Multiple-view Imaging of a Small-diameter Detonation Tube at 5 MHz

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1 Introduction and Background

A Detonation occurs when a shock wave and combustion reaction are coupled together. Compared to the case of deflagrative combustion, detonation combustion results in increased peak temperature, global reaction rate, and enthalpy due to the combustion occurring at increased pressure. These characteristics make detonation combustion an appealing option in the design of combustors with limited flow residence time, e.g. scramjets. However, in addition to the measurement challenges inherent in any combustion research, detonations present additional difficulties due to short timescales.

High-speed imaging is an effective method for directly observing the unsteady behavior of detonation waves. Optical techniques such as schlieren, shadowgraph, and chemiluminescence allow the researcher to image a detonation wave. Recent advances in camera technology – in both speed and sensitivity – allow for the direct investigation of transient behavior in detonations. In order to temporally resolve the unsteady features of a typical detonation, a camera needs to operate at frame rates on the order of 200 kHz. For over a decade now, commercially available scientific CMOS-based cameras have been capable of reaching these frame rates by partitioning the sensor into several sections – trading active pixels for speed. The research presented here employs a framing camera, the *Shimadzu HPV-X2*, capable of full-frame imaging (250-by-400-pixel sensor) at 5 MHz – fast enough to resolve all major structures in a detonation. The tradeoff with this camera is the total frame limit of 126 continuous images. At a 5-MHz frame rate, 126 frames cover a 2-inch (51-mm) length of travel for a typical air-fuel detonation (less for oxygen-fuel detonations), and is well-suited for our research.

The Combustion Optimization and Analysis Laser (COAL) Lab at the Air Force Institute of Technology (AFIT) recently installed and instrumented a small detonation tube designed by, and in collaboration with, the Air Force Research Laboratory (AFRL). This rig was designed with full optical access to the tube while being small enough to mitigate many of the safety concerns common in detonation research. In addition to the optical access typically seen in laser labs, this rig is equipped with retroreflecting mirrors allowing for multiple views of the traveling detonation. We designed this optical setup quickly

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as a proof of concept, but the idea of using mirrors to image multiple views could be extended for other applications such as spectroscopic filtering or for tomographic reconstruction of detonation front. In this paper we present the small-diameter detonation tube rig, the optical system involved in imaging multiple views (top, bottom, and front) simultaneously, and the image processing required to track wave speed and the movement of transverse detonation waves.

2 Experimental System and Methods

The detonation tube employed in this research was originally designed as a pre-detonation device, or "pre-det," used for igniting other research combustion rigs such as rotating detonation engines. It employs small solenoid valves to feed the fuel and oxidizer reactants into the common detonation tube, a sparkplug to initiate the combustion, and a spiral-based obstruction to promote the deflagration-to-detonation (DDT) transition. The pre-det is fitted with a clear tube with 0.25-in and 0.125-in outer and inner diameters. The detonation tube rig is shown in Figure 1, and the clear tube is highlighted in pink.

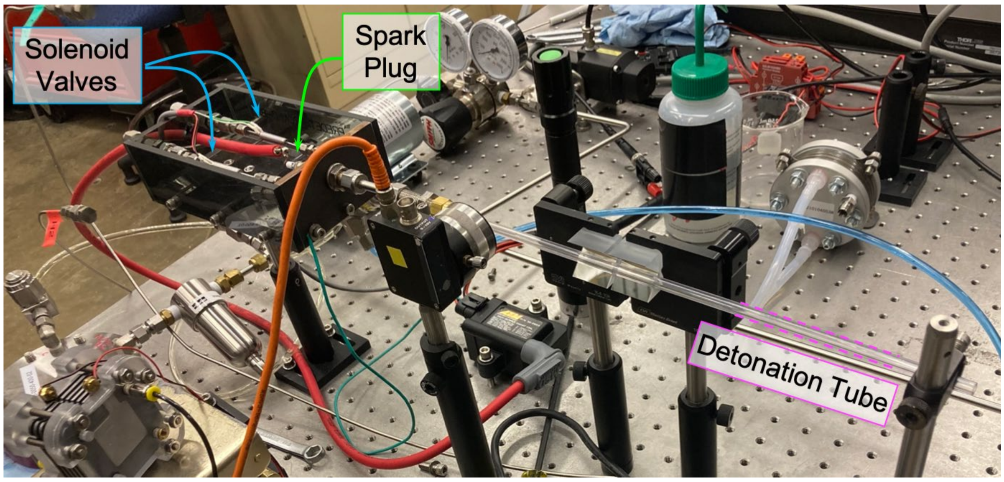

Figure 1: View of the experimental setup showing the detonation tube rig.

An 85-mm lens with an aperture of f/4.5 was mounted to the camera which was positioned such that the field of view was approximately two inches wide. At full resolution (250 x 400 pixels), the Shimadzu camera has a maximum frame rate of 5 MHz and captures 128 images. During this investigation, the camera was operated at 5 MHz for most cases which corresponds to a period of 200 ns and a total video capture time of 25.6 μs. Due to this short duration and the natural variability in the DDT process, the sparkplug command could not be used to reliably trigger the camera. Instead, a lensed photodiode was used as the trigger source which significantly increased timing precision. Despite the cable's shielding, EMI from the spark plug was visible in the photodiode signal. An oscilloscope was used to manually select the signal threshold to be higher than the noise from the spark plug, but lower than the peak signal from the photodiode, and the oscilloscope "trigger out" was used to trigger the camera. In this way the camera trigger was reliably synchronized to the arrival of the detonation in the field of view, and the chemiluminescence imaged. The lensed photodiode, camera, and oscilloscope are shown in Figure 2.

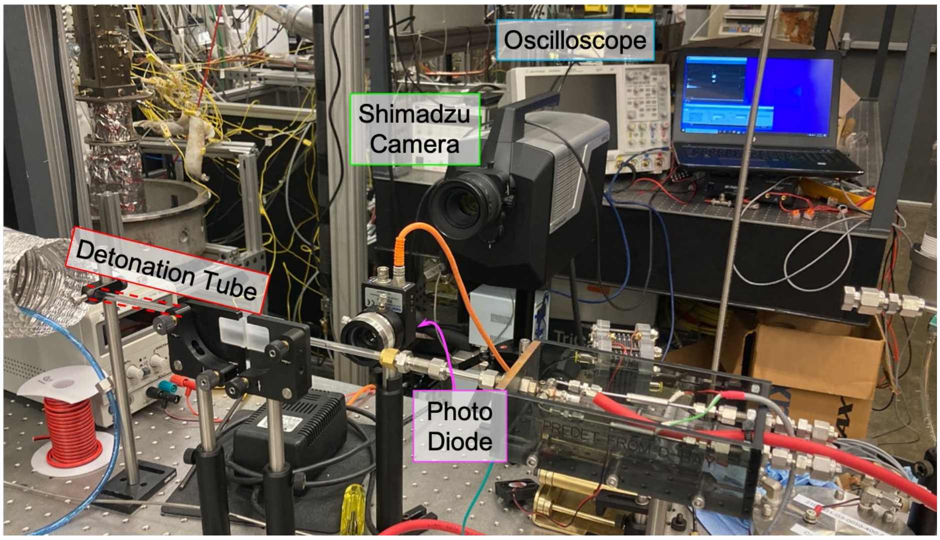

Figure 2: View of the experimental setup showing the photodiode, camera, and oscilloscope.

The description of the experimental setup up to this point may be common to other optical diagnostics laboratories investigating detonation chemiluminescence imaging. One novel aspect of this investigation is the use of retro-reflecting mirrors to project views of the top and bottom of the detonation to the camera. The detonation tube in the field of view is 2 inches wide and ¼" high while the camera sensor is 400 pixels wide and 250 high which means that the aspect ratio of the region of interest is five times larger than that of the camera sensor. Said another way, only one fifth of the camera sensor is being effectively utilized. By reflecting two additional images, we increase this utilization to three fifths, and capture imagery from the two additional views. The front-coated, silvered, retro-reflecting mirrors employed here are shown on the left panel of Figure 3. Please note that this image was taken with a smartphone camera equipped with the standard wide-angle lens; the strong parallax error visible in Figure 3 is not representative of the imagery acquired in the experiments. The right panel in Figure 3 is a calibration image taken by the Shimadzu. To ensure the 85-mm lens was properly focused, an electrical wire was placed inside the detonation tube. The lens was adjusted to bring the letters on the wire's insulation into focus. Such calibration images were taken before each data set to provide scale, but the field of view was always approximately two inches in width. For this calibration, the spatial resolution was 6.7 pixels per mm.

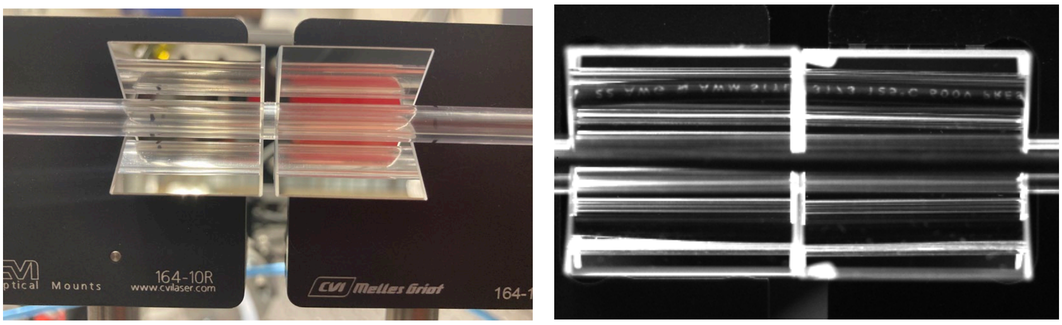

Figure 3: Retroreflectors used to project images of the top and bottom of the detonation tube (left) and calibration image of a wire placed inside the detonation tube (right).

The tubing used as the detonation tube has outer and inner diameters of 0.25 and 0.125 inches. Plexiglass was used during the initial shakeout testing with intention to switch to glass tubing for increased image clarity. Plans to use the glass tubes were scrapped after the glass tube shattered, likely due to detonation overpressure that resulted in hoop stress exceeding the material strength. The shattered tube is shown in Figure 4.

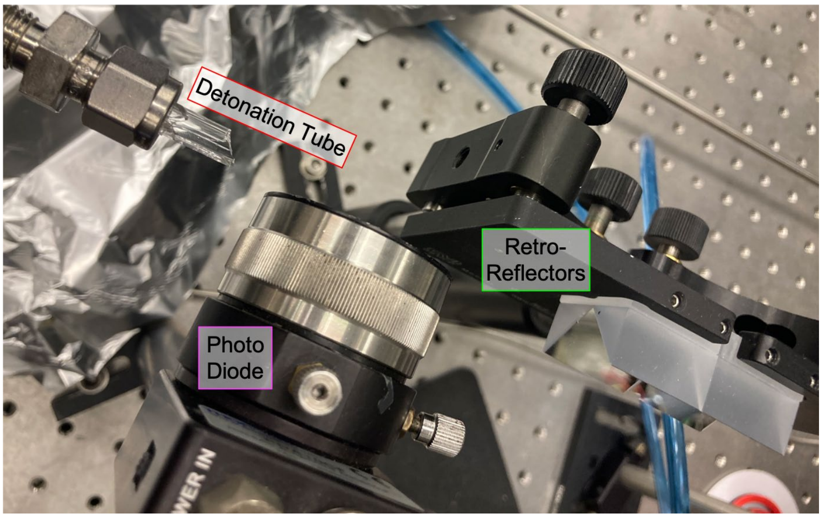

Figure 4: View of the experimental setup showing the shattered detonation tube.

The plexiglass tubes proved their worth in another sense: the chemiluminescence from the H_2-O_2 detonations in the glass tubes was not strong enough to be reliably detected. Hydrogen-oxygen detonations emitted strongly enough to image reliably only when traveling through the plexiglass tubes. The authors posit that this strong increase in chemiluminescence strength could be due to trace amounts of plexiglass material reacting to emit visible radiation or heating to the point of incandescence.

The images were exported as bitmaps and then processed in MATLAB. A 3-by-3-pixel median filter was applied to images with low SNR. The inter-frame detonation displacement was then found via cross-correlation. This inter-frame displacement of the detonation was then converted to physical wave speed using the image scale and the camera frame rate.

3 Results

The Shimadzu recorded 8-bit monochrome images, and the chemiluminescence intensity for each pixel was stored as an integer value from 0 to 255. The chemiluminescence intensity was observed from the ethylene-oxygen detonations was significantly stronger than that of the hydrogen-oxygen flames, likely due to emission from CH radicals. Image number 100 from three detonations – an H_2-O_2 detonation, a C_2H_4-O_2 detonation, and a C_2H_4-O_2 detonation with a neutral density filter – are shown in Figure 5. The maximum intensity recorded in the hydrogen-oxygen detonation image was only 13 (panel a) and is not visible unless the image is scaled to that maximum value (panel a'). The ethylene-oxygen detonation, on the other hand, radiated so strongly that the image is saturated in the reaction zone (panel b). The ethylene-oxygen detonation was repeated using a neutral density filter of optical density 0.5 to avoid saturation (panel c) where a maximum intensity of 224 was recorded. Assuming the camera sensor scaled linearly, these two observations suggest that the ethylene-oxygen detonation was more than 54 times more luminous than the hydrogen-oxygen detonation. We also observe from Figure 5 that the reaction zone appears to be shorter in the ethylene-oxygen detonations, as is expected due to the smaller cell size compared to hydrogen-oxygen detonations.

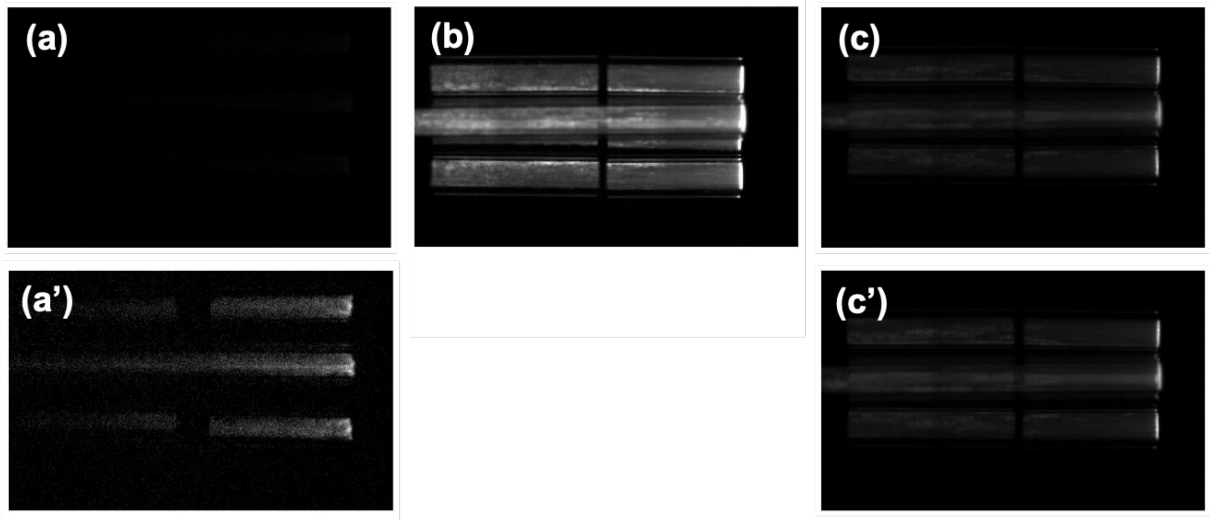

Figure 5: Image #100 for three runs with and without scaling to max observed signal: (panel a) H_2-O_2 no scaling, (panel a') same image scaled to max value of 13, (panel b) C_2H_4-O_2 no scaling, (panel c) C_2H_4-O_2 with ND 0.5 filter and no scaling, and (panel c') same image scaled to max value of 224.

Figure 6 was produced from the same imagery used in panel c of Figure 5 and shows the temporal evolution of the wave speed for the ethylene-oxygen detonation. For reference, the Chapman–Jouguet speed for a C_2H_4-O_2 detonation is about 2,370 m/s. This calculation of wave speed is based on the movement of the detonation in pixels – as estimated from image cross-correlation – and the physical scale of 6.7 mm/pixel. At this combination of spatial resolution and frame rate (5 MHz), one pixel of image displacement corresponds to a relatively course velocity resolution of 742 m/s. This large 'step size' manifests as apparent discontinuities in the velocity measurement, and is evident in the left panel of Figure 6. This effect is mitigated somewhat by fitting the pixels around the detonation front with a polynomial for sub-pixel interpolation of the detonation front location in each frame.

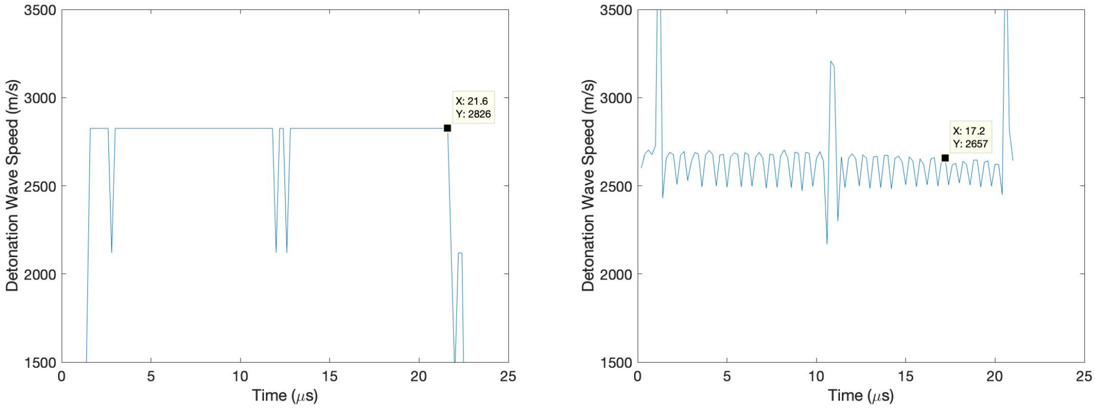

Figure 6: Wave speed profile of an ethylene-oxygen detonation determined using cross-correlation of successive images (left panel) and sub-pixel interpolation (right panel).

The right panel of Figure 6 shows the detonation velocity determined with this interpolation method. We have yet to determine the cause of the small oscillations, but the large spikes correspond with the locations where the detonation reaches the retroreflectors, passes over the gap between the retroreflectors, and exit past the retroreflectors. The jumps at these locations are an artifact of the present interpolation scheme which bins each column prior to estimating the detonation front location. Future work will partition the binning to measure the signal each of the reflected views independently.

The data have been analyzed for the three test cases described above. The remaining 50 tests, in which argon diluent was employed in increasing proportions, will be analyzed next to investigate the effect on wave speed and cellular structure. The transverse detonation waves will then be analyzed for size and stability. Finally, differences in the top, front, and bottom views will be examined to determine if there is any perceptible tilt or curvature in the wave front.

4 Conclusions

This investigation was successful in analyzing the detonation wave speed for a range of reactants and diluents as well as demonstrating the basic optical technique of imaging multiple views of the same detonation simultaneously.