Front Tracking of DDT from Ultra-high Speed Video Films

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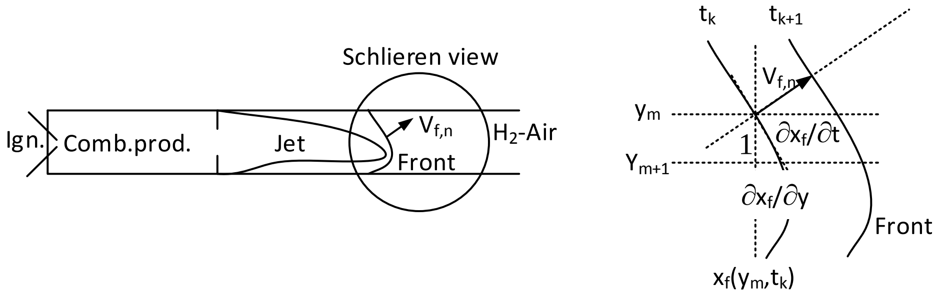
1 Introduction

The main objective of this study is to observe and extract detailed information of the deflagration to detonation (DDT) process in hydrogen-air by using an ultra-high speed camera, schlieren technique and image processing. Since the ultra-high speed camera has the capability of frame rates up to 5 million frames per sec it gives us a unique tool for observation of the DDT process. As discussed by Teodorczyk [1] the history of DDT in tubes goes all the way back to 1880s. In the 1960s Oppenheim and co-workes made some classic experiments filming different modes of DDT. There are large number of reviews on transition to detonation among them Thomas [2]. The interaction between the Mach-stem and boundary layer may cause DDT for even weaker incident shocks. Bhattacharjee et. al. [3] discussed five mechanisms that could lead to transition to detonation behind a Mach-stem including flow instabilities. The effect of the bifurcated shock on DDT was shown numerically by Gamezo et. al. [4]. It appears that transvers waves play a fundamental role in DDT and detonation propagation. The importance of understanding mechanisms involved in the DDT process is not only of scientific interest it is also of major practical interest. We know from experiments and accidents that DDT may occur when we have large clouds or the fuel is reactive like hydrogen. The hazard potential of a gas explosion is strongly linked to the likelihood of DDT. The hazard of detonations in QRA-analysis is generally not taken into account. It is therefore a need for more detailed knowledge of the DDT process in order to implement detonation models in numerical simulations and QRA-analysis. This work is part of the Norwegian contribution to IEA HIA Task 31 and 37 on hydrogen safety.

2 Method and Experimental Set-Up

Fig 1a illustrates the experimental set-up. The set-up consists of a 3 m long channel with 10 x 10 cm^2 cross section. The channel was closed in the ignition end and an obstacle was placed 1 m from ignition. The side walls of the channel were made of transparent polycarbonate. The obstruction was a baffle type obstacle creating an open slit with a blockage ratio of 0.85. A more detailed description of the channel can be found in Gaathaug et al [5]. We used Kistler 603B transducers for pressure measurements. A Z-type schlieren setup was used for imaging. The image was captured on a Kirana camera. It is an ultra-high speed camera with a framing rate of up to $5 \cdot 10^6$ fps, 180 frames and 924 x 768 pixels. In the present study the camera was operating at 500 000 fps. The gas mixture was stoichiometric hydrogen-air at atmospheric pressure. The gas was ignited by a weak spark. The image processing was done in Matlab. We used background subtraction similar to our previous work on shock tracking [6]. The front was detected by thresholding the 1-order gradient of the image intensity level. When the position of the front in x-direction $x_f(y,t)$, is established, the normal velocity of the front $V_{f,n}$, was the found as illustrated in Fig.1b:



$$V_{f,n} = \frac{\dfrac{\partial x_f}{\partial t}}{\sqrt{1+\left(\dfrac{\partial x_f}{\partial y}\right)^2}}$$

Figure 1. a) Experimental set-up, b) Method of estimating the normal front velocity, $V_{f,n}$, from front tracking contour

3 Results and Discussion

In this extended abstract we will present tree different cases; i) Overdriven transverse detonation wave, ii) Mach-stem leading up to DDT, and iii) Detonation propagating downstream of the DDT site.

Fig. 2 shows four images of first case i) where we observed an overdriven transvers detonation wave. As shown in Fig. 1a the DDT appears to be a result of a Mach reflection occurring at the left part of the upper wall. Unfortunately the Mach stem formation is not part of the sequence and has occurred outside the camera field of view. In Fig.2a there is a reaction bubble slightly in front of the main turbulent reaction front trailing the lead shock. However, this bubble is not directly involved in the main transition to detonation event. In Fig. 2b the transverse detonation that establishes a self-sustaining detonation front in the undisturbed mixture ahead of the coupled shock- reaction front has by now nearly reached the bottom of the channel. The velocity of this transverse detonation front propagation in the shocked gas head of the reaction front, trailing the shock front, both propagating from the left, is approximately 2700 m/s which is significantly greater that the CJ-velocity for the initial mixture . Thomas [7] has speculated that it is the overpressures associated with detonations established in post shocked gases that are responsible for the large pressure transients measured during onset of detonation events in shocked gas following flame acceleration processes; a point argued again more recently, Thomas [2], while attempting to dispel occasional misunderstanding and generalization when using the term DDT. In Fig. 2c, an inclined self sustaining detonation front is seen to have been established over the entire height of the channel. In final frame, Fig. 2d, the reflection at the lower wall of the transverse detonation wave and oblique incidence of the detonation it established in the undisturbed mixture, have given rise to a transverse pressure wave that propagates upwards through the combustion products

Fig. 3a shows the pressure records for case i). Ch #4 (red) and #5 (cyan) are located at the bottom and the top of the schlieren view at x = 495 pixels. Unfortunately the pressure recording #5 was cut off at 6 MPa, but record indicates peak pressure of at least 10 MPa. In Fig. 3b shows the contour from the front tracking for each frame. On the left side the shock front has a velocity of 600 to 800 m/s and the contours are closely spaced. When the detonation is formed the front velocity reaches 2000 m/s and distance between the contours are increasing. Fig. 3a shows the calculated front velocity, $V_{f,n}$ along

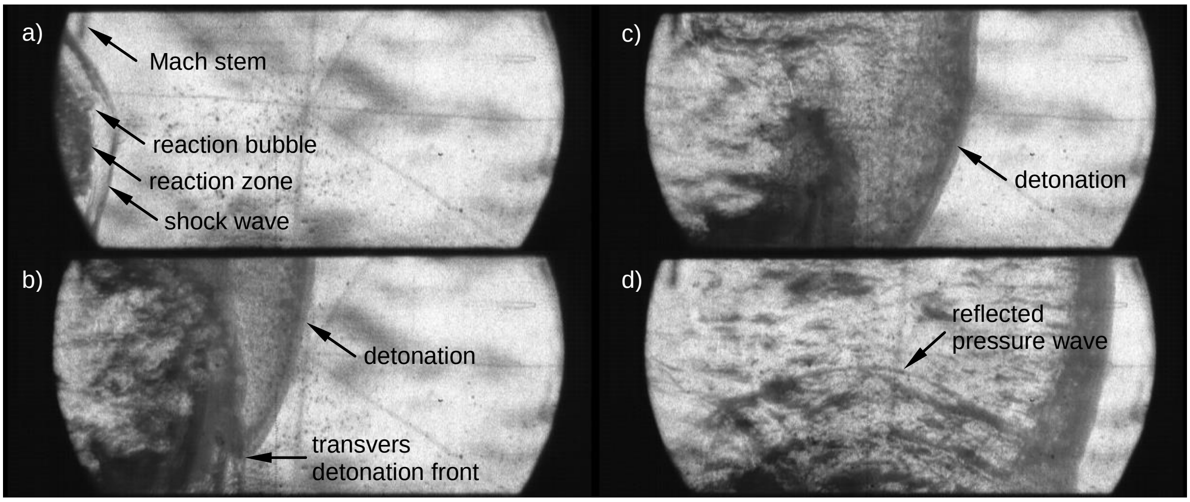


Figure 2. Frame #37 (74 µs), #76 (152 µs), #85 (170µs) and #101 (202 µs)

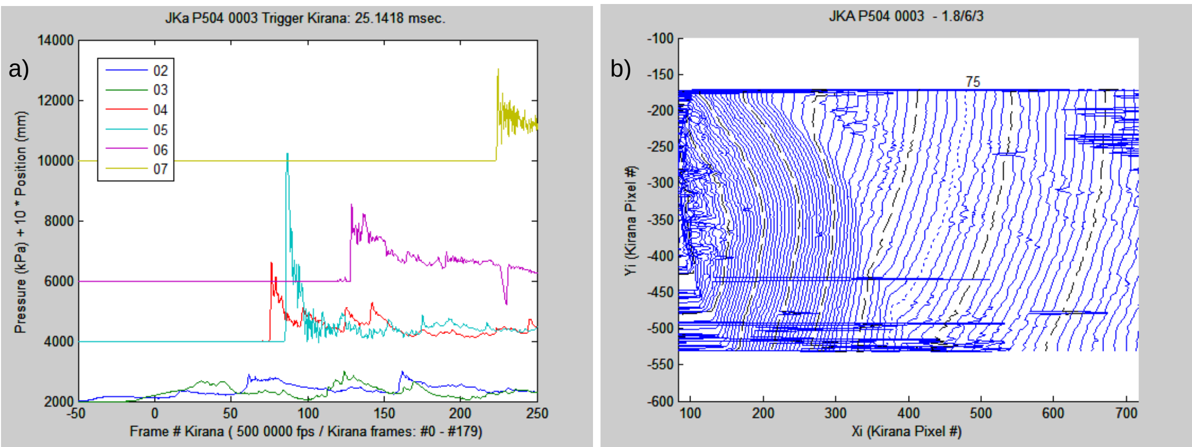


Figure 3. a) Pressure + position vs. frame # b): Front contours

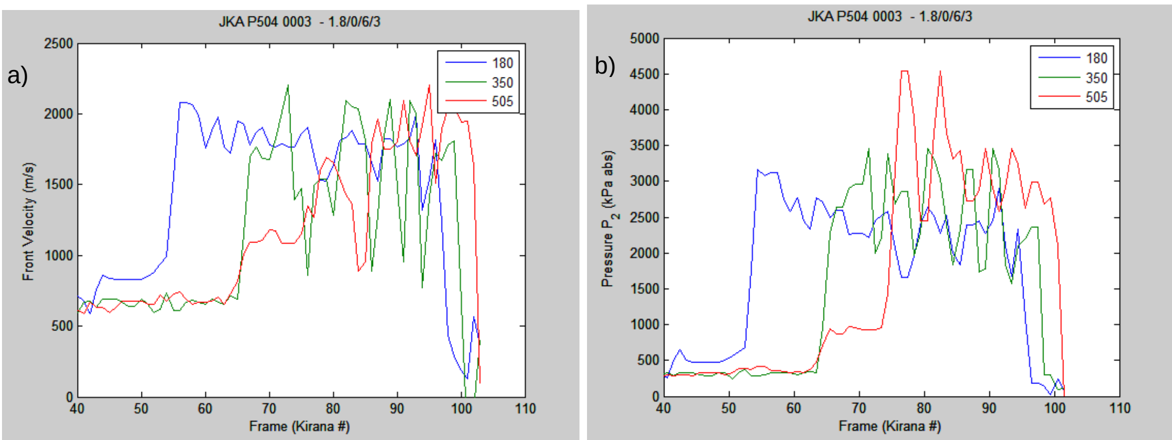


Figure 4. a) Front velocity vs. frame # b) Estimated pressure behind the front vs. frame #

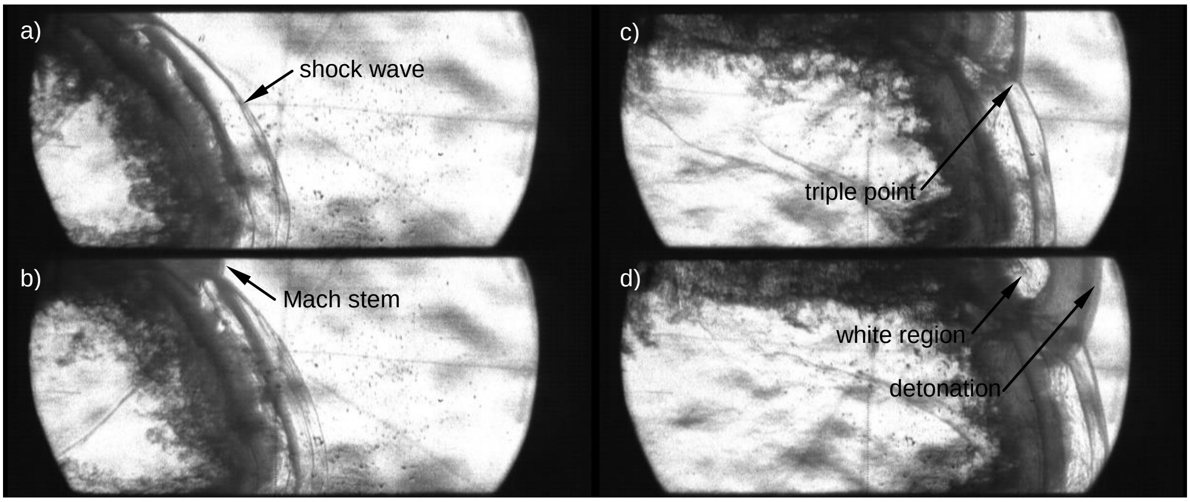


Figure 5. Frame #48 (96 μs), #59 (118 μs), #94 (184 μs) and #106 (212 μs)

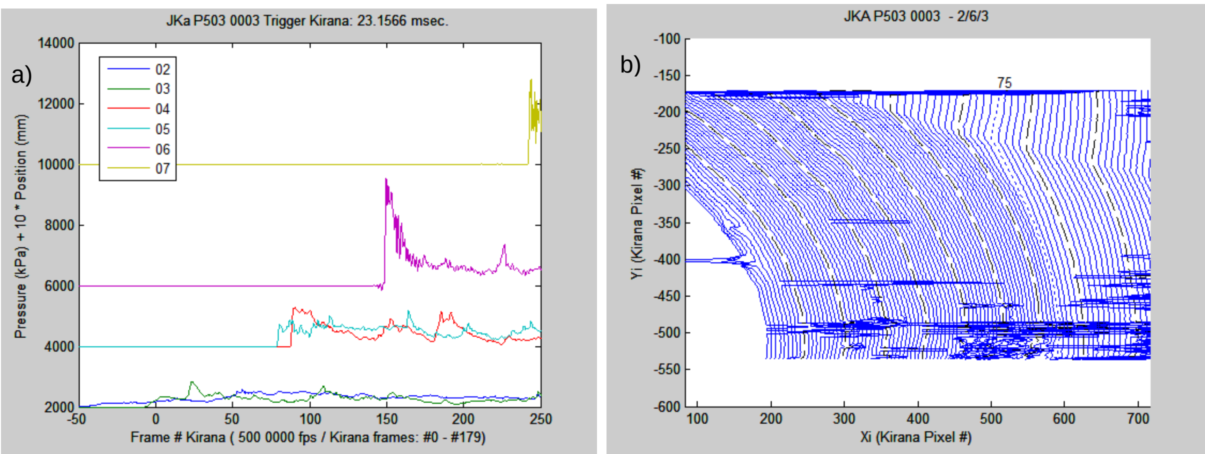


Figure 6. a) Pressure + position vs. frame # b): Front contours

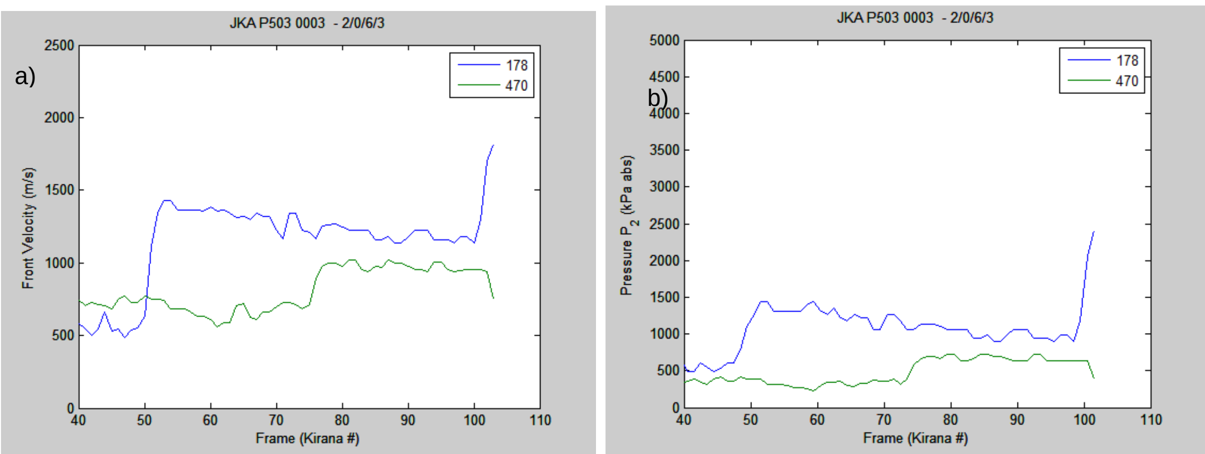
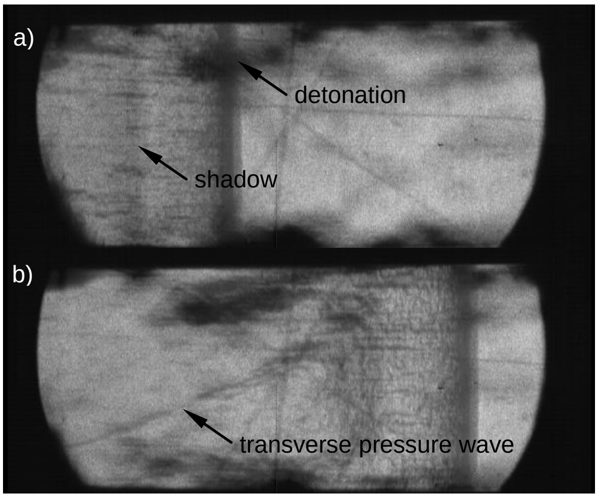


Figure 7. a) Front velocity vs. frame # b) Estimated pressure behind the front vs. frame #

y =180 (top), 350 (middle) and 505 (bottom). At the top of the channel the front wave moves at 600 m/s for then to jump to 800 m/s at frame #42. At frame #55 the wave jumps to velocity of 2000 m/s. As the wave propagates in the upper part it is slightly decaying as it propagates out of view. In the middle part the overdriven transvers detonation wave reach y=350 at frame #66. At the bottom the shock start to accelerate before the overdriven transvers wave pass over it. From the shock relations and front velocity we estimated the pressures behind the front wave. The results are shown in Fig. 3b. When the shock enters from the left the pressure behind the shock is around 0.5 MPa. After DDT the estimated pressure increases to 3 MPa.

Fig. 5 shows four images from case ii) when a Mach-stem are formed at the upper wall. This planer Mach-stem at the upper wall propagates approximately 100 mm before it forms a curved detonation. The curved detonation is shown in Fig 5d. The triple point is the joining point of the curved shock front ahead of the highly turbulent deflagration front and the Mach stem, initially normal to the top wall. Also that this Mach stem is actually composed of typical detonation font transverse waves, or “detonation cells” cellular structure also probably propagates along the curved leading shock, between it and the turbulent combustion front trailing behind. The triple point propagates along shock at speed comparable to the CJ-velocity. The pressure records and the contour plot are shown in Fig. 6a. The Fig. 7 gives the front velocity and estimated pressures. The pressure transducer #4 and #5 are located at y = 578. Pressure record #5 shows a shock front followed by constant pressure plateau indicating a trailing reaction front. Also in this case we notice that the fronts are slowly decaying when they propagates from left to right. In frame #96 a white region becomes visible behind the Mach-stem. Five frames later the front starts to curve and the normal velocity of the front steps up to velocity near the CJ-velocity. This white region might be the burned vortex that is discussed in Bhattacharjee et. al. [3].



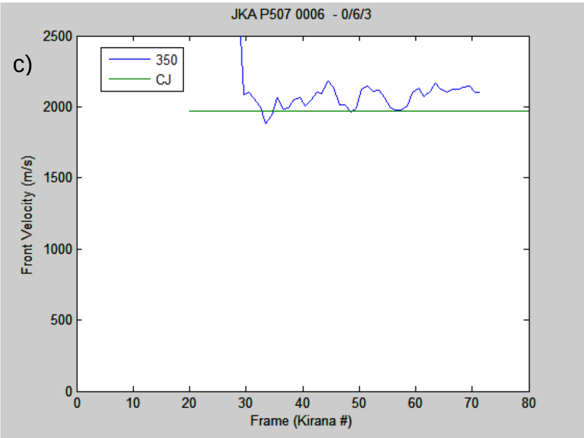


Figure 8. a) Frame #48 (96 μs)and b) frame #73 (146 μs), c) Front velocity vs. frame #

In the last case, as shown in Fig.8, the onset of detonation occurred before the wave entered the schlieren field of view and an almost planar a self sustaining has developed. The image of the detonation front is rather diffuse. This might be due to the width of the channel. The width of the channel is around 10 detonation cell sizes. The front velocity from the front tracing is slightly above the CJ-velocity. From the images in Fig. 8b we can see a transvers pressure wave present in the combustion products. This transverse wave may have caused the detonation wave to become slightly overdriven. We can also see a shadow about 30 mm behind the donation front. If this shadow is a fluid dynamic phenomena (head of the Taylor wave) or optical refection is not clear and need to be investigated further. One possible interpretation is that it is similar in nature to the oblique waves observed using schlieren by Edwards et al.[8] which, they speculated, were caused by streamline divergence, linked to boundary layer development.

4 Conclusions

The experiments demonstrates that it is possible with an ultra-high speed camera, schlieren technique and image processing to observe and extract detail information of the deflagration to detonation (DDT) process. We have been able to follow the shock wave and the transition process in atmospheric hydrogen at 500 000 fps and 924 x 768 pixels resolution. From the images we can find the front velocity and estimate the pressure behind the front wave. For the same experimental conditions two different modes of DDT was observed; i) Overdriven transverse detonation wave, ii) Mach-stem leading up to DDT. In case i) we observe the transvers front propagates at 2700 m/s while the leading detonation propagates at near CJ velocity. In case ii) a triple point propagates close to CJ velocity In both cases the Mach-reflection appears to be of major importance. We believe the images and the experimental technique can be improved by reducing the width of the channel. In the present channel the detonation from seems to be smeared out. The present image processing scheme is relatively simple and improvements should be possible. We believe that present experimental results in combination with CFD simulation can further improve the understanding of DDT mechanism(s) and modes of DDT.

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