surrounded by wall and combustion products. The exact cause could not be determined from the experiments, but the resulting pressure wave was indicated on the high-speed film, and recorded at the first pressure transducer. This wave reflected at the walls and likely caused other small local explosions, but also heated the reactants in front of the flame. One area of special interest was closer to the front of the flame. There the unburned mixture between the flame and the wall was preheated and a gradient of reactivity was formed. As pressure waves reflected at the wall where we had these gradients, we could have had a chemical energy release which amplified a shock wave and in many cases this was enough to onset a detonation. It propagated first along the top wall and later

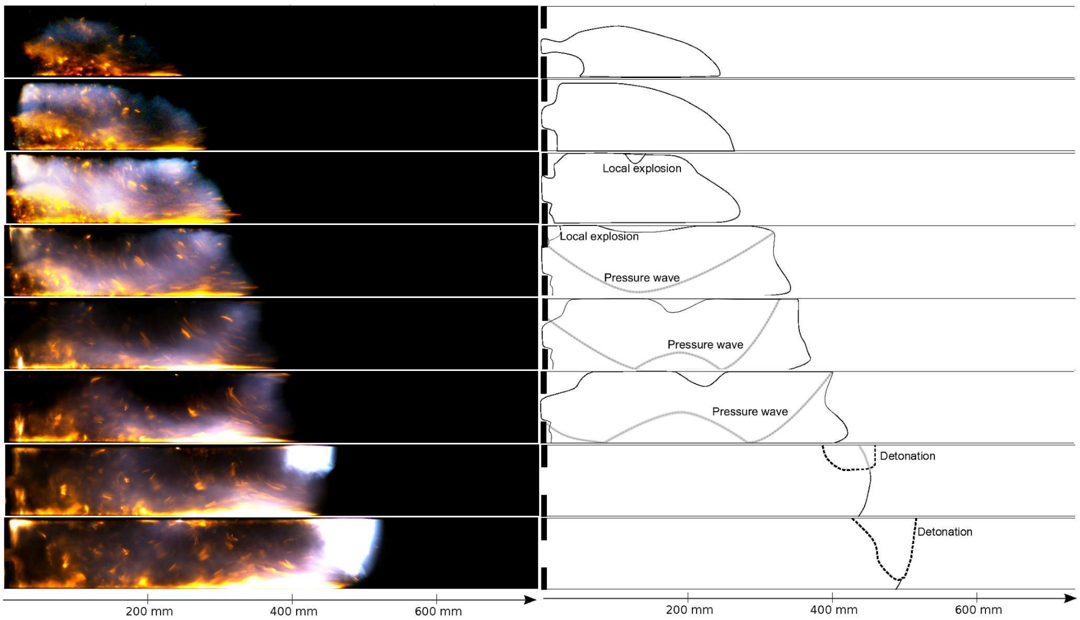

Figure 3: Photos and sketch of the flame propagation and development of detonation. Time difference between frames are $1/30000sec$. 30% H_2 in air with $BR = 0.84$.

developed into a detonation in the whole channel height, as we see in figure 3. This fits the mechanism described by Lee [2].

Figure 4 shows a pressure plot of the same experiment as figure 3. The vertical lines correspond to the frames of figure 3 and we see that there was a small pressure increase after the second frame, this could be from a small local explosion, not visible on the high speed film. There was also a larger pressure increase between frame 4 and 5. This pressure wave came from the top local explosion which reflected at the bottom wall. As the detonation developed and propagated towards the bottom wall we saw a pressure spike on the second pressure transducer. The small pressure increases from the local explosions was visible in most of the experiments where we recorded DDT. The explosions were too small to develop into a detonation by them self, but they contributed as a series of local explosions that added up and for the most reactive mixtures it lead to DDT. Some experiments did not transit from deflagration to detonation. In some of the cases where we did not see DDT, there were indications that the mixture auto ignited at the same place as we saw a detonation develop. This was according to theory and experiments described earlier.

Numerical investigations of similar cases as the experiments were simulated with an CFD code [8]. Even though the experimental phenomena was three dimensional, we still choose to simulate in two dimensions as it was less computational expensive. The simulations showed that there were many hot spots that exploded between the flame and the wall. Some went off independently of each other, while some could have exploded as a result of a pressure wave from an earlier explosion.

Many of these hot spots failed to develop into a detonation because they went off in isolated islands of reactants. Others propagated in a layer of insufficient height to initiate a detonation. There was a critical hot spot size necessary for the initiation of a detonation. The critical size of a hot spot was likely related to the detonation cell size or induction time [2], but in these simulations the gas was heated and compressed and subject to pressure oscillations so it was not possible to define a local cell size. It should however be much smaller that the cell size of the fresh unburned and unheated mixture.

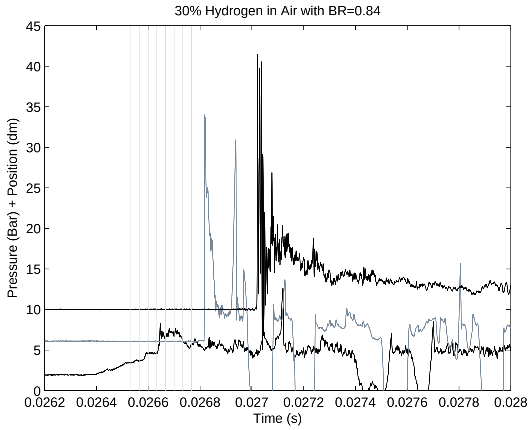

Figure 4: Pressure record of experiment. 30% $H2$ in air with $BR = 0.84$. The vertical lines correspond to the frames of figure 3.

In figure 5 we show simulation results of a deflagration (frame 1 and 2) as it propagated through an obstacle. There were several hot spots visible (frame 3,4 and 5). One hot spot at the bottom wall developed into a detonation (frame 6). It died out because there was no fresh gas ahead of the detonation. The bottom wall detonation propagated in the thin layer of heated reactants, and the oblique shock behind the detonation propagated fast in the hot products and reflect at the upper wall (frame 6). After this reflection at the top wall, we saw that a detonation swept along the wall (frame 7) and into the fresh mixture in front of the flame (frame 8). The detonation along the bottom wall could have happened in the experiments as well. In frame 5 and 6 of figure 3 there is a bright light along the bottom wall. This could be similar to the failing detonation we saw in the simulations.

5 Conclusion

Experimental investigations of DDT in hydrogen-air have been done and it showed that the distance behind the obstacle to the position where DDT was observed varied with concentration and blockage ratio. The distance decreased with increased concentration and blockage ratio. High speed film and pressure records showed that there were several hot spots, especially along the top and bottom wall. Most of the hot spots failed to propagate as a detonation, however for the most reactive fuel-air mixtures we observed DDT from one of the hot spots. The flame propagation was non symmetric, but in most cases we observed DDT at the top wall. Numerical simulations of similar experiments showed similar behaviour before DDT. Many hot spots developed in the layer between the flame and the wall, but they needed a certain size to develop into a detonation. The onset of detonation was observed near the front of the flame, but the hot spots and explosions that were assumed to add up to the onset took place far behind the leading edge of the flame.

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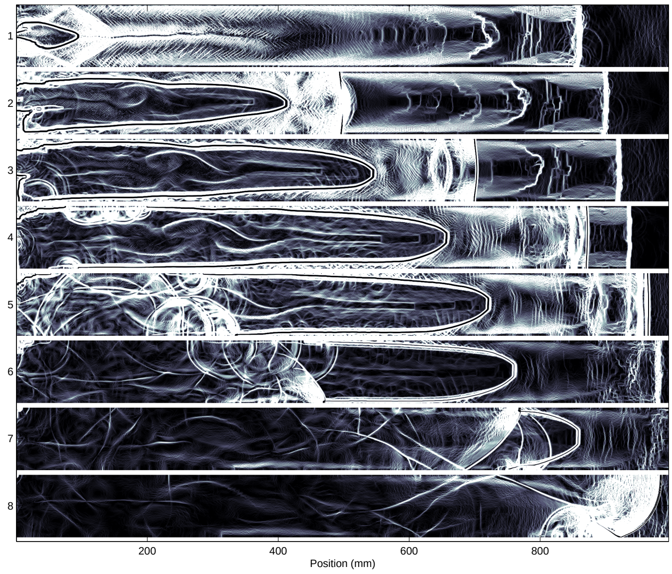

Figure 5: Density gradient field from simulation. Similar case as figure 3.

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