Experimental Study of DDT in Homogeneous and Inhomogeneous 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, see figure 1. After ignition the flame propagated as laminar and tulip flame (I and II). A jet was formed behind the obstacle as the flame expanded and pushed the reactants ahead of itself (III). After the flame propagated through the obstacle it detonated (IV) in some experiments. Inhomogeneous conditions were made by letting air flow into the channel before ignition, and the detonation propagated in a layer of reactants bound by a layer of air. The main objective of this study was to investigate where the detonation started. The experimental results showed a series of local explosions at the walls which added up to DDT. The detonation propagated through the rest of the channel, also in inhomogeneous cases where the reactants were bound by a layer of air.

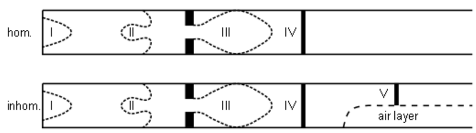

Figure 1: A sketch of the experimental setup, homogeneous on top and inhomogeneous below.

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"*. 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. An other possibility is the continuous amplification of transverse waves that progress into a detonation. 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 the generation of large scale energetic turbulent eddies, and sufficient small scale eddies to promote mixing and generation of induction time gradients as a DDT criteria. Moen *et.al.* [6] did large scale version of similar experiments. Thomas and Jones [7] investigated jet initiation of detonation, and showed, in their experiments, that there were high reaction rates caused by the intense shear in the flame front. They recognized the small scale (order of reaction front thickness) turbulence as cause of the DDT, rather than the larger external eddy.

Detonations in inhomogeneous horizontal layers have been studied by Dabora [9] in 1963 and Williams in 1982 [8]. More recent work have been reported in [10-12]. Kessler *et.al.* [13] have pointed out that there are still questions about DDT and detonation propagation in inhomogeneous gases. Real world gas explosions are seldom homogeneous in composition of reactants.

Vaagsaether [14] investigated numerically the onset of a detonation in a circular pipe with one obstacle (i.e. orifice plate). The simulations 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 [15] 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.* [6].

This work will investigate the onset of a detonation as a deflagration propagate through a single obstacle in a square channel. The main focus is to report DDT and events that lead up to the onset of detonation. This work will investigate where the transition to detonation occur, if it is at the tip of the flame, behind a leading shock or along the walls. The results are based on both homogeneous and inhomogeneous gas mixtures behind the obstacle. The method of investigation is high speed film and pressure records.

3 Experimental setup

The experimental setup was a $3000mm$ long 100 by $100mm^2$ square channel, see figure 1. 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 ($BR = \frac{A_{obst}}{A_{tot}}$). In the experiments it ranged from $BR = 0.2$ to $BR = 0.9$. The obstacle opening was a rectangular slit in the middle of the channel.

The gas mixtures used in the experiments were hydrogen and air, and the concentrations varied from 15% hydrogen to 40%. The channel was filled using two rota-meters and adjusting the ratio of fuel to air. The inhomogeneous mixtures were made by letting air flow into the channel as a gravity current [16] after filling. This created a pocket of air at the bottom of the channel with a tickness of about half the channel height. 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. This propagation was investigated earlier by the authors [17].

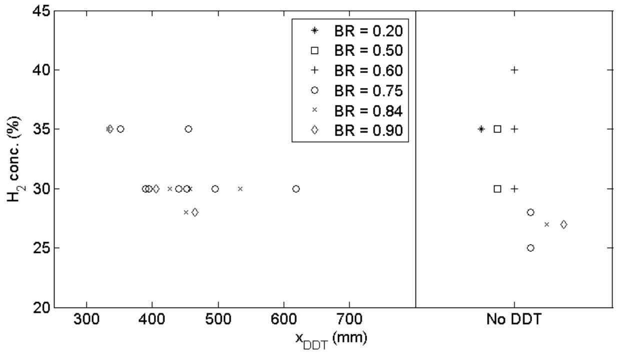

Figure 2: The distance behind the obstacle where DDT was observed for varying concentration and blockage ratios. Experiment marked at the right side of the vertical line did not detonate.

In this work the effects of hydrogen concentration and blockage ratio were studied. The blockage ratios studied were $BR = 0.2$, $BR = 0.5$, $BR = 0.6$, $BR = 0.75$, $BR = 0.84$ and $BR = 0.90$. Figure 2 summaries the experiments and show that DDT was observed when the blockage ratio was $BR \geq 0.75$. 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 hydrogen concentration. DDT were observed first at the top wall of the channel in all but two experiment. DDT was observed at the bottom wall in two experiments. 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 frames 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 generated transverse waves to propagate in the channel, see frame 4 to 6. Theses pressure waves were recorded at the pressure transducers. The pressure plot is given in figure 4 and the pressure wave from the local explosions are seen the 4th and 5th vertical line. The strength of the pressure wave was about 3 bar in an already precompressed gas of about 5 bar. In frame 7 there is a bright light appearing at the top of the channel after two or more reflections of the transverse waves. This bright light develops into a detonation which was recorded at pressure transducers further down the channel.

The local explosions originated 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 high shear flow. This preheated layer ignited and burned very fast. Some of these local explosions failed to propagate further, probably because they burned in pockets of fresh gas surrounded by wall and combustion products, and they were not strong enough to directly onset a detonation. The resulting pressure wave was indicated on the high-speed film, and recorded at the first pressure transducer behind the obstacle. This wave reflected at the walls and likely caused other

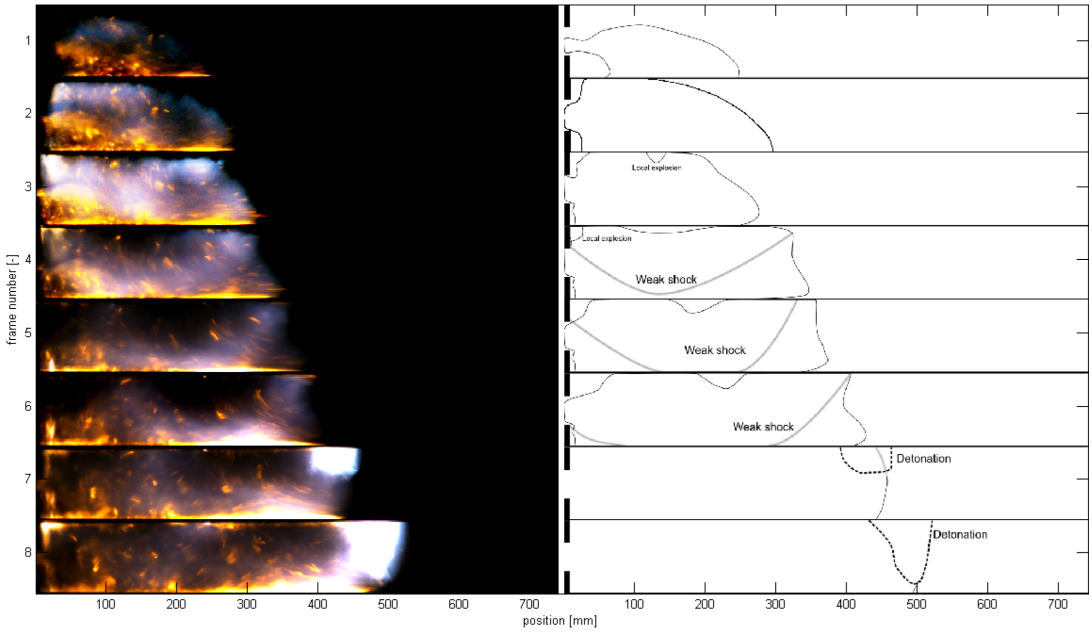

Figure 3: Photos and sketch of the flame propagation and development of detonation. Time difference between frames are $1/30000 sec$. 30% H_2 in air with $BR = 0.84$.

small local explosions which added up and heated the reactants in front of the flame. This is similar to the ignition spots observed by Meyer at al. [3]. One area of interest was closer to the front of the flame. The high shear flow and compression waves from the local explosions generated gradients of reactivity close at the wall, and a coupling of the high reaction rate and the generated transverse waves onset the detonation. It propagated first along the top wall and later developed into a detonation in the whole channel height, as we see in figure 3. This fits the mechanism described by Lee [2]. This work shows that DDT resulted from a series of smaller local explosions at the walls far behind the leading flame front. The resulting transverse waves couple with the reaction zone and lead to DDT at the flame front close to the wall.

Analysis of the flame propagation showed that the flame reached a lab frame velocity above half the CJ detonation velocity for the experiments were DDT was observed. This is consistent with other work explained by Lee [2].

The inhomogeneous experiments were conducted similar to the homogeneous ones, but only with $BR = 0.84$. After filling of the channel, air was allowed to flow back into the channel as a gravity current [16]. This resulted in a layer of air roughly about half the height of the channel. This inflow time was between 7 and 10 seconds. When the fuel-air mixture was ignited, the flame pushed reactants through the obstacle opening which in turn displaced the air layer away from the obstacle. In experiments with less than 10 seconds inflow time, DDT was observed. The local explosions prior to DDT were also observed very similar to to the homogeneous experiments. High speed frames of DDT and a detonation propagating into the volume of inhomogeneous are shown in figure 5. In frames 1 to 8 the detonation propagates in the whole height of the channel, while from frame 9 to 16 the detonation propagates in a top layer of reactants bound by a layer of air below. Assuming that the air layer h is half the channel height and using detonation cell size λ data [18], shows that $\frac{h}{\lambda} = 3.7$. This is consistent with the critical height of 3λ given by [10].

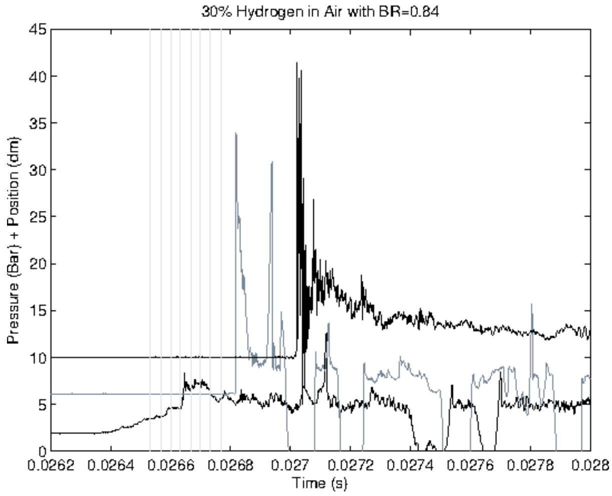

Figure 4: Pressure record of experiment. 30% $H2$ in air with $BR = 0.84$. The vertical lines correspond to the time instance of the frames of figure 3.

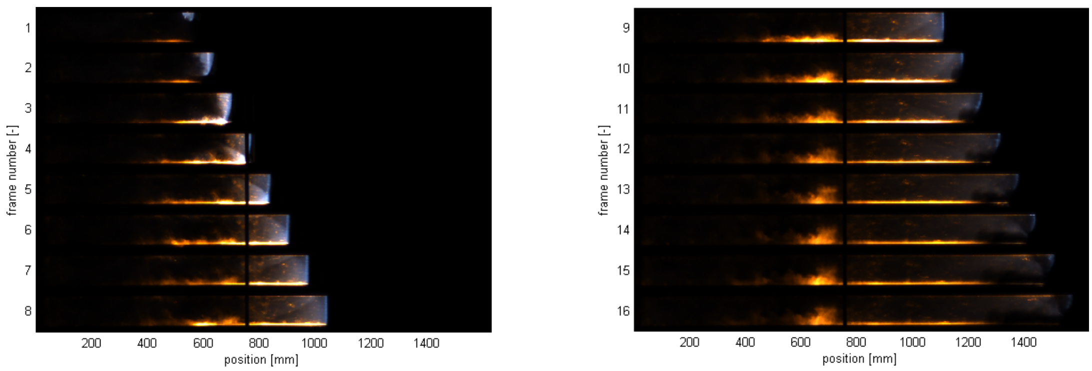

Figure 5: Photos of the DDT and propagating detonation in inhomogeneous gas mixture. Time difference between frames are $1/30000sec$. 30% H_2 in air with $BR = 0.84$ inflow time 7 seconds after filling. Density ratio $\rho_{air}/\rho_{H_2} = 1.4$

5 Conclusion

Experimental investigations of DDT in hydrogen-air have been done to investigate where DDT occurred. It is shown that for hydrogen-air mixtures in channels with one obstacle, DDT always occur at the walls. The study showed that the distance behind the obstacle to the position where DDT was observed varied with concentration and blockage ratio. High speed film and pressure records showed that there were several local explosions along the top and bottom wall far behind the leading tip of the deflagration. These local explosions added up to a transition to detonation for mixtures with more than 28% H_2 in air and blockage ration grater than $BR = 0.75$. In most cases DDT was observed at the top wall, after the flame reached a lab frame velocity greater than half the CJ detonation velocity. Inhomogeneous conditions were made by letting air flow into the channel after filling. This created a layer of air about half the channel height behind the obstacle. When the detonation reached this layer in propagated through the reactants on top of the air layer.

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