# Photographic Study of the Two-Dimensional Dynamics of Irregular Detonation Waves

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### Introduction

The classical model of a detonation, originally proposed by Zel'dovich-von Neumann-Döring model, is a one-dimensional model. The steady detonation wave is modeled as a plane shock wave followed by a reaction zone. This model does not account for spatial variations of the fluid properties and velocity perpendicular to the direction of propagation. Although this model is able to predict some parameters of a detonation, there are several experimental observations that point to the inadequacies of this model. Transverse wave activity has been observed experimentally in all self-propagating detonation waves in gases using pressure readings, smoked foils and open shutter and schlieren photographs. All of these studies indicate that transverse activity takes place near the leading shock and the transverse wave spacing, or cell size, is used to characterize this unsteadiness. (Edwards 1969, 1970, 1971, 1972, Strehlow 1974, Vasiliev 1978)

Detonable mixtures are classified in two categories, regular and irregular, with each type of detonation exhibiting different behaviors in similar geometries. (Lee et al. 1996, Radulescu et al. 2002) In regular mixtures, the characteristic spacing of the transverse waves does not change and the pattern etched in smoked foils or the lines traced out on an open shutter photograph are straight and regularly spaced. The mechanism of combustion in detonation of regular mixtures is the result of adiabatic heating by the lead shock front, which triggers chemical reactions after a certain induction period. In irregular detonations, the cell size is highly variable. (Shepherd 1986) One may also observe local failure and re-initiation via localized explosions, and fine cellular sub-structure associated with these reinitiation events. Some studies have indicated that unburned pockets of material are found behind the lead shock wave and that those burn at a later time, due to turbulent mixing of the pockets. (Oran et al. 1982, Radulescu et al. 2005, Austin et al. 2005) It is yet unclear what role this transverse structure plays in the propagation of the detonation, or through which physical mechanism the pockets of unburned material react in irregular detonations.

### **Experimental Setup**

A thin channel is used. The cross-section of the channel is 100 mm wide by 25 mm thick. The length of the detonation channel is 1300 mm. Both front and back windows are made of glass, permitting visual access. A detonation is initiated at one end using a high-energy spark. A nominal energy of 1600 J is stored in a capacitor bank at a voltage of 4 kV. A Z-type schlieren apparatus with a continuous light source (Hg-Xe short arc lamp) is used to visualize density perturbations. A thin pellicle beam splitter is used in the schlieren beam, downstream of the analyzer knife-edge. This enables two different cameras to look at the same test section. A high-speed digital framing camera and a digital streak camera are used to visualize the schlieren field.

The framing camera is composed of 4 CCD's looking through the same lens by way of a set of

semi-reflecting surfaces. Each CCD has a maximum resolution of 1024 by 1240 pixels and can take up to 2 images, which enables a maximum of 8 schlieren images to be taken. The streak camera has a maximum resolution of 512 x 480 pixels and a temporal window of 160 us. A second high-speed digital framing camera with a maximum of 2 images taken by a single CCD is utilized to take photographs of the self-emitted light. Piezo-electric pressure transducers are also used in the test section to record the pressure history on one side wall. This recording was mainly used to time the visual diagnostics, but also provided a check of the successful initiation of the mixture. It also provided an independent average measurement which velocity to velocity measurements from the visual diagnostics could be compared.



Figure 1: Sketch of idealized triple point tracks at initial pressures of  $P_0 = a$ ) 3.4 kPa, b) 6 kPa and c) 10 kPa.

The tube is initially filled with a stoichiometric

mixture of methane and oxygen at a low pressure of  $P_0 = 3.4$ , 6, or 10 kPa. The cell size of this irregular mixture at those pressures is respectively  $\lambda = 200$  mm, 100 mm, and 50 mm, respectively. As can be seen in the sketch of figure 1, these initial pressures permit geometries in which, respectively, 1, 2 and 4 transverse waves are present. Upon rapid deposition of the energy stored in the capacitor banks at one end of the tube, a detonation is initiated and propagates down the length of the tube. Both framing cameras were timed using the initiator circuit of the capacitor bank. The self-luminescent images were timed coincidently with some of the schlieren images so that the two images could be superimposed.

### Results

#### Multi-Headed Detonation Wave

At an initial pressure of  $P_0 = 10$  kPa, global features of the detonation front can be observed as seen in fig. 2a. Non-uniformities in the detonation front are observed as was noted in previous studies. (Radulescu et al. 2005) Several scales are observed ranging from spherical structures only a few millimeters in diameter to more oblong density perturbations a few tens of millimeters in length.

At an initial pressure of  $P_0 = 6$  kPa, the characteristic cell size of a stoichiometric methane/oxygen mixture is  $\lambda = 100$  mm, which is approximately equal to the width of the channel used. Experiments conducted at such pressures show the same basic features observed at higher pressures, as shown in figure 2b. Pockets of gas at a different density are observed behind the front. The pockets decreased in frequency as they moved away from the front, with the greatest separation being about one cell width from the front. The intensity of the schlieren record around those pockets, dark on the right and light on the left, shows that the density inside these structures is higher than that of its surroundings.



Figure 2: Single frame schlieren image of a detonation in  $CH_4+2O_2$  at an initial pressure (a)  $P_0 = 10$  kPa and (b)  $P_0 = 6$  kPa, showing the multi-headed front with transverse waves, the fine scale structure as well as randomized density perturbations.

#### Single-Headed Detonation Wave

In this propagation mode, with the characteristic spacing between transverse waves being twice the width of the channel, a single wave propagates back and forth. Although this transverse wave cannot always be identified on the schlieren photographs, a triple point can always be observed, as in figures 3 and 4.

Shown in fig. 3 are two simultaneous images of a detonation traveling from left to right. The triple point has traversed <sup>3</sup>/<sub>4</sub> of the channel width and travels downward. The Mach stem is



Figure 3: Single frame a) self-luminescent and c) schlieren image of a detonation in  $CH_4+2O_2$  at an initial pressure  $P_0 = 3.4$  kPa. Both images are superimposed in b). Features are sketched in frame d). P denotes region where products are found and R regions where reactants are found.

located above the triple point and the incident shock wave below. Reactions occur behind the Mach stem and are located close to the shock front. The reaction front behind the incident shock is decoupled and lags some distance behind the shock front.

A tongue of material at a different density is present behind the Mach stem. Reaction of this unburned pocket does appear to occur, as can be seen from the records of self-emitted light. Close to the triple point, light is emitted at the interface between the unburned pocket and the burned gas on either side. Further back, the light emission is distributed across the entire area of the unburned pocket. This interfacial light emission is indicative of a diffusive type of combustion at the edges of the unburned pocket. The double Mach stem configuration implies that two shear layers are present, which coincide with the edges of the unburned pocket. The interfacial luminosity conjugated with the presence of shear layers strongly suggests that reactions along the pocket edges occur through turbulent diffusion. The distributed luminosity at the tip of the pocket does not necessarily imply ignition of the pocket's core due to shock compression. Furthermore, this distributed luminosity was not present on all experiments.

A sequence of 8 schlieren and 2 self-emitted light images is shown in figure 4. The formation of the unburned pocket is evident from the sequence of images. The incident shock wave is located below the triple point, while the Mach stem is located above. The triple point thus moves up.

The sequence starts with the triple point near the top wall of the channel and the incident shock wave spanning most of the channel width. The reaction front has presumably already decoupled from the shock front, but is still located close to it.

As the reaction front lags further behind the shock wave, an interstitial space is created where shocked but unburned mixture is located. This interstitial space is most visible behind the incident shock at 20, 30 and 40  $\mu$ s of figure 4.

While the reaction front lags further and further behind, the transverse wave moves down. Material in this interstitial space is "engulfed" by the transverse wave. It is this material that forms the unburned tongue of material behind the Mach stem.



Figure 4: Sequence of a) schlieren and b) self-luminous frames of a detonation in  $CH_4+2O_2$  at an initial pressure  $P_0 = 3.4$  kPa. Inter-frame time is 10 µs for the schlieren images and 20 µs for the self-luminous images.

When the triple point reaches the bottom wall of the channel, the pocket detaches and is further convected by the flow. In figure 4, such a detached pocket, left over from the prior cell cycle, is visible on the left of frames at 0 to 50  $\mu$ s. It reduces in size as material burns.

Shown in figure 5a is the streak record corresponding to the sequence of images shown in figure 4. The field of view of the streak camera is a thin horizontal line close to the bottom wall of the channel and is thus looking at the incident shock wave and decoupled reaction front. The main features visible in the streak photograph are highlighted in figure 5b.



Figure 5: a) Streak schlieren record and b) sketch of the salient features for a detonation in  $CH_4+2O_2$  at an initial pressure  $P_0 = 3.4$  kPa. Streak record is taken simultaneously with the framing images shown in figure 4.

The incident shock wave and the back of the lagging combustion front are readily identifiable. A grey circle indicates the location of the collision of the triple point with the top wall of the channel. The transverse wave catching up to the incident shock wave is also visible. The velocity of the different waves can be obtained from the streak records.

### Analysis

We first calculate what fraction of the total mass within a detonation cell burns via the Mach stem and coupled reaction, the lagging reaction front, or the unburned pocket.



Figure 6: Description of the different parameters measured in the detonation structure. Incident shock and combustion front velocities are measured from the streak schlieren record. Mach stem velocity and all capture lengths are measured on the framing schlieren images.



Figure 7: Characteristics of the different features found in the detonation front. a) Velocity of the incident shock, Mach stem and combustion front. The particle velocity behind the incident shock is also shown. The velocities of the incident shock and combustion front are measured from the streak record. The particle velocity is calculated using the normal shock relations. The velocity of the mach stem is measured from the framing images and is thus shown as discrete points. Streak record measurements are shown as continuous lines. b) Capture length for the Mach stem, incident shock and combustion front.

Different features of the detonation front are measured, namely the different capture lengths and wave velocities. The "capture length" of a feature refers to the length visible in the framing images through which mass flows, while its velocity is measured in the framing images, thus with respect to a fixed observer in the laboratory reference frame. These different measurements are sketched in figure 6 and their variation with distance is shown in figure 7. The particle velocity behind the incident shock is obtained using the normal shock relations. From the framing images, we also measure the position of the triple point as a function of time.

The triple point track divides the unreacted mass in two distinct regions. Mass that is situated below the triple point track is processed by the incident shock wave. Conversely, mass that is situated above the triple point track is processed by the Mach stem. Integrating the area bounded by the walls of the channel on either side of the triple point track, we can determine that 52% of the mass within the detonation cell is compressed by the incident shock wave and the remaining 48% by the Mach stem. The amount of mass compressed by the Mach stem was also calculated by integrating the mass flux through the shock surface, using the measured value of the shock velocity. Knowing the capture length and velocity of the shock wave along the cell length as well as the initial density of the mixture, we can calculate the mass flux going through the Mach stem surface agreed with the integration of the area bounded by the triple point track to within 10%. The agreement between the two different measurements is very good, despite that only 8 data points were available from the framing images.



Figure 8: Normalized mass flux through the Mach stem, incident shock and combustion front.

The mass flux through the lagging reaction front was found to be on the order of  $5 \times 10^{-10}$  kg/mm. $\mu$ s. The mass flux through the incident shock wave was found to be on the order of  $3x10^{-9}$  kg/mm. $\mu$ s. The mass fluxes through the different features can be normalized with the mass flux through a steady CJ wave propagating through the same mixture. The normalized mass fluxes through the incident shock, the Mach stem and the combustion front are shown in figure 8. The total mass flux through the detonation wave was roughly 80% of the mass flux through the steady This discrepancy is not CJ wave. surprising as boundary layers present on the walls of the channel slow down the detonation wave. Velocity deficits of 20% have been observed before for selfpropagating detonation waves in irregular mixtures (Radulescu 2003).

The integration along the cell of these mass fluxes shows that on the order of 20% of the mass compressed by the incident shock wave is burned by the lagging combustion front. The

remainder, 80% of the mass compressed by the incident shock wave, is thus "engulfed" by the transverse wave into the unburned pocket.

For some experiments, the triple point collided with the side wall of the channel around the mid-point of the channel. It is then possible to look at the transition from Mach stem (i.e. before triple point reflection) to incident shock wave (i.e. after triple point reflection). One such experiment is shown in figure 9. The distinct dark zone in the center of the unburned pocket is easily visible in this particular experiment. Interfacial luminosity is also easily visible on the records of selfemitted light.

The streak field of view was again a thin line, this time at the top wall of the channel and it was therefore possible to measure the velocity of the shock and combustion front around the mid-point of the cell. By measuring the capture length in the different frames, it was possible to obtain a measure of the mass flux through the lead shock wave and the combustion front. Mass flux measurements are shown in figure 10. It should be realized that the framing images span a time window shorter than that of the corresponding streak record. The capture length measurements were thus fitted with polynomial fits and extended to match the data available from the streak record. The length over which we have confidence in the measurements extends from



Figure 9: Succession of a) schlieren and b) self-luminous frames of a detonation in  $CH_4+2O_2$  at an initial pressure  $P_0 = 3.4$  kPa. Inter-frame time is 10 µs for the schlieren images and 20 µs for the self-luminous images.

 $x \sim 50$  mm to  $x \sim 160$  mm. The location of the triple point reflection from the side wall is shown by a vertical arrow.

Around x = 50 mm, the mass flux through the shock surface and the combustion front is seen to be equivalent. Decoupling occurs early on, which corresponds to a plateau in the mass flux through the combustion front. As the shock and combustion fronts are decoupled, the velocity of the combustion front gradually decreases from the lead shock velocity to slightly more than the particle velocity.

A sudden decrease in the mass flux through both the shock surface and combustion front occurs around the triple point collision location. Also after collision, the mass flux through the combustion front quickly reduces from 60% to 30% of that through the shock wave. After the

collision, the transverse wave and triple point reverse direction and so the capture length of the shock wave reduces.

Although the uncertainty on this measurement is relatively high, it shows that a substantial amount of mass compressed by the incident shock wave is "engulfed" by the transverse wave. The mass compressed by the transverse wave while the Mach stem is still small (cf. fig. 4, frames  $10 - 30 \ \mu$ s) is likely to influence the Mach stem as it reacts. Conversely, mass compressed by the transverse wave at a later time (cf. fig. 4, frames  $50 - 70 \ \mu$ s) is more likely to be part of a detached pocket. The transverse wave, after reflection, quickly sweeps over the detached pocket, bringing it back inside the zone of influence of the Mach stem (cf. figure 9, frame 7).



Figure 10: a) Velocity of the lead shock, reaction front and particle velocity along the wall of the channel and b) mass flux through the lead shock and reaction front. Measurements of velocity are from the streak record. Particle velocity behind the incident shock is calculated from the normal shock relations. Measurements of the capture length (not shown) from the framing schlieren images. Location of the triple point colliding with the side wall of the channel is indicated by an arrow.

#### **Induction Time Calculations**

The induction time for a particle after crossing a shock of strength  $M_s$  is calculated for the mixture under consideration. We compute this induction time by considering the constant volume combustion of a particle initially at the post shock state. We used the GRI detailed mechanism (Smith et al.) as a kinetic model. We first consider the induction time of a particle that is shocked by an initial shock of strength  $M_s$  and again by a shock of a strength varying between M = 1 and 2. The results of those calculations are shown in figure 11a. We also consider the induction time of a particle initially compressed by a shock wave of strength  $M_s$  and subsequently undergoing a gas dynamic expansion. The variation of temperature and pressure along the particle path is related to the decay rate of the shock wave. We used the self-similar solution of the point blast problem to calculate the decay rate of temperature and density along a particle path. Although the self-similar point blast equation are not integrable analytically, we can find an analytic solution if we first approximate the velocity profile by

$$u(r,t) = \dot{R}_s(t) \frac{r}{R_s(t)}$$

Here, *r* is the space coordinate, *t* is time  $R_s = At^N$  is the shock position and  $\dot{R}_s$  is the shock velocity. This We can then relate the density variation along a particle path to the shock decay. We find that

$\frac{\rho}{\rho}$ =	$\left(\underline{T}\right)^{\prime(\gamma-1)}$	$=\left(\frac{t}{-1}\right)^{-\nu}$
$ ho_1$	$\left(T_{1}\right)$	$\left(t_{1}\right)$

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Figure 11: a) Velocity of the lead shock, reaction front and particle velocity along the wall of the channel and b) mass flux through the lead shock and reaction front. Measurements of velocity are from the streak record. Particle velocity behind the incident shock is calculated from the normal shock relations. Measurements of the capture length (not shown) from the framing schlieren images. Location of the triple point colliding with the side wall of the channel is indicated by an arrow.

In this case, we assume that the heat release by the reacting gas behind the blast wave does not influence the flow field significantly. The expansion is thus isentropic. This argumentation is similar to that found in Lundstrom and Oppenheim (1969). The exponent v is a function of the decay rate of the shock. This decay rate is described by the parameters *A* and *N*. Induction times of a particle for two different decay rates are shown in figure 11b. These decay rates are typical of experiments performed in this study. When fitting the decay of the incident shock, we found the decay rate exponent *N* to be approximately 0.75 - 0.9. The constant *A* was found to be on the order of 5-15. The Mach number of the incident wave was of the order of 4.5 - 5.2.

The induction time of a particle compressed by a second shock was seen to be reduced by up to 2 orders of magnitude. For typical strengths of the incident shock wave, this corresponds to a reduction of the induction time from 10000  $\mu$ s to 50 – 100  $\mu$ s. However, for a particle undergoing expansions, the induction time is seen to be increased by several orders of magnitude. Note however that this is for shock strengths above M = 5. This effect of the gas dynamic expansions on the induction time of the particles may be more important than the effect of multiple shock compression by the transverse wave. This therefore suggests that the mechanism for the combustion of the pocket of unreacted material is not auto-ignition by shock compression.

### **Cellular Irregularity**

Seemingly random local explosions can lead to the formation of new structure. Shown in figure 12 is the interaction of a detonation cell with the waves generated by a local explosion, located along the bottom wall of the channel. In the present case, the local explosion occurs slightly before the apex of the detonation cell and is sketched in figure 13.



Figure 12: Succession of a) schlieren and b) self-luminous frames of a detonation in  $CH_4+2O_2$  at an initial pressure  $P_0 = 3.4$  kPa, showing the development of the detonation structure after a random local explosion. Inter-frame time is 10 µs for the schlieren images and 20 µs for the self-luminous images.



Possible Local Explosion Site



A new detonation cell overtakes the old structure and the transverse wave associated with this new triple point propagates into the previously formed pocket. It also engulfs material that has been shocked by the weaker top shock wave but has not reacted yet. This leads to the creation of an unburned pocket, which seems attached to the previous one. This pocket exhibits an enlarged section near the lead shock wave (see frames 40 and 50  $\mu$ s). This portion will later deform and result in a seemingly curved pocket of unreacted mixture. This structure was in fact created by two different detonation cells. After such a random

explosion, the region where heat will be released is concentrated near the lead shock front. Parts of the unburned pockets have also been shocked three times, which may also speed up the reaction rate through an enhanced turbulence.

### **Concluding remarks**

This study aims at determining experimentally the dynamic structure of irregular detonations. Framing and streak schlieren photography has been employed to visualize qualitatively the gasdynamic features of the detonation structure and their velocity. Direct photography of the selfemitted light was also used to estimate the regions of more intense chemical reaction. By comparing the regions of more intense luminescence with the qualitative density variations, it was possible to identify features of the structure of irregular  $CH_4/O_2$  detonations. Reaction zones, both coupled and decoupled from the leading shock wave, as well as pockets of unburned gas were identified. These pockets were seen to form behind the Mach stem. Evidence suggesting the presence of turbulent mixing at the edges of these unburned pockets was observed. Induction time calculations were performed, which further suggest the mechanism of auto-ignition via shock compression is insufficient to explain the reaction of the pockets.

It was estimated that approximately 40% of the mass contained within a detonation cell is burned via the pocket. Once the unburned pocket detaches from the main detonation front, it is quickly swept back into the zone of influence of the Mach stem. Hence, most of the mass thus influences the decay of the Mach stem rather than the incident shock.

An example of the more complex dynamics of irregular detonation waves resulting from the random local explosions was outlined. It was noted that a flow field where heat is likely to be released closer to the front and more rapidly was generated. The influence of the occurrence of local explosions on the location of heat release in the detonation wave combined with the observation that a substantial amount of mass may burn in pockets might serve as a coupling mechanism to explain the propagation mechanism of irregular detonation waves.

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