Application of a Novel Optical System to Conduct Schlieren Imaging of Detonation Waves

Brandon Donald[1] and Christopher S. Combs[2]
The University of Texas at San Antonio, San Antonio, TX, 78249, United States

A novel optical system was designed, manufactured, and implemented to perform schlieren imaging of detonation waves and associated reacting flow fields in a cylindrical detonation tube at the University of Texas at San Antonio (UTSA) Hypersonics Lab. The optical system employs a cylindrical positive plano-convex lens to offset the diverging effects of a negative meniscus-like thick-walled acrylic tube. Preliminary ray tracing was conducted considering spatial constraints to determine both the type and focal length of lenses required to maintain light collimation within the detonation flow field. The optical configuration, based on a typical single-mirror coincident schlieren arrangement, utilizes a FASTCAM Photron SA-Z camera for high-speed imaging of detonations produced by stoichiometric ethylene-oxygen mixtures. The novel optical configuration allows a maximum field-of-view of 25.4 mm in diameter and shows the time evolution of the reacting flow field during and after its deflagration-to-detonation transition. Wavespeed measurements provided by the optical system are compared to 1D Chapman-Jouguet detonation theory, with excellent agreement. It is anticipated that the optical system will enable novel in-situ, nonintrusive diagnostics in the UTSA Hypersonics Lab Detonation Tube, and improved visualization of detonation characteristics such as detonation cell size and induction length.

Nomenclature

CJ	=	Chapman-Jouguet
DDT	=	deflagration-to-detonation transition
FOV	=	field of view
P	=	pressure
t	=	time
T	=	temperature
dt	=	time increment
x	=	position relative to the lab reference frame
ϕ	=	equivalence ratio

I. Introduction

Detonation combustion has gained growing interest in recent years for both propulsion and energy applications due to its theoretical thermodynamic advantages and potential for mechanical simplicity relative to conventional thermodynamic cycles and systems. This is especially so for chemical propulsion systems such as pulse detonation engines (PDEs) and rotating detonation engines (RDEs), where high combustion performance, high cycle efficiency, and a lower system mass are desirable [1]. To study detonations and their thermochemical properties in a controlled and repeatable manner, impulse facilities such as detonation tubes are often used. However, owing to extreme pressures and temperatures produced by detonation combustion, detonation tubes have typically had limited optical access, often restricting visualization characterization to only portions of the flow accessible through small-diameter optical probes or windows. Detonation tubes with full flow field optical accessibility typically have planar

[1] Graduate Research Assistant, Department of Mechanical Engineering, and AIAA Student Member.
[2] Assistant Professor, Department of Mechanical Engineering, and AIAA Senior Member.

configurations such as in [2–5], which simplifies optical setup, but limits the allowable detonation pressures to regimes which are less relevant for practical combustion devices. Planar configurations also create multi-dimensional nonuniformities in the boundary layer, which makes comparison to simplified and computationally-tractable detonation models difficult.

A well-established technique used to observe density gradients is schlieren imaging, which allows the effects of shocks and thermochemical reactions created by detonations and high-speed flows to be easily seen [6]. Schlieren imaging of detonation waves, however, has generally been restricted to planar configurations, as the collimation of light through an optically accessible test section—a critical aspect of schlieren imaging—is difficult through non-planar detonation channel cross sections. This is due to the divergence of light rays as they pass through the thick curved surfaces of an optically accessible tube [7]. This divergence of light would severely limit the field of view (FOV), as only the central portion of the beam will reach the detector [7], while the distal portions are left undetected.

Previous studies, although few, have worked to remedy the preceding issues in automotive applications. A group from Toyota Central R&D Labs developed a transparent cylinder engine in which the cylinder itself was shaped to collimate the incident light [8,9]. The resulting design was an optical engine with a cylindrical inner surface (83 mm bore), and an eccentric outer surface. This enabled schlieren measurements of the gasoline fuel combustion to be captured, which was acquired at a frame rate of 4.8 kHz. Another study was conducted more recently at the Combustion Research Facility at Sandia National Laboratories [7]. The study implemented custom-made corrective lenses designed specifically to a cylindrical optical engine, which ignited hydrogen fuel. The experimental setup allowed schlieren measurements to be taken at a frame rate of 18.2 kHz.

The study conducted in this paper expands on the previous concepts to an optically accessible detonation tube without the need for (1) custom-made corrective optics or (2) manufacturing complexity due to optical integration in a cylindrical vessel. Instead, readily available corrective optics are implemented in the setup to enable schlieren imaging of the reacting flow field. This flow field comprises the products of a stoichiometric mixture of ethylene and oxygen during and after its deflagration-to-detonation transition (DDT). It is anticipated that the resulting high-speed schlieren images will allow for accurate comparison against 1D Chapman-Jouguet (CJ) detonation models, and further enable in-situ, nonintrusive visual diagnostic capabilities, and detonation characterization.

II. Background Theory

A general schlieren arrangement is shown in Fig. 1 [7], where light traverses from a point source through an optical setup and through a test medium or object. As the collimated light travels through the test object, light rays are refracted due to the change in density of the travel medium. The exiting light is condensed and then filtered with a knife edge

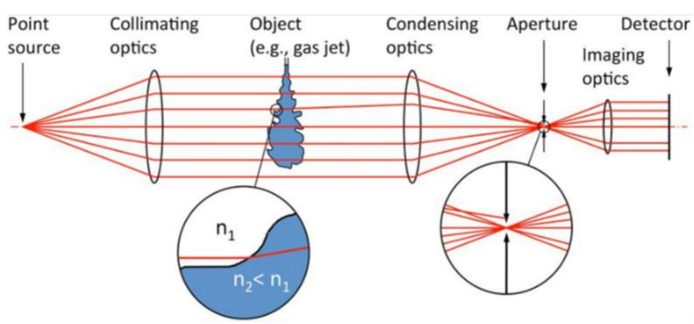


Figure 1. General schlieren arrangement

at a focal point, where a detector captures the remaining light downstream. Note that other types of schlieren setups exist [6], but the underlying principle is the same. The knife edge filter is crucial to schlieren imaging, as blocking the refracted light will allow density gradients to be more prominently seen. The absence of the knife edge would otherwise result in a shadowgraph image that is less sensitive and less detailed than its schlieren counterpart.

In this study, light traverses through a cylindrical acrylic tube. As previously discussed, the divergence of light rays as they pass through the tube will severely limit the FOV, as only the central portion of the beam will reach the detector. The diverging behavior as a result of the light-tube interaction is illustrated in Fig. 2 [7]. To increase the FOV, corrective optics are implemented into the setup. The setup entails the use of an optical element to converge the outcoming light to offset the strong divergent effects of the optically accessible tube.

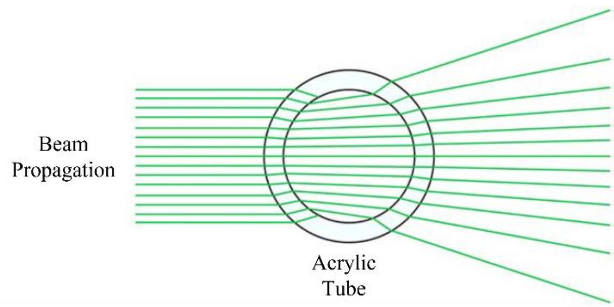


Figure 2. Beam propagation through an acrylic tube

III. Methodology

A. Detonation Facility

The study was performed with The University of Texas at San Antonio Hypersonics Lab Detonation Tube. The pulse-detonation tube facility was designed with three main sections: (1) the ignition section, (2) the visual section, and (3) the test section. These sections are mated together by weldless flanges and are constructed with a continuous channel with inner diameter of 38.1 mm, and wall thickness of 12.7 mm. **Error! Reference source not found.** [10] highlights the different sections of the detonation tube. Downstream of the detonation tube is a 1600-gallon vacuum tank that allows for expansion and cooling of the combustion after each test. The detonation tube and vacuum tank are separated by a mylar diaphragm to contain the reactant gases as the tube is filled.

The ignition section is constructed from a portion of 304 stainless steel tube. This section is where the fuel-oxidizer mixture is fed and initiated. For this study, a 3:1 stoichiometric mixture of ethylene and oxygen (ϕ = 1.00, P_0 = 20.6 kPa, T_0 = 296 K) is ignited by a spark plug ignition system. The combustion reaction is allowed to transition from deflagration to detonation through the aid of a Shchelkin spiral [11] with a length-to-diameter ratio of 9.6, and a blockage ratio (d/λ) of 46%.

To view the reacting flow field, the visual section comprises a portion of cast acrylic tubing and made to be interchangeable. The acrylic material was chosen for its optical clarity and compatibility with several fuel types. This allowed for high-speed imaging of the reaction and its time evolution as it travels down the detonation tube.

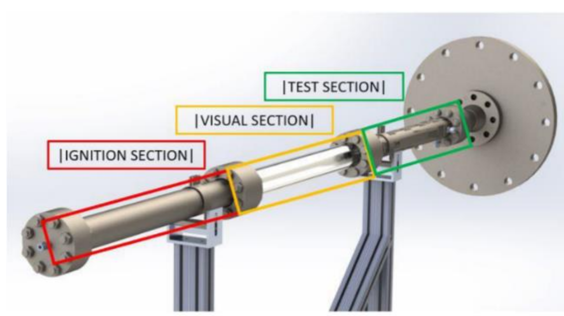


Figure 3. Major subsections of the optically accessible detonation tube

The test section is the final portion that the reacting flow field travels through. The section is of similar construction to the ignition section. However, modifications have been made to include instrumentation ports in fourteen locations along the outer diameter of the tube. Piezoelectric time-of-arrival (TOA) sensors (Dynasen, Inc.) were mounted along the top five ports—equally-spaced 4 inches apart—to record the detonation wavespeed of the fully developed flow. The detonation facility and its instrumentation are depicted in Error! Reference source not found.. The TOA sensor data were recorded at a sample rate of 10 MHz via an in-house LabVIEW VI and an NI PXIe-1083 chassis/PXIe-6386 module setup.

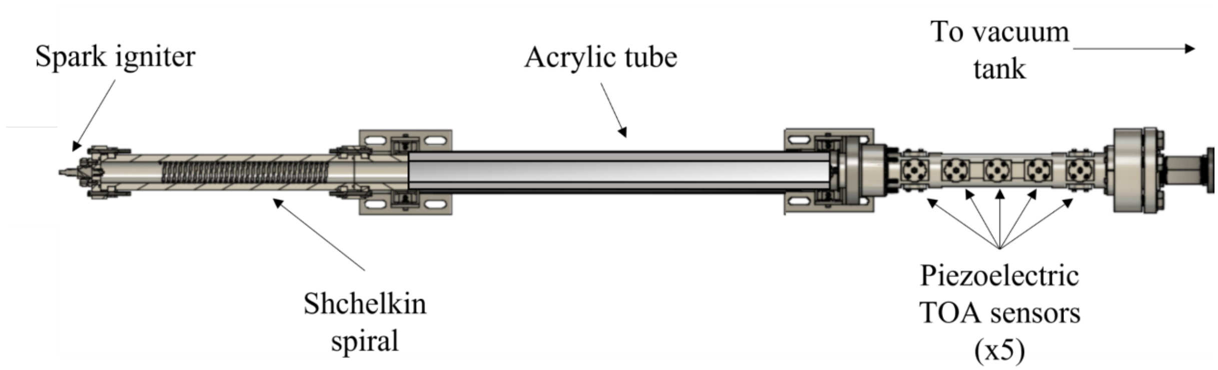


Figure 4. Diagram of the detonation facility instrumentation

B. Schlieren Setup

The optical setup is depicted in Fig. 5. The setup resembles that of a typical single-mirror coincident schlieren arrangement and includes an additional flat mirror to redirect the light from the parabolic mirror to a high-speed camera. This was done to prevent the reflected light from propagating back into the detonation tube, as well as to accommodate for spatial constraints in the facility. Components were aligned in the same plane as the center horizontal axis of the detonation tube using a three-axis alignment laser.

The light source comprised of a variable-intensity short-pulsed LED passing through a variable-diameter iris to imitate a point source. The light was allowed to propagate perpendicular to the length of the optically accessible test section. The parabolic mirror (50.8 mm diameter, f = 508 mm) and corrective lens (plano-convex lens, f = 200 mm) were placed on the opposite side of the test section and aligned with (coincident to) the LED. The corrective lens was positioned so that the outcoming diverging light would converge onto the parabolic mirror. This parabolic mirror

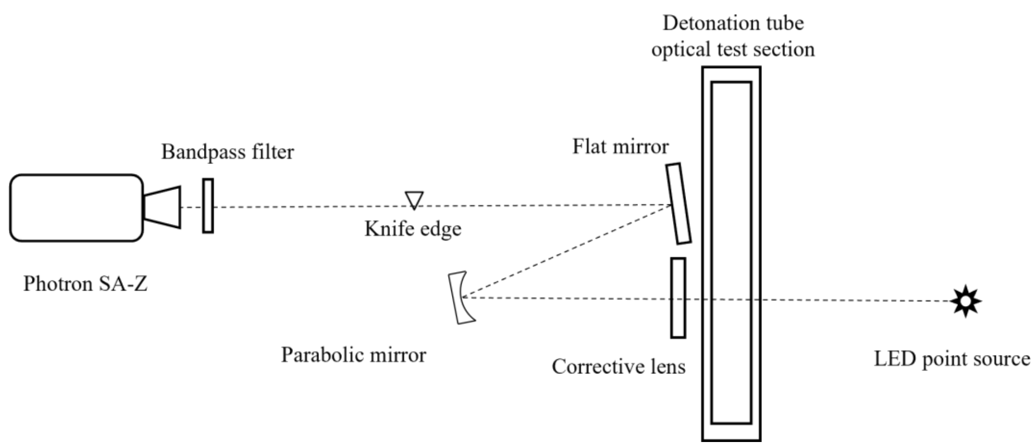


Figure 5. Schematic of the schlieren setup (not drawn to scale)

focused the beam onto a flat mirror to be redirected to a bandpass filter before being transmitted to a high-speed camera (Photron SA-Z, 70-200mm lens) capable of frame rates up to 2.1 MHz. For the knife edge filter, a razor blade was placed in a vertical orientation at the vertical focal point, as the primary interest was to visualize the density gradients across the horizontally traveling detonation waves.

The optical setup was implemented in two variations: (1) a short-pulsed UV LED coupled with a double UV bandpass filter setup and (2) a short-pulsed white LED coupled with a 532 nm bandpass filter. Each filter was positioned directly in front of the high-speed camera. The two distinct setups were pursued to troubleshoot oversaturation of the camera sensing array—detonation emission spectra in the UV range [12] often overpowered the light generated by the UV LED, dramatically reducing the sensitivity of the schlieren technique. To address this issue, the setup was modified with the aforementioned 532 nm bandpass filter, but this posed additional difficulties, which is discuss later in the manuscript.

For this study, images were captured at a frame rate of 100 kHz and a resolution of 640 pixels x 280 pixels. The short-pulsed LED was synced with the camera exposure time via TTL signals to achieve maximum illumination duration without exceeding the heat dissipation threshold of the LED.

IV. Results and Discussion

A. 1D Model

Chapman-Jouguet detonation parameters were determined by NASA CEA [13]. Initial mixture conditions included a 3:1 stoichiometric mixture of ethylene and oxygen ($\phi = 1.00$) at an initial pressure of 20.6 kPa and initial temperature of 296 K. The resulting speed of sound was 326.3 m/s, and CJ velocity was determined to be 2361.1 m/s—this served as the baseline for comparison of the experimentally observed detonation reactions.

B. Preliminary Data and Validation

Preliminary images and TOA data of previous detonations without schlieren optics are demonstrated in Fig. 6 and Fig. 7, respectively, as validation of the DDT condition and optical capability. The detonation tube was filled to an initial pressure of 20.6 kPa at 296 K with a 3:1 stoichiometric mixture of ethylene and oxygen for each experiment, and captured at a 100 kHz frame rate. Select frames were chosen to demonstrate the time evolution of the detonation wave and the induced mass motion of the flow. However, it can be seen in run 5 (Fig. 6a) that oversaturation of the camera by the detonation reaction rendered the visualization of the detonation wave front to be impossible, even after postprocessing. Oversaturation was still present in run 6 (Fig. 6b), despite adjusting the shutter speed from 1250 ns to 248 ns to reduce exposure time. It was concluded that detonation emission was too intense for the preliminary setup, and presumably filters would be required in hopes of addressing oversaturation in the detonation wave front.

a) Run 5, 1250 ns shutter speed   b) Run 6, 248 ns shutter speed

Figure 6. Time evolution of the detonation wave and trailing gas flow of at P_0 = 20.6 kPa, T_0 = 296 K, sampled at 100 kHz

The average time between sequential TOA signals of run 5 and run 6 were dt = 43.8 μs and dt = 44.5 μs, respectively. The velocity profile of the detonation wave in the test section is reproduced by the TOA signals in Fig. 8. The maximum velocities recorded for each run were 2346.4 m/s and 2283 m/s, respectively. These values fall within ±2% of the expected CJ velocity, confirming that the facility is capable of producing detonation flow regimes.

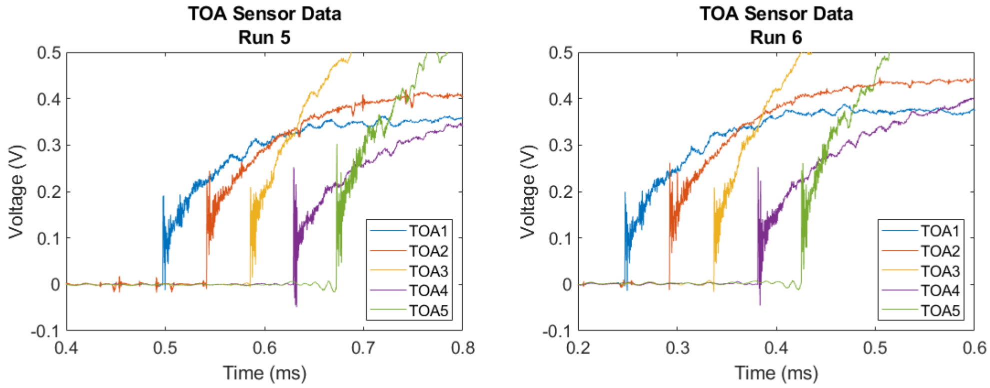


Figure 7. Time history of TOA signals of run 5 (left) and run 6 (right) in the test section, sampled at 10 MHz

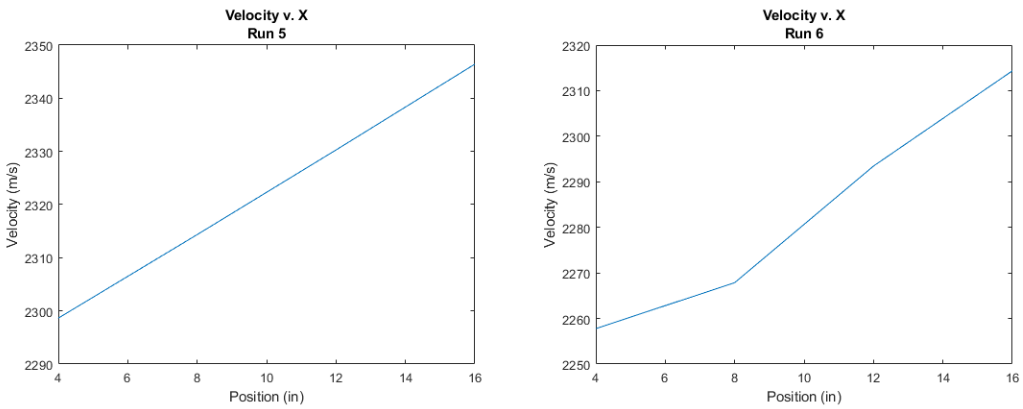


Figure 8. Velocity profiles of run 5 (left) and run 6 (right) in the test section

C. Schlieren Results

As an initial test, the system was applied to visualize a jet of compressed gas in the optical path of the schlieren setup outside of the detonation channel. Postprocessing of the images was not successful in completely isolating the foreground. However, it did help to reduce the visible striations of the acrylic tube presumably caused by the

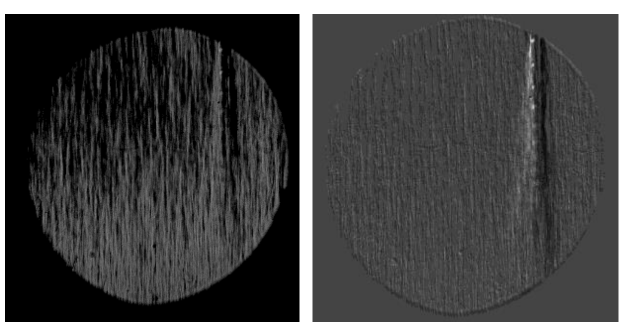
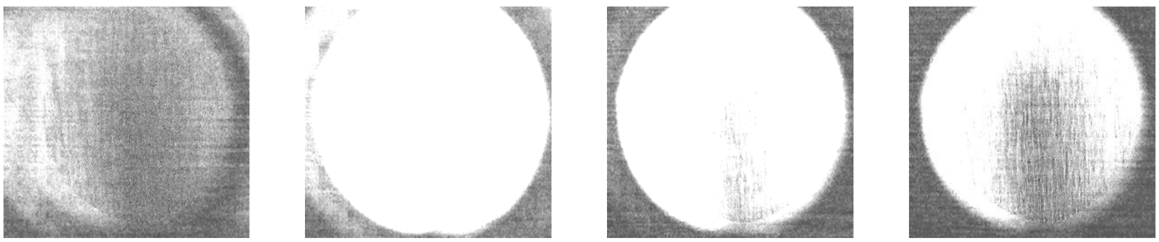


Figure 9. Images of the compressed gas jet before (left) and after postprocessing (right)

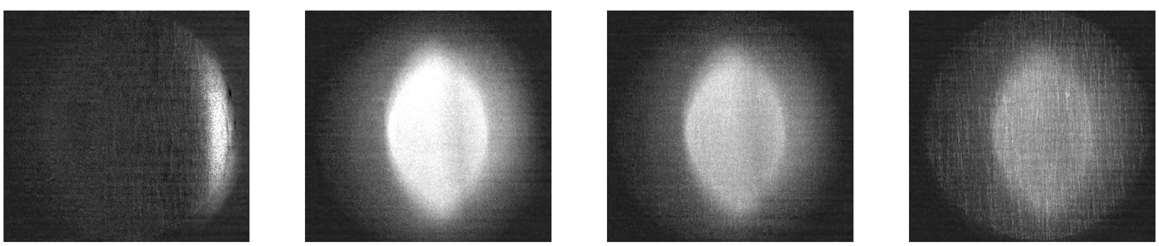
manufacturing process. Further postprocessing of the images revealed the schlieren more clearly. Shock diamonds can also be seen forming in the flow as they exit the nozzle. The presence of these shock diamonds and the contrast across them further validated that schlieren could be detected by the system.

Figures 10 and 11 depict the time evolution of the detonation wave front when implementing the 410 nm UV LED and double UV bandpass filter setup after postprocessing. The initial images at time t = 0 ms were taken when the detonation wave front was first seen in the FOV. Similar to the preliminary images in Fig. 6, oversaturation of the camera sensing array was seen. The detonation was first captured at the max shutter speed setting of 8393 ns, as shown in Fig. 10. As the detonation wave front propagates, saturation occurs and continues far after the detonation wave exits the FOV. Similarly, the detonation captured at a lower shutter speed of 2500 ns in Fig. 11 saturated the image. The shutter speed was set to minimize the exposure time while still detecting the UV LED light with an acceptable signal-to-noise ratio. It was observed that although saturation was not as intense or as long as the previous experiment, detonation structures were still unable to be seen. This was attributed to (1) the short exposure time of the camera introducing noise to the image and (2) the intense detonation emission in the UV range overpowering the UV LED light.



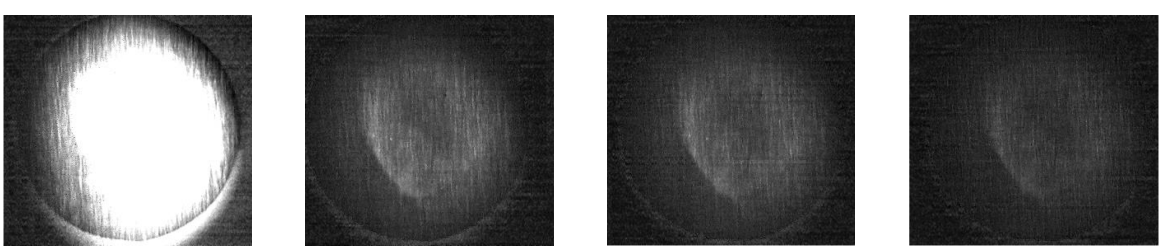
a) 0 ms b) +1 ms c) +2 ms d) +3 ms

Figure 10. Time evolution of the detonation wave front using the 410 nm UV LED and double UV bandpass filter, captured at a 100 kHz frame rate and 8393 ns shutter speed



a) 0 ms b) +0.5 ms c) +1 ms d) +1.5 ms

Figure 11. Time evolution of the detonation wave front using the 410 nm UV LED and double UV bandpass filter, captured at a 100 kHz frame rate and 2500 ns shutter speed



a) 0 ms b) +0.5 ms c) +1 ms d) +1.5 ms

Figure 12. Time evolution of the detonation wave front using the white LED and 532 nm bandpass filter, captured at a 100 kHz frame rate and 5000 ns shutter speed

To troubleshoot the issue in oversaturation, the UV LED and UV bandpass filters were swapped with a white LED and a 532 nm bandpass filter. The 532 nm bandpass filter was chosen for the ethylene-oxygen mixture, which emits strongly in the UV range upon combustion. The white LED was chosen for its broadband wavelengths. Additionally, the shutter speed was set to 5000 ns to minimize exposure time while still attaining an acceptable signal-to-noise ratio. This setup fared better in the reduction of oversaturation, seen in Fig. 12, as the UV emissions were filtered. The lifetime of oversaturation was also reduced, seen in the following images in Fig. 12b-d. Saturation was no longer seen 0.5 ms after the detonation wave front entered the FOV, whereas saturation was still evident after 1 ms (Fig. 11c) with the previous setup.

The latter setup posed another issue, however. The 532 nm bandpass filter severely reduced the sensitivity of the schlieren technique, as most of the broadband light was blocked from reaching the camera—only a relatively small range centered around 532 nm was able to be detected. The lack of adequate light rendered visualization of the reacting flow to be difficult, even after postprocessing. It is suggested that a monochromatic light source in the 532 nm range be used to rectify this issue. However, this light source was unavailable at the time of the investigation. Another suggestion would be to change the fuel from ethylene to hydrogen, which emits more strongly in the 550 nm and above range according to [12]. Hydrogen was also unavailable at the time of the investigation, but studying its detonation reaction would be more feasible with the UV LED and UV bandpass filters. Further considerations would need to be examined for this investigation, which is still ongoing at the time of writing this manuscript.

V. Conclusion

A novel optical system was designed, manufactured, and implemented to enable in-situ, nonintrusive visual diagnostic measurements, and characterization of detonation flow fields. The visual section of the detonation tube enabled high-speed imaging of the detonation wave front and the trailing gas flow. The test section allowed characterization of the fully developed flow and validated that Chapman-Jouguet conditions were met. However, the schlieren setup was unsuccessful in visualizing the density gradients across the detonation wave and the reacting flow. Oversaturation of the camera sensing array was a recurring issue due to the intense detonation emission spectrum of the ethylene-oxygen mixture, even though two variations of the setup were implemented. Suggestions to overcome this issue include the use of a monochromatic light source in the 532 nm range, or using hydrogen as a fuel to conduct schlieren in the UV range.

Acknowledgments

Special thanks to Dr. Daniel I. Pineda of the UTSA Laser Spectroscopy and Chemical Propulsion Lab for his oversight and expertise of detonations and more. Also, special thanks to Dean Kaialau for the design and construction of the UTSA Hypersonics Detonation Tube. Lastly, special thanks to Elijah LaLonde, Angelina Andrade, Ben Steavenson, and everyone from the UTSA Hypersonics Lab for their help in preparing for the experiments.

References

[1] Lu, F. K., and Braun, E. M. "Rotating Detonation Wave Propulsion: Experimental Challenges, Modeling, and Engine Concepts." *Journal of Propulsion and Power*, Vol. 30, No. 5, 2014, pp. 1125–1142. https://doi.org/10.2514/1.b34802.

[2] Radulesco, M. I., Sharpe, G. J., Law, C. K., and Lee, J. H. S. "The Hydrodynamic Structure of Unstable Cellular Detonations." *Journal of Fluid Mechanics*, Vol. 580, 2007, pp. 31–81. https://doi.org/10.1017/S0022112007005046.

[3] Kellenberger, M., and Ciccarelli, G. "Propagation Mechanisms of Supersonic Combustion Waves." *Proceedings of the Combustion Institute*, Vol. 35, No. 2, 2015, pp. 2109–2116. https://doi.org/10.1016/j.proci.2014.08.002.

[4] Driscoll, R., st. George, A., Stoddard, W., Munday, D., and Gutmark, E. J. Thermodynamic and Visualization Study of Shock Transfer in a Dual Pulse Detonation-Crossover System. No. 1 PartF, 2013.

[5] Sosa, J., Rosato, D., and Ahmed, K. A. The Propagation Characteristics of a Detonation Wave in a Supersonic Flow. 2018.

[6] Adrian, R. J., and Gharib-W Merzkirch Rockwell -J H Whitelaw, M. D. *Experimental Fluid Mechanics*.

[7] Kaiser, S. A., Salazar, V. M., and Hoops, A. A. "Schlieren Measurements in the Round Cylinder of an Optically Accessible Internal Combustion Engine." *Applied Optics*, Vol. 52, No. 14, 2013, pp. 3433–3443. https://doi.org/10.1364/AO.52.003433.

[8] Kozuka, K., Ozasa, T., Fujikawa, T., and Saito, A. "Schlieren Observation of Spark-Ignited Premixed Charge Combustion Phenomena Using a Transparent Collimating Cylinder Engine." *Journal of Engineering for Gas Turbines and Power*, Vol. 125, No. 1, 2003, pp. 336–343. https://doi.org/10.1115/1.1496774.

[9] Ozasa, T., Kozuka, K., Fujikawa, T., and Francisco, S. *Schlieren Observations of In-Cylinder Phenomena Concerning a Direct-Injection Gasoline Engine International Fall Fuels and Lubricants Meeting and Exposition*. 2022.

[10] Nair, A. P., Jelloian, C., Morrow, D. S., Bendana, F. A., Pineda, D. I., and Spearrin, R. M. Mhz Mid-Infrared Laser Absorption Sensor for Carbon Monoxide and Temperature behind Detonation Waves. No. 1 PartF, 2020.

[11] Dean Kaialau Jr, by K., and Basu, D. *DESIGN AND CONSTRUCTION OF A DETONATION TUBE FOR USE AS A NON-INTRUSIVEDIAGNOSTICS TESTING APPARATUS*. 2021.

[12] Kaneshige, M. *Detonation Spectroscopy: Results, Problems, and Directions*.

[13] Gordon, S., McBride, B. J., Gordon, S., and McBride, B. J. *Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications*. NASA, 1996.