Experimental Measurement of Detonation Cell Size at High Pressure

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1 Motivation

The soot foil technique has been an important tool in the study of detonation since its first use in 1959 [1]. It records the path of shock triple points along the wall of a detonation tube [7]. The simplicity of the technique led to extensive use in measuring the cell sizes of various detonable mixtures [2] [3]. On soot foils, the cell size is measured directly as shown in Figure 1.

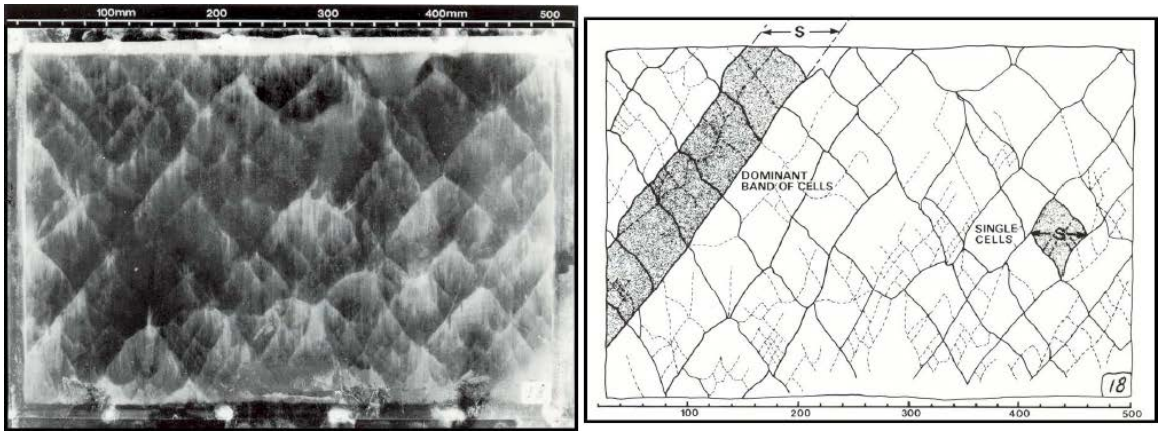

Figure 1: Soot foil record and hand-drawn interpretation of a detonation [4]

Despite the ease with which cells are measured with a soot foil, there are some downsides. The process is slow because there are several steps to producing a useable soot foil. A foil must be coated

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with an even layer of soot and secured within the detonation tube before the tube is sealed. Too much soot or too little soot results in poor contrast between the triple point paths and the remainder of the foil. An uneven soot coating may also result in locally poor contrast. At high pressures, the severity of the detonation may remove the entire soot layer leaving no triple point paths. At lean equivalence ratios, the soot may be consumed as fuel for the remaining oxidizer also resulting in a lack of visible triple point paths. Soot foils are also limited by the necessity of attachment to the tube wall. The triple point paths are affected by the rigid boundary of the tube wall and the associated boundary layer. It is important to eliminate the effects of tube geometry when measuring cell size because is it thought to be related to the chemical kinetics of detonation.

For these reasons, a schlieren imaging technique was developed with a very small focal depth of field. Schlieren imaging records the density gradients in a transparent medium [5]. Schlieren is appropriate for imaging the triple points because detonations exhibit strong density gradients and high pressures at the lead and transverse shocks. A modification to the classic schlieren technique allows a finite, arbitrary depth of field. With sufficiently small depth of field, a slice of the detonation front is imaged far from the influence of the tube walls. The technique is analog, and images may be captures at any rate and resolution. Entry into the detonation tube is not required, and no preparation of test articles between runs is necessary. This allows relatively fast data collection compared to soot foils with no sacrifice of resolution. The limits on data collection are determined by the specifications of the camera used to record the images. High speed cameras with frame rates exceeding 1 million frames per second and exposures lass then 294 ns are able to freeze the motion of a detonation front while capturing multiple images of a single detonation at is crosses a moderately sized schlieren field of view.

2 Experimental Methodology

The modified schlieren system is based on the classic z-type configuration (Fig. 2). In the classic configuration, the light source is a pinhole or a slit simulating a point source. When placed as the focal point of a parabolic mirror, this results in a parallel beam of light which is refracted by density gradients in a gas. Because the light beam is parallel, the entire segment between the two parabolic mirrors is focused. The result is vertical integration of all density gradients in the parallel segment of the beam. This is not desirable when measuring cell size because it superimposes all of the triple points in the entire detonation front.

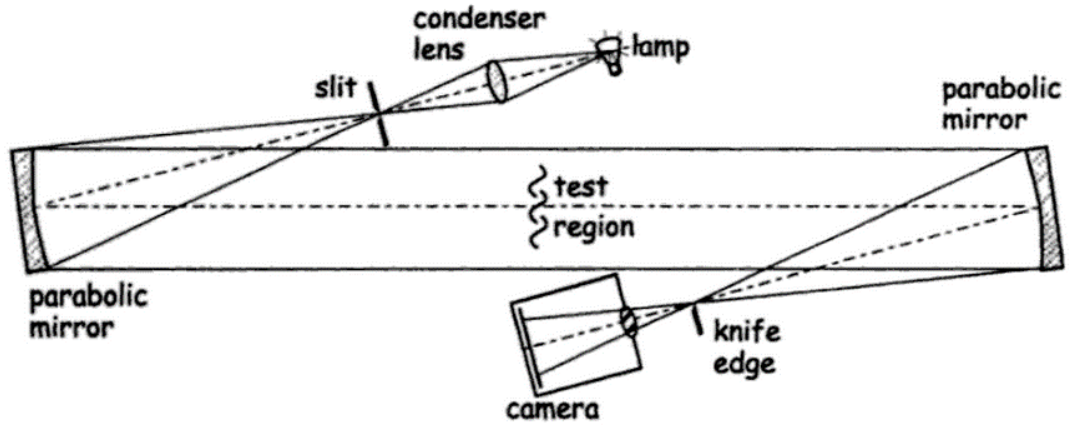

Figure 2: Classical schlieren configuration [5]

In this research, the classical configuration was modified by increasing the source slit width resulting in a source image instead of a point source (Fig. 3). The light beam is no longer parallel, and there is a focal plane between the mirrors. The focal depth of field is a function of the desired circle of confusion, in this case the width of a pixel, (δ), the focal length of the mirror (f), and the width of the source image (b). A wider the image results in a smaller the depth of field (Eq. 1).

$$\Delta z = \frac{\delta * f}{b} \tag{1}$$

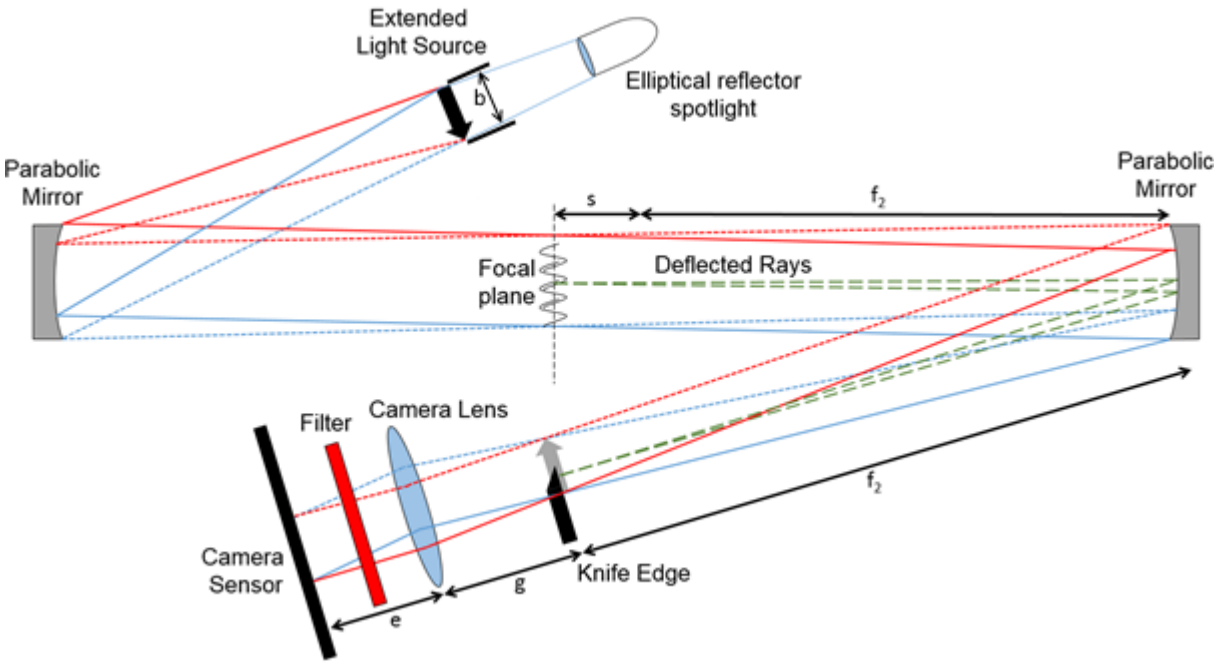

Figure 3: Schematic of the modified imaging system

An elliptical-reflector-spotlight produced the source image in this research. The spotlight combines an elliptical reflector an iris and a lens to produce a bright, uniform source image of adjustable diameter. The image was set at 0.61 m in diameter, the focal length of the parabolic mirrors was 2.54 m and the desired circle of confusion was 0.020 mm. The resulting focal depth of field was 0.41 mm. An additional feature of the imaging system was a 590 nm cut-off, long-pass filter. The filter blocked chemiluminescence emissions from the detonation to prevent washout when imaging hydrocarbon-air mixtures.

Detonations at high initial pressure were initiates and contained within a 18.6 MPa rated stainless-steel detonation tube. To allow the light beam to pass through the tube, a test section was built with two horizontally opposed windows. The windows were constructed from engineered quartz and were 51 mm thick each. The cross-section of the detonation tube changed to allow a smooth transition to and from the windows with 0.30 m of constant cross=section before and after the windows. Images were captures by a Phantom ® v711 high-speed camera. The camera has a maximum frame rate of 1.4 million frames per second a 128 by 3 pixel image size, and the rate is less for larger image areas. In this research, the image size was 544 by 232 with resolution of 0.21 mm per pixel. At this image size, the maximum frame rate was 40000 frame/s. The frames were exposed for 294 ns during which the detonation traveled 0.27 mm. The motion blur associated with the detonation movement was on the order of one pixel. The resulting images clearly show the triple points as notches on the detonation front. Figure 4 shows a representative set of frames.

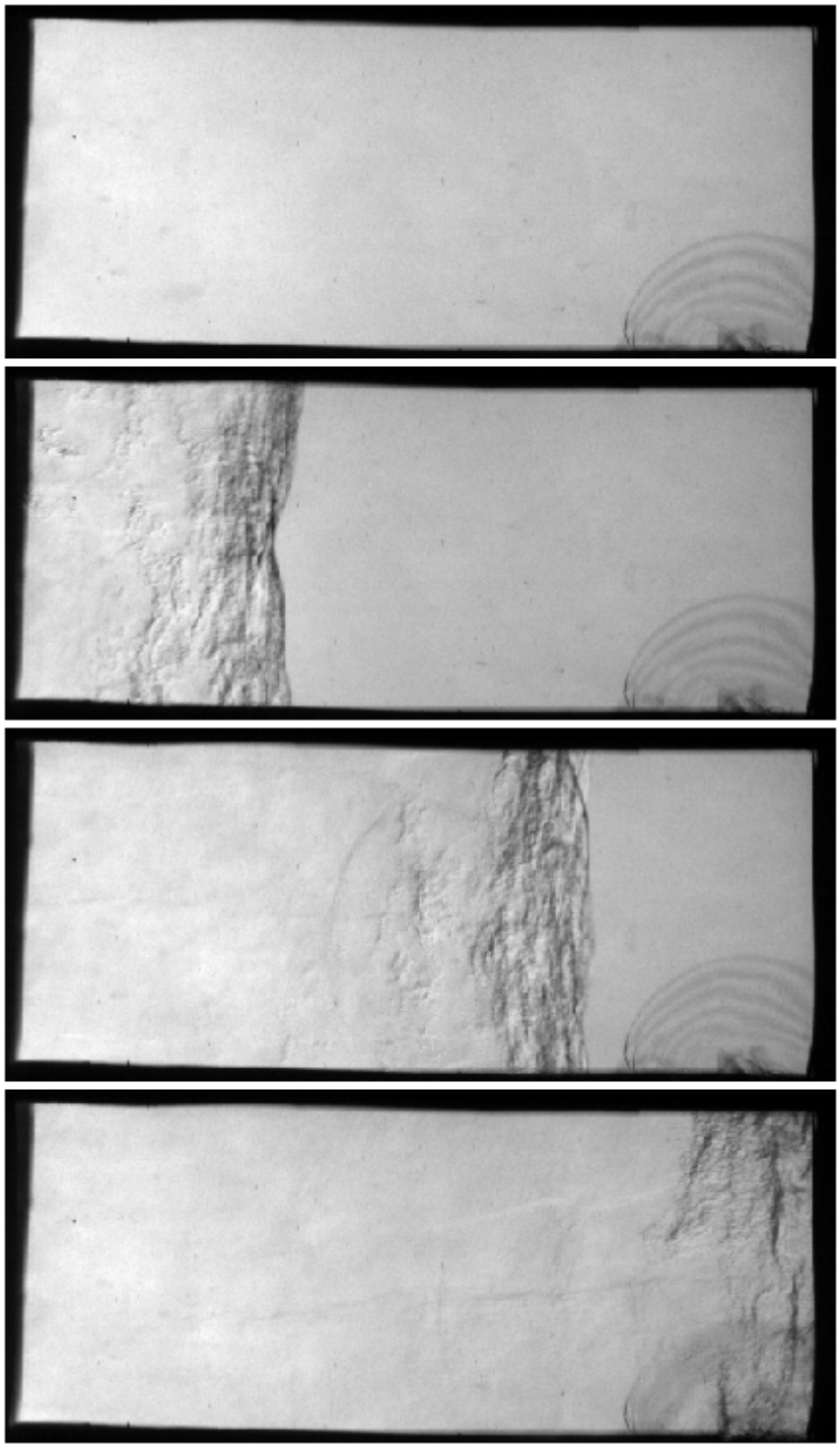

Figure 4. Raw Frame Sequence, Ethylene/Air Phi = 1.2

3 Data Analysis

There is as yet no automated detection algorithm to detect triple points in a detonation front, and the triple point locations were cataloged by hand. An effort is under way to develop an automated method to identify and catalog triple points. Figure 5 shows an example detonation front image with the triple points marked.

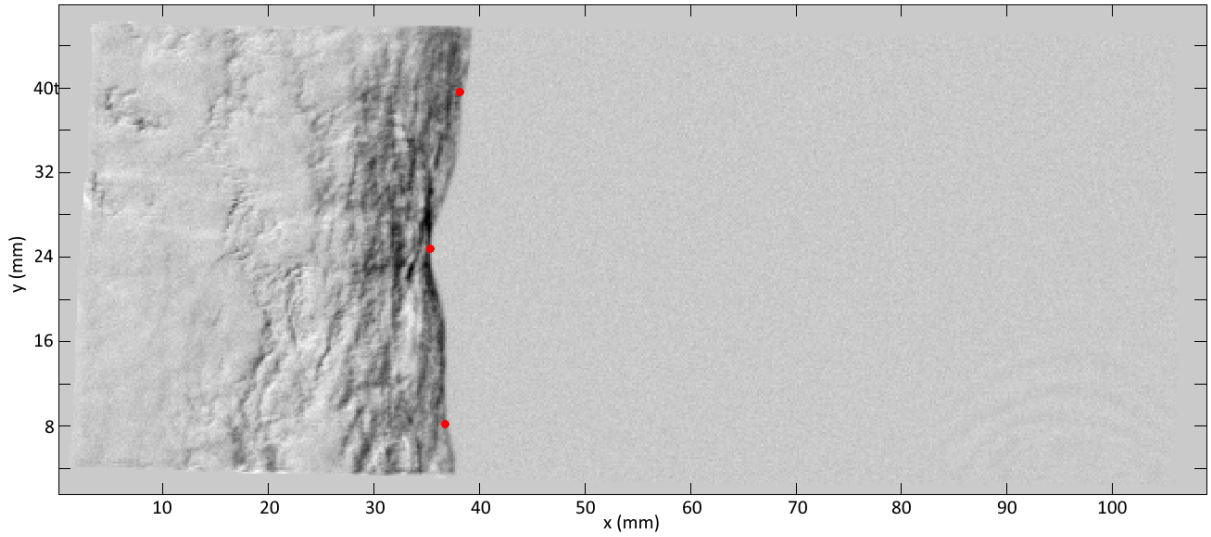

Figure 5: Example triple point locations

Hydrogen-air and ethylene-air mixtures were used because ample published data is available for hydrogen-air and because ethylene-air is interesting as an easily detonated hydrocarbon-air mixture. Data at elevated initial pressure is rare for hydrogen-air and non-existent for ethylene-air. The test cases consisted of hydrogen-air and ethylene-air mixtures at 1.00 atm and 10.00 atm initial pressure (Table 1).

4 Results

In all test cases, the distribution of distances between triple points was uniform with roughly equal probability between zero and the maximum measured distance. The mean and median both fall at the midpoint between the highest and lowest values in a uniform distribution, and the cell size was calculated to be twice the median distance between triple points. The measured cell size for stoichiometric hydrogen-air at 1.00 atm initial pressure was 6.14 ± 2.79 mm. While the uncertainty is over 45% of the measured value, it is less than the standard deviation of the published values at the same conditions, and there is no statistically significant difference between the measured cell size and the mean of the published values. The measured cell size for stoichiometric hydrogen-air was too small to measure at 10.00 atm initial pressure so the equivalence ratio was reduced to 0.85. At 1.00 atm, the cell size was 8.73 ± 2.80 mm. Cell sizes at 10.00 atm initial pressure are still to be determined.

The measured cell size for stoichiometric ethylene-air was 9.84 ± 2.41 mm. This differs significantly from the published cell size of 24.8 ± 5.73 mm and may be influenced by the size of the detonation tube. The measured cell size is nearly a third of the tube diameter, and there is simply not enough room for a cell to develop that does not interact with the tube wall. At 10.00 atm initial pressure, the cell size of stoichiometric ethylene-air is still to be determined.

Table 1: Test condition and results

Fuel	Equivalence ratio	Initial pressure (atm)	Cell size (mm)
Hydrogen	1.00	1.00	6.14 ± 2.79
Hydrogen	0.85	1.00	8.73 ± 2.90
Hydrogen	0.85	10.00	TBD
Ethylene	1.00	1.00	9.84 ± 2.41
Ethylene	1.00	10.00	TBD

The measured cell size of the two mixtures at 1 and 10 atm suggests that the cell size depends on $exp(P_{initial})$. For hydrogen-air at $\phi = 0.85$ the relation is $\lambda = a_{H2} * exp(P_{intial} * b_{H2})$, and for stoichiometric ethylene-air the relation is $\lambda = a_{C2H4} * exp(P_{intial} * b_{C2H4})$. The coefficients are undetermined until the high pressure measurements are complete.

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