2022

The Effects of Supersonic Reacting Flow Over a Wedge

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THE EFFECTS OF SUPERSONIC REACTING FLOW OVER A WEDGE

by

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A thesis submitted in partial fulfillment of the requirements
for the Honors in the Major Program in Aerospace Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Spring Term, 2022

Thesis Chair: Kareem Ahmed, Ph.D.

ABSTRACT

There is a growing need for a fundamental understanding of how detonations are formed and sustained as propulsion technology advances toward the use of detonation-based engines. The deflagration-to-detonation transition (DDT) phenomenon is studied to better understand both the fundamentals of detonation physics and the conditions surrounding how detonations are formed and sustained. This research aims to study the effects of a wedge on DDT and detonation formation. A hydrogen-air mixture is pumped into a chamber and ignited by a spark plug. Turbulence-driven flame acceleration is induced by turbulators in the chamber through which the flame propagates. The flame then flows over and interacts with a wedge in a test section, which has quartz windows for viewing. Schlieren and chemiluminescence imaging are used to collect data from the test section. The contact of the wedge with the reacting flow creates reflected shocks that interact with and accelerate the flame front. It is also shown that DDT is repeatedly induced across from the wedge.

ACKNOWLEDGEMENTS

The author would like to acknowledge the sponsorship of this work by the Air Force Office of Scientific Research (FA9550-16-1-0403 and FA9550-19- 1-0322 by Program Manager Dr. Chiping Li), The National Science Foundation (NSF Award #1914453), the American Chemical Society Petroleum Research Fund (54753- DNI), and the Burnett Honors College.

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CHAPTER 1: BACKGROUND

The development of detonation-based propulsion engines, such as rotating detonation engines (RDEs) and oblique detonation wave engines (ODWEs), is an ever-increasing sector of current propulsion research. Detonation-based propulsion is advantageous because these engines have a simple, easy to manufacture design and use less fuel than traditional combustion engines. Additionally, detonations can extract more work per volume than traditional combustion [1]. However, stabilized detonations, which detonation engines require for operation, are notoriously elusive and hard to control [1]–[3]. To better understand how to stabilize detonations for detonation-based propulsion, more work is needed to understand the fundamental nature of detonations. Studying the deflagration to detonation transition (DDT) helps to reveal more about the formation and stabilization conditions for a detonation. In addition, analyzing DDT can help give industry a better understanding of how to handle hazardous materials to prevent more tragedies [4]. Unconfined DDT is also believed to be the mechanism behind supernovae explosions, so further research may give insight into this natural phenomenon as well [5].

First, it is important to clarify the differences between deflagrations and detonations when discussing DDT. A deflagration is a subsonic explosion where the shock wave travels ahead of the flame front, with significant separation between the two. A detonation is a supersonic form of combustion where the shockwave and flame propagate as a coupled pair, augmenting the pressure significantly in comparison to deflagrations. Detonation waves are also compressive, in contrast to deflagrations which are expansive [6]. DDT occurs when the flame front of a deflagration catches up to the shockwave as it propagates through space, transforming into a detonation. This phenomenon is due to the unsteady nature of flame propagation, though there are several different methods of DDT. Some of these methods include heat-driven, pressure-driven, and turbulence-driven DDT; turbulence is the driving mechanism of DDT in these experiments.

In DDT, detonations are likely incited by hot spots in a turbulent flow region [6]. Much simulation research has shown that these hot spots often lie at the boundary layer [7]. At the boundary layer, there are increased pressure and temperature gradients, which create a more favorable environment for the onset of DDT. However, boundary layer effects are unnoticeable until the boundary layer reaches a certain thickness [6]. Therefore, to ensure that this experiment is solely achieving turbulence-driven DDT, the experimental facility has a series of perforated plates in the chamber. These plates serve to break up the formation of a boundary layer and incite turbulence into the flow.

Researchers have extensively studied the use of a wedge for detonation stabilization through direct numerical simulations (DNS). Recently, Xi et al. published work characterizing hydrogen-mixed methane for Schramjets, shock-induced combustion ramjets, using a wedge for detonation stabilization [8]. Liu et al. used a wedge to stabilize an oblique detonation wave at atmospheric conditions and studied its structure [9]. In addition, Li et al. studied how the wedge shape used for ODW stabilization affects detonation geometry and the type of reflection observed, including using a wedge with a rounded corner [10]. Many of these studies are simulation-based [8]–[10] or are performed in vacuum conditions [8], [10], further showing the necessity for more experimental, atmospheric study.

Zhang and Guo performed experimental testing and numerical simulations at various pressures and ramp angles to study the relationship between ramp angle and cell size after Mach reflection in the DDT regime [11]. They found that the cell structures decline with increased pressure and wedge angle. This study was performed at low pressures, ranging between 16kPa and 40kPa. It contributes important work describing these relationships and characterizing the critical angle between the wedge and triple point.

Rosato et al., through both experimental testing and numerical simulations, studied stabilized oblique detonation wave based propulsion [12]. In their experimental testing, they stabilized the oblique detonation wave using a wedge for several seconds at flight conditions. Both simulation and experimental results saw a no-slip boundary formation on the ramp surface, causing a burning boundary later. The burning boundary layer intersected with an ignited induction region, forming a triple point out of which the detonation wave forms. In addition, the turning angle of the ramp, which is 30 degrees, allows the detonation to stay stable on top of the wedge due to the structure of the flow [12]. The present work used the same wedge from the facility of Rosato et al.. However, this work explores supersonic reacting flow, where Rosato et al. studied hypersonic flow [12].

The power of the reflected shock has been known to the combustion community for a long time. Direct initiation of a detonation can occur when a strong shock ignites a gaseous mixture and the shock reflected off the closed end of the detonation tube causes autoignition, driving the detonation [6]. Experiments by Teodorczyk et al. showed how reflected shocks created by obstacles in high-speed flow increase the speed and intensity of the reaction and help DDT occur earlier [13]. More recently, experiments were done by Nagura et al. also explored a detonation that experienced a change in velocity. It initially de-coupled, but the interaction of the transverse wave with the hot, dense gas re-ignited the mixture and created a detonation again [14]. These experiments show how reflected shocks can significantly strengthen the combustion process.

One and two-dimensional simulations performed by Gamezo et al. explored transverse waves formed from pulsating instabilities of flames [15]. They found that pulsating instabilities of flames caused both transverse deflagration and detonation waves. The transverse detonation waves could only propagate into areas of hot, unburned, or partially burned material and are thus unable to exit the flame front into the cold, unburnt material, despite their supersonic speed. These strong shocks can compel the fast flame into a detonation, but not always. The simulations were done with subsonic flames.

The present work explores the effects of introducing a wedge in the path of supersonic reactant flow, focusing on the DDT regime. This work will build on existing research by performing experimental testing at atmospheric temperature and pressure.

CHAPTER 2: EXPERIMENTAL SET UP AND PROCEDURE

The experiment was conducted at the University of Central Florida (UCF) Propulsion and Energy Research Laboratory (PERL). As shown in Figure 1, the facility is a 1.5 meter long, square-tube channel that exhausts to quiescent conditions; the channel has a 45mm square cross-section [16]. There is a spark plug at the beginning of the channel which is used to ignite the mixture inside once filled. Additionally, the flow moves left to right in this configuration. Along the channel, between the spark plug and test section, a series of perforated plates induce turbulence into the flow. The test section is located near the end of the channel with 25mm thick fused silica windows. The test section windows are used to capture images of the flow as it moves through the facility. The ramp is mounted at the bottom of the test section so that the effects of the wedge can be viewed clearly.

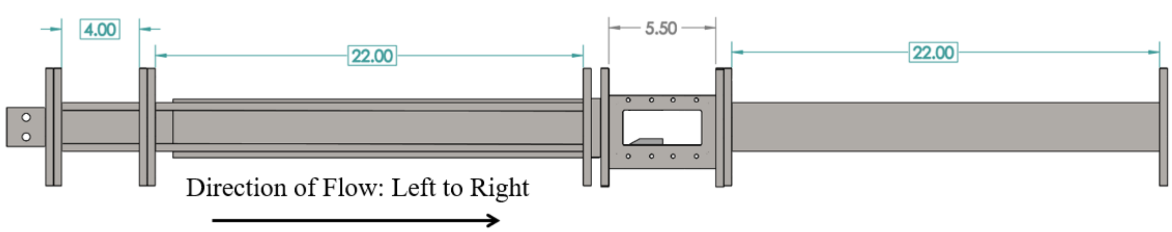

Figure 1: Experimental Facility

The channel is first filled for 20 seconds with a pre-mixed, hydrogen-air mixture and then ignited with the spark plug. Fill of fuel an oxidizer is controlled through two Dwyer VFA-4 flow meters regulated to 50 kPa which have a resolution up to 0.1 SCFH [17]. The flow meters allow flow rate to be modified to produce the desired equivalence ratio for each run. There is also a solenoid valve to control the timing of the flow and prevent flashback.

The camera recording and spark plug are synced through a timing box. Throughout the investigation, multiple equivalence ratios were tested to find the most conducive ratio for achieving DDT with each fuel used. Using many different equivalence ratios over different regimes helps to reveal how exactly the wedge affects this process. The equivalence ratios used range from $\varphi = 0.79 - 1.09$.

For imaging, both Schlieren and Chemiluminescence techniques were used. Schlieren imaging shows the density gradient of the fluid as it moves through the test section. A classical Z-Schlieren set-up was used, and recording was done with a Photron SA-Z FastCam. The images were taken with the frame rates and pixel resolutions shown in Table 1.

Table 1: Schlieren Frame Rates and Resolution

Frame Rate (kHz)	Pixel Resolution
60 kHz	896x352
75 kHz	768x328
84.6 kHz	384x144
100.8 kHz	512x328
210 kHz	384x160

Figure 2 shows the imaging set-up for the various testing campaigns. Chemiluminescence was also recorded on a Photron SA-Z FastCam and is used to track burning products. Specifically, it allows tracking of the flame front itself and helps confirm the location of the flame front for velocity measurements. The chemiluminescence images were taken with a frame rate of 90kHz and a pixel resolution of 384x128 pixels. The angle for chemiluminescence is around 7 degrees and has been accounted for.

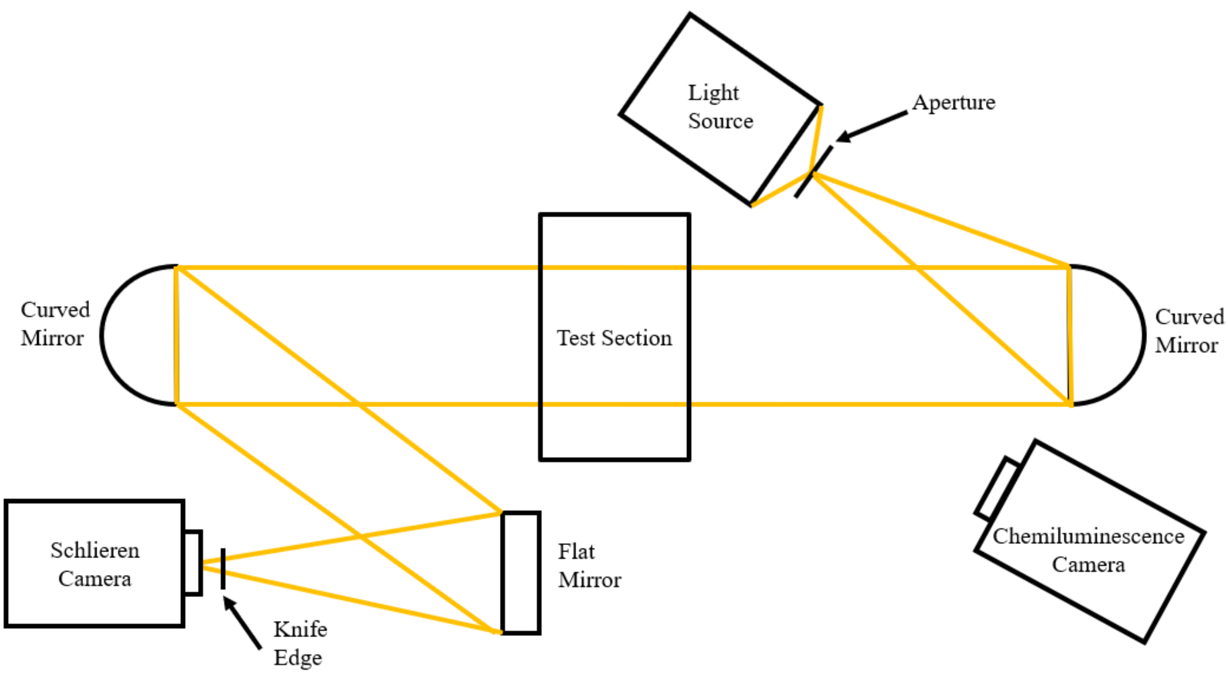

Figure 2: Experimental Set-Up

CHAPTER 3: RESULTS

Baseline Cases

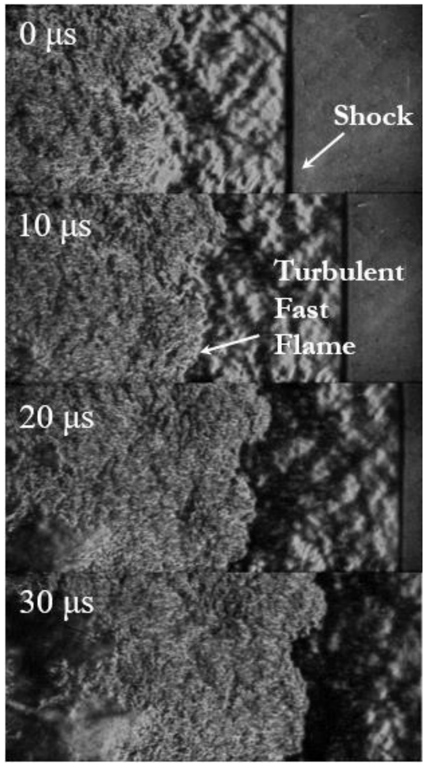

Figure 3: Baseline Flame Evolution

Before discussing the results of adding the wedge into the flow, it is important first to discuss the baseline conditions used for comparison. These test cases were performed with a hydrogen-air mixture with an equivalence ratio of 0.91. Figure 3 shows the flow moving through the test section. Notably, the shock and flame front remain relatively linear. Additionally, the flame front velocity of the baseline case remains relatively constant, with a less than 5% increase. Results from experimentation with the wedge differ in these respects, which is discussed in the following sections.

Global Effects of Wedge

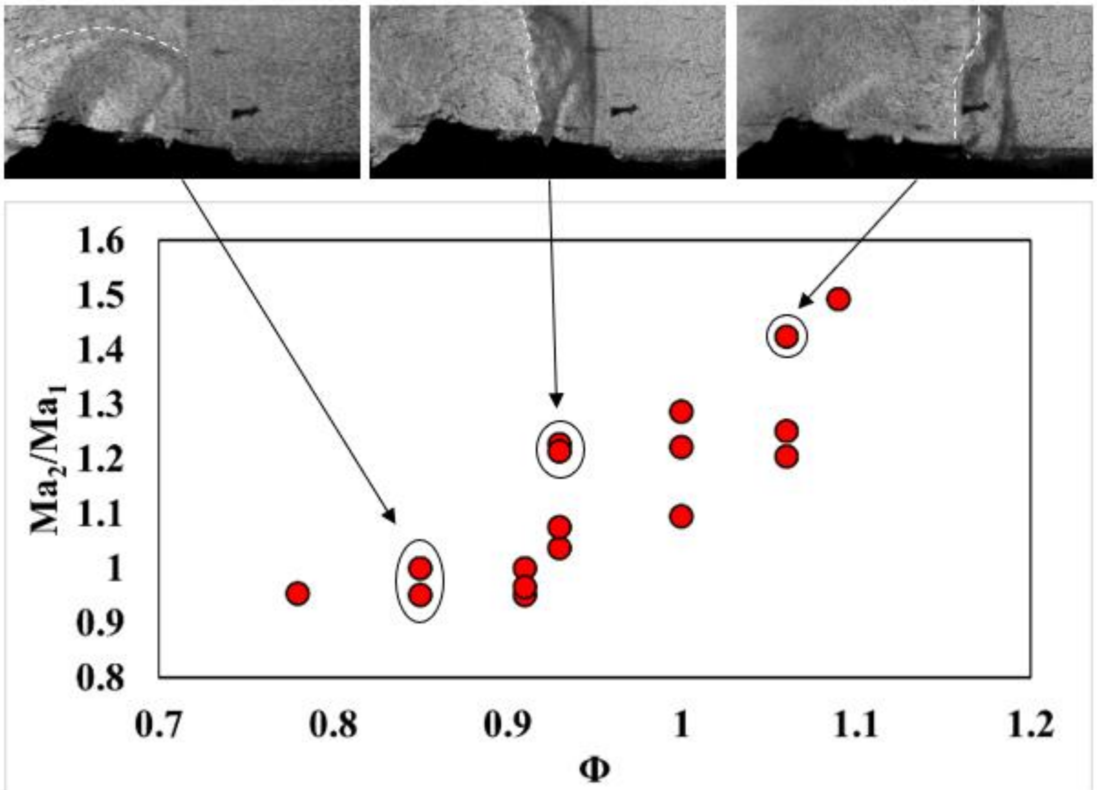

Figure 4: Mach Ratio versus Equivalence Ratio with Examples of Each Regime

The present work strives to characterize the results of adding a wedge into supersonic reacting flow. The general sequence of events across all tests started with the reacting flow entering the test section with a leading shock. The interaction of the leading shock and the wedge formed reflected shocks. These reflected shocks often then interacted with and accelerated the flame front. An exception to this was that in some strongly deflagrated cases, the shock and flame were so distant that the reflected shocks were not strong enough to significantly influence the flame front behavior by the time they collided. Figure 4 shows the plot of Mach ratio versus equivalence ratio. For this calculation, the Mach ratio is defined as the Mach number of the shock following passing over the wedge over the initial Mach number of the shock. The data was taken at a range of equivalence ratios to show trends at different regimes. Figure 4 shows the various regimes and their corresponding locations on the graph. From left to right, they are strong deflagrations, weak deflagrations, and DDT. The data shows that as the equivalence ratio approaches a stoichiometric mixture, the ratio of Mach ratio versus equivalence ratio increases. Note that highly rich mixtures were not considered in this work but would eventually decay. Across all regimes, the wedge caused significant acceleration of the flame front velocity.

Reflected Shock Interactions

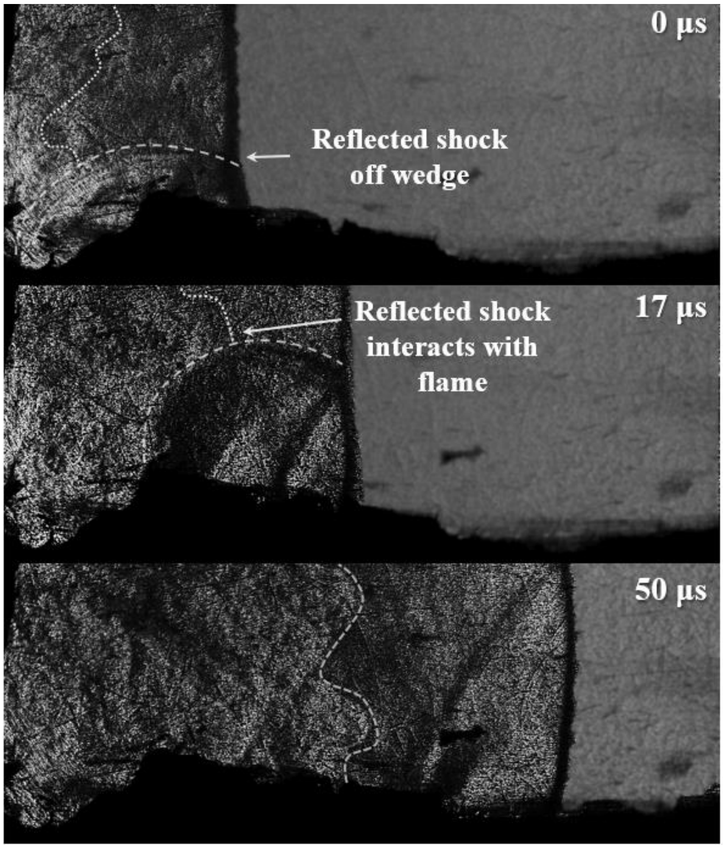

Figure 5: Schlieren Images of Reflected Shock and Flame Interactions

Throughout multiple equivalence ratios and Mach regimes, the phenomena of reflected shocks forming after flow passes over the wedge persisted. When shock and flame are relatively close, the reflected shocks propagate into and interact with the flame front. Figure 5 demonstrates this flame evolution, highlighting the reflection of the shock off the wedge and its propagation into the flame. The first frame at 0 μs shows the reacting flow entering the test section with a leading shock shortly followed by a flame front. The shock has just passed over the convergent portion of the wedge and created a reflected shock. Here the flame is traveling at a speed of 453 m/s. At 17 μs, the reflected shock interacts with the flame front and accelerates it; the flame speed at this location is 555 m/s. Further along the test section, at 50 μs, the reflected shock has dissipated into the flame. The flame speed is now 781 m/s. In addition, the leading shock is curved outward here after passing over the wedge. As shown in figure 3, previous baseline cases had a very linear shock and relatively linear flame front. In figure 5, it is evident that the wedge causes flame front expansion and deformation as well.

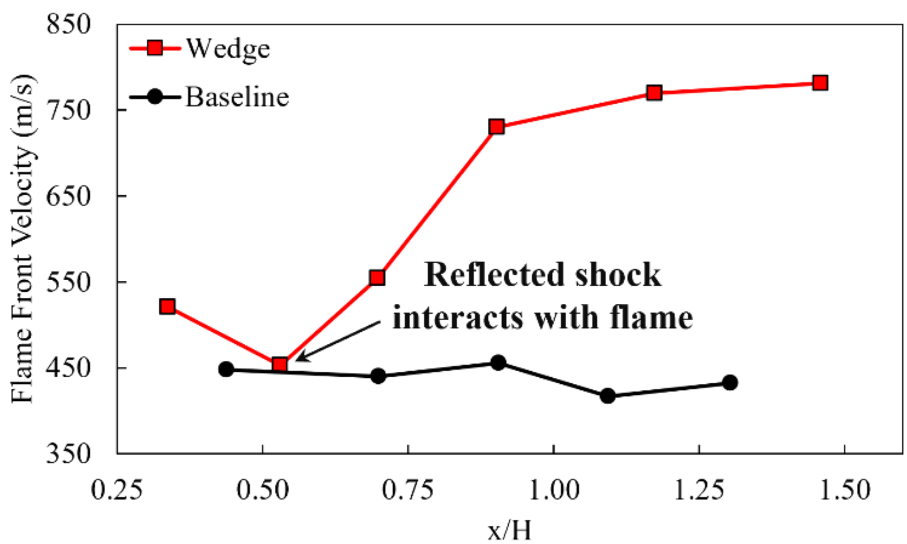

Figure 6: Flame Front Velocity vs. x/H

The velocity of the flame helps to show how significantly the wedge affects the flow. Figure 5 shows the flame front velocities of two test cases with an equivalence ratio of 0.91, where one flow includes the wedge in the chamber and the other does not. The velocities are also collected from the same point in the flow along the Y-axis. The flame propagates steadily through the test section in the baseline case, as expected for flames in the fast deflagration regime. With the addition of the wedge, the flame enters the test section with a comparable velocity but then slows when reaching the largest point of the wedge when the reflected shock crosses the flame front, temporarily stalling the flame. Then the flame steadily accelerates through the diverging section to a velocity much higher than the baseline.

DDT Phenomenon

Several cases were run in the deflagration-to-detonation (DDT) regime. In this case, a reflected shock forms off the collision of the shock wave with the wedge. An area of high density in the flow appears at the front of the wedge. There forms a hot spot in the compression region, which leads to DDT. This evolution is shown in Figure 7.

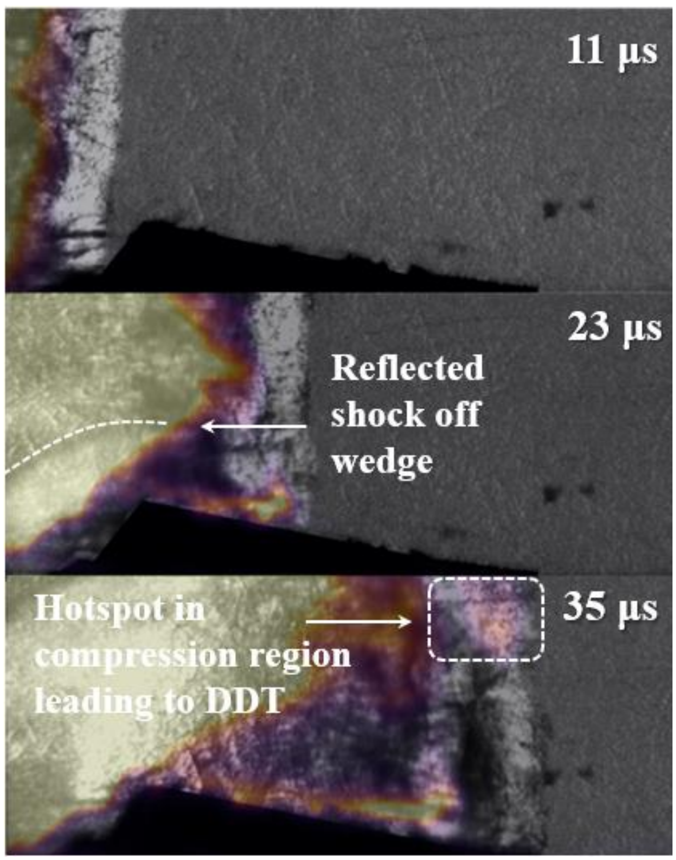

Figure 7: Schlieren Images Overlaid with Chemiluminescence Images of DDT off the Wedge

In addition, Figure 8 shows the correlation between shock and flame velocity and x/H, to describe the flame's position. From this figure, it is clear there is a significant increase in velocity around 0.5 x/H, located over the wedge. The presence of the wedge in the flow creates an initial convergent section in the flow. Velocity of the flame front as it passes through the test section, as shown in figure 8, illustrates the effect of the convergent section. As the wedge protrudes into the flow, it chokes, and pressure increases. According to Bernoulli's equation and experimental support, an increase in pressure corresponds to a decrease in the velocity of the flow [18]. After the flow passes over the wedge, the flame accelerates significantly. The dashed line also denotes the Chapman-Jouget velocity.

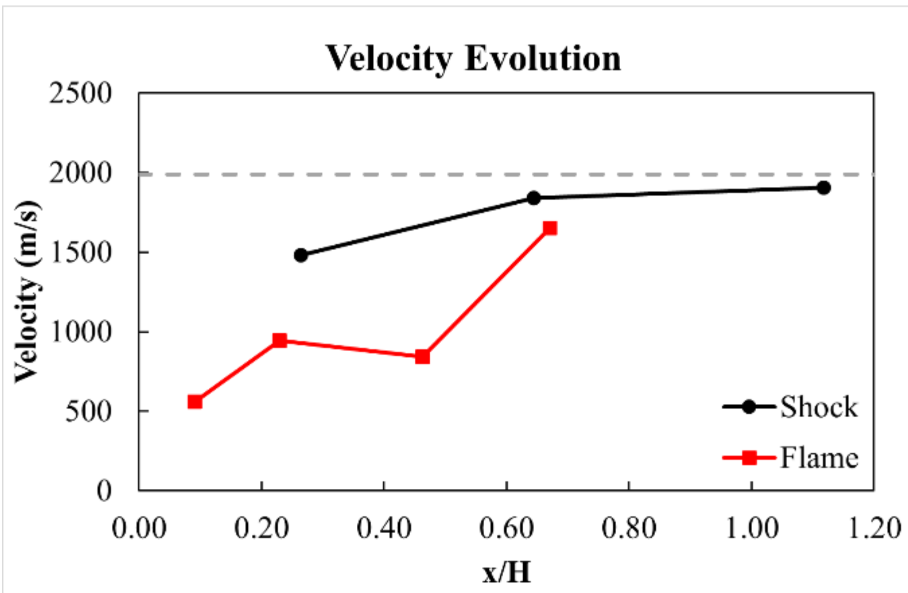

Figure 8: Velocity Evolution of Shock and Flame

DDT Initiation

Because of the DDT case previously discussed, there was a need for further investigation into the repeatability of this case to study the induction of DDT due to the wedge. The figures discussed above showed a clear example of DDT initiating across from the wedge due to the influence of the reflected shock and flame interaction. Additional testing cases showed DDT inciting repeatability in relatively the same location in the test section. These testing cases were all performed at a constant stoichiometric equivalence ratio. Figure 9 highlights detonation formation across from the wedge.

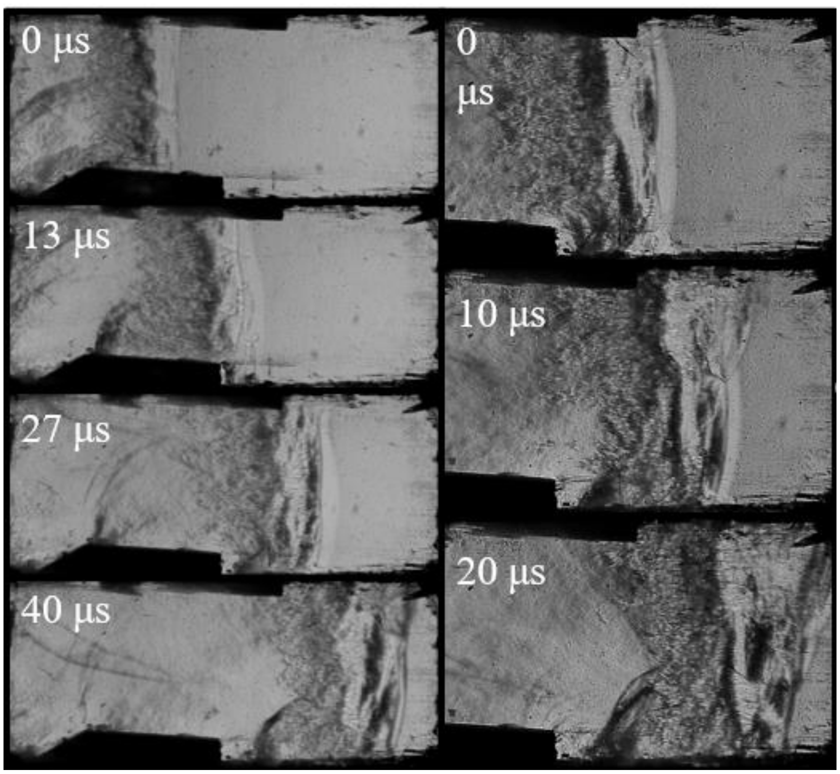

Figure 9: DDT Initiation from the Wedge

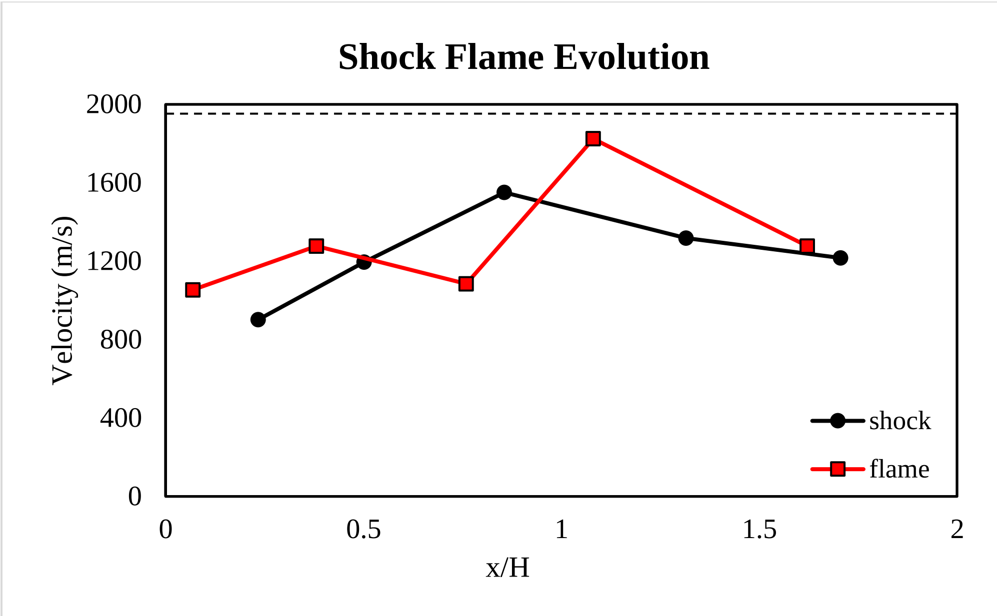

Figure 10: Shock Flame Evolution

Figure 10 above shows the shock-flame evolution for a DDT case. Initially, the shock and flame enter the test section at relatively similar speeds. The flame is slowed by the convergent section of the wedge but then accelerated. Shortly after, DDT initiates, and the shock and flame couple as a detonation. The dashed line denotes the Chapman-Jouget velocity of 1965m/s on the graph. The flow exits the test section while undergoing DDT, and the shock and flame are very close to one another. The exit shock velocity is 1216 m/s, which is 61.9% of the Chapman-Jouget velocity.

CHAPTER 4: CONCLUSIONS

Some conclusions that can be drawn from this work include confirmation of reflected shock formation when supersonic reactant flow collides with a wedge. These reflected shocks are shown to strengthen flame front acceleration significantly. In addition, increasing the equivalence ratio of the fuel-oxidizer mixture strengthened the shock and emphasized flame acceleration. It is clear that the presence of reflected shocks in the flow, chamber geometry, and equivalence ratio all contribute to flame acceleration.

The wedge incited DDT in relatively the same spot across many test cases. Therefore, there is repeatability in stabilizing DDT happening in the same place. This will allow for further investigation into the structure and processes behind detonation formation via providing an area of focus for enhanced imaging.

Future work seeks to further explore and characterize the relationships between the wedge and flame acceleration, including repeat test campaigns with different fuels. Besides Hydrogen, which was used for these cases, some of these additional fuels may include methane, ethylene, and propane. Using a variety of fuels would help explore further repeatability and how wedge effects may differ with other fuels. Further testing will allow more insight into the DDT process and detonation structure.

REFERENCES

[1] K. Kailasanath, "Review of propulsion applications of detonation waves," *AIAA J.*, vol. 38, no. 9, pp. 1698–1708, 2000, doi: 10.2514/2.1156.

[2] K. Kailasanath, "Recent developments in the research on pulse detonation engines," *AIAA J.*, vol. 41, no. 2, pp. 145–159, 2003, doi: 10.2514/2.1933.

[3] B. A. Rankin *et al.*, "Overview of performance, application, and analysis of rotating detonation engine technologies," *J. Propuls. Power*, vol. 33, no. 1, pp. 131–143, 2017, doi: 10.2514/1.B36303.

[4] E. S. Oran, G. Chamberlain, and A. Pekalski, "Mechanisms and occurrence of detonations in vapor cloud explosions," *Prog. Energy Combust. Sci.*, vol. 77, 2020, doi: 10.1016/j.pecs.2019.100804.

[5] A. Y. Poludnenko, J. Chambers, K. Ahmed, V. N. Gamezo, and B. D. Taylor, "A unified mechanism for unconfined deflagration-to-detonation transition in terrestrial chemical systems and type Ia supernovae," *Science (80-.).*, vol. 366, no. 6465, Nov. 2019, doi: 10.1126/science.aau7365.

[6] J. H. S. Lee, *The detonation phenomenon*. Cambridge University Press, 2008.

[7] E. S. Oran and V. N. Gamezo, "Origins of the deflagration-to-detonation transition in gas-phase combustion," *Combust. Flame*, vol. 148, no. 1–2, pp. 4–47, Jan. 2007, doi: 10.1016/j.combustflame.2006.07.010.

[8] X. Xi, C. Tian, and K. Wang, "Effects of hydrogen addition on oblique detonations in methane–air mixtures," *Int. J. Hydrogen Energy*, no. xxxx, 2022, doi: 10.1016/j.ijhydene.2021.12.195.

[9] Y. Liu, Y. S. Liu, D. Wu, and J. P. Wang, "Structure of an oblique detonation wave induced by a wedge," *Shock Waves*, vol. 26, no. 2, pp. 161–168, 2016, doi: 10.1007/s00193-015-0600-5.

[10] J. Li, J. Pan, C. Jiang, Y. Zhu, Y. Zhang, and A. Oluwaleke OJO, "Numerical investigation on cellular detonation reflection over wedges with rounded corner," *Acta Astronaut.*, vol. 181, no. February, pp. 503–515, 2021, doi: 10.1016/j.actaastro.2021.01.053.

[11] D. Zhang and C. M. Guo, "Experimental study and numerical simulation of cellular structures and Mach reflection of gaseous detonation waves," *Shock Waves*, pp. 353–358, 2005, doi: 10.1007/978-3-540-27009-6_51.

[12] D. A. Rosato, M. Thornton, J. Sosa, C. Bachman, G. B. Goodwin, and K. A. Ahmed, "Stabilized detonation for hypersonic propulsion," vol. 118, no. 20, 2021, doi: 10.1073/pnas.2102244118/-/DCSupplemental.y.

[13] A. Teodorczyk, J. H. S. Lee, and R. Knystautas, "The structure of fast turbulent flames in very rough, obstacle-filled channels," *Symp. Combust.*, vol. 23, no. 1, pp. 735–741, 1991, doi: 10.1016/S0082-0784(06)80324-3.

[14] Y. Nagura, J. Kasahara, and A. Matsuo, "Multi-frame visualization for detonation wave

diffraction," *Shock Waves*, vol. 26, no. 5, pp. 645–656, 2016, doi: 10.1007/s00193-016-0663-y.

[15] V. N. Gamezo, A. Y. Poludnenko, E. S. Oran, and F. A. Williams, "Transverse waves resulting from pulsating instability of two-dimensional flames," *Combust. Flame*, vol. 161, no. 4, pp. 950–957, 2014, doi: 10.1016/j.combustflame.2013.09.027.

[16] H. M. Chin, J. Chambers, J. Sosa, A. Poludnenko, V. N. Gamezo, and K. A. Ahmed, "The evolution of pressure gain in turbulent fast flames," *Combust. Flame,* vol. 234, p. 111641, 2021, doi: 10.1016/j.combustflame.2021.111641.

[17] R. Hytovick, H. Chin, and K. Ahmed, "Investigation of controlled deflagration-todetonation transition of hydrocarbon fuels," in *AIAA Scitech 2021 Forum*, 2021, pp. 1–6, doi: 10.2514/6.2021-1146.

[18] F. Halter, C. Chauveau, N. Djebaïli-Chaumeix, and I. Gökalp, "Characterization of the effects of pressure and hydrogen concentration on laminar burning velocities of methane-hydrogen-air mixtures," *Proc. Combust. Inst.*, vol. 30, no. 1, pp. 201–208, 2005, doi: 10.1016/j.proci.2004.08.195.