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# The Early Propagation And Burning Of Hydrogen In The Process Of The Deflagration To Detonation Transition

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# THE EARLY PROPAGATION AND BURNING OF HYDROGEN IN THE PROCESS OF THE DEFLAGRATION TO DETONATION TRANSITION

by

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# ABSTRACT

The safe and efficient propagation of the Deflagration to Detonation Transition (DDT) is a topic that has been researched for many years due to its applications in Aerospace and Mechanical Engineering. DDT is when fire caused by the burning of fuel is accelerated to the upper CJ point on the Rankine Hugoniot curve due to instabilities in the flame and the turbulence caused by these instabilities. The complex flame dynamics that go along with DDT have ensured that the process is yet to be fully understood and defined. This research will work towards observing the early stages of burning hydrogen-air mixtures in DDT conditions in order to better understand the processes that cause DDT. The research will also involve the testing of multiple different equivalence ratios of hydrogen known to undergo DDT. This research will assist in making places that store reactive gasses such as hydrogen safer by searching for the method of DDT formation and ways to prevent it. This research will also allow for safer commercial use of DDT in Detonation Based Engines. The research was tested in a secure facility and observed the first four inches of ignition and deflagration using schlieren and chemiluminescence imaging techniques. Through the research, it was found that flames at higher equivalence ratios tend to be longer, more top biased, and have more instabilities than flames of lower equivalence ratios, better preparing them for DDT. This study will be elaborated on in future research using a variety of different fuels to solidify the findings of the research performed and to assist in the ability to innovate using DDT.

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# INTRODUCTION

Fuel safety and efficiency for aircrafts is a large topic of research in the current day. Hydrogen is one of the more prominent alternative fuels, due to its low levels of harmful emissions. However, hydrogen also has many safety concerns that accompany it such as its low ignition energy [1–3]. As a result of these concerns, other alternative fuels, including methane, propane, and ethylene have gained prominence in recent years [4–6]. The proposed research will investigate the early stages of the deflagration to detonation transition (DDT) of hydrogen-air mixtures, under different equivalence ratios (the ratio between air and hydrogen). Deflagration is the burning of fuel and detonation is the explosion of the fuel that causes the acceleration of the flame.

DDT still has many unsolved problems in the field due to the complexity of flame dynamics [7], [8]. Common methods of initiating DDT are through the formation of a gradient of reactivity in the testing chamber [6]or using obstacles such as perforated plates to create turbulence in the flame and cause the flame to accelerate [9–12]. Both methods have been found to be able to cause DDT in modern experiments [13, 14]. The gradient of reactivity that causes DDT is formed in the second of the three main stages of DDT [15] with the formation of the preheated zone. This occurs when the uniform flow of the flame thins out into a finger flame and accelerates. After this, the flame bends back into a tulip flame that deteriorates quickly as the flame hits the walls of the chamber causing flame deceleration. The shocks then form immediately in front of the flame and form the preheat zone of the flame and the gradient of reactivity that initiates DDT. When the formation of the preheat zone occurs naturally during leakage of fuel, DDT can follow. There are many unknowns about the propagation of DDT still around due to the expansive systems of flame dynamics and lack of a mechanism to solve both flame dynamics and detonation equations [10]. DDT occurs naturally often due to the proliferation of premixed flame through natural obstacles causing sudden explosion and accidents in the field [9, 10]. In this regard, understanding how the initial burning of fuel and flame formation would affect interactions with obstacles and final flame speed may give insight into preventing such accidents. For example, hydrogen leakage has high risk due to the spontaneous ignition property of hydrogen and the fact that hydrogen is often stored under high pressure [16, 17]. Learning more about DDT would allow for more secure storage of gasses and allow for DDT to be utilized rather than feared in fields such as aviation technology.

Looking at the factors that lead up to DDT will help us learn more about the outcome of DDT. There are two important phenomena observed in early DDT [18], the tulip and distorted tulip flames. These terms are used to describe the shape of flames that form early on in DDT and are two types of flame instabilities. A flame will change from spherical, to finger shapes, and finally to tulip and distorted tulip flames early in DDT causing instabilities and sudden deceleration of the flame due to surface area reduction and pressure increase. Bychkov et al. [19] formulated the modern theory of the tulip flame and early flame acceleration. The theory assumes an infinitesimally thin flame front exists and is formed when the flame changes from spherical to finger shaped to tulip shaped. This theory has been able to predict flame shape reasonably in the past [20]. Continuing research on the early portion of DDT will allow for better safety procedures to be implemented in high-risk locations.

Past experiments have found flame instabilities that form early in DDT and discussed the effects on the later stages of DDT [4, 18, 20]. Current speculations that have come from further study of DDT have determined that flame instability that forms in DDT comes from the flame hitting the edges of the channel and caving in, creating the tulip and distorted tulip flames. On the other hand, not much has been done to control these instabilities that lead to DDT. A handful of formulas established by Bychkov et al. [19] have shown some degree of accuracy for predicting flame shape, but even in the current day, we still do not have the formulas or tools to properly determine and control flame shape with a set of equations. The research will take an in-depth look at the early stages of DDT to improve the current knowledge of DDT. In this experiment, observations of the effects of instabilities that are formed early in the process will be detailed and methods to control the instabilities and shape of flames will be sought out. Hydrogen will be tested at different hydrogen-air equivalence ratios that have previously been found to undergo DDT [25] to search for common trends in the early stages of DDT. The results at different equivalence ratios will be compared to determine any common trends that occurred. Based on the results discovered, further testing of hydrogen along with other fuels prone to DDT should be considered to back the findings.

# METHODOLOGY

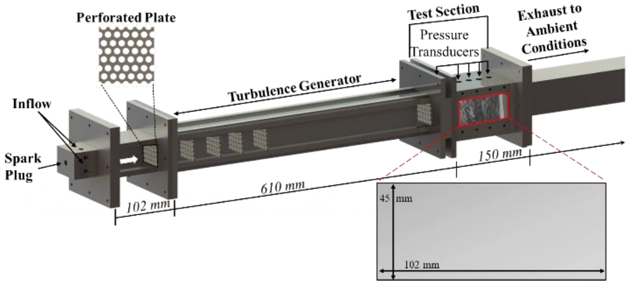

Figure 1: Normal DDT Channel | Hytovick, 2022. PROCI

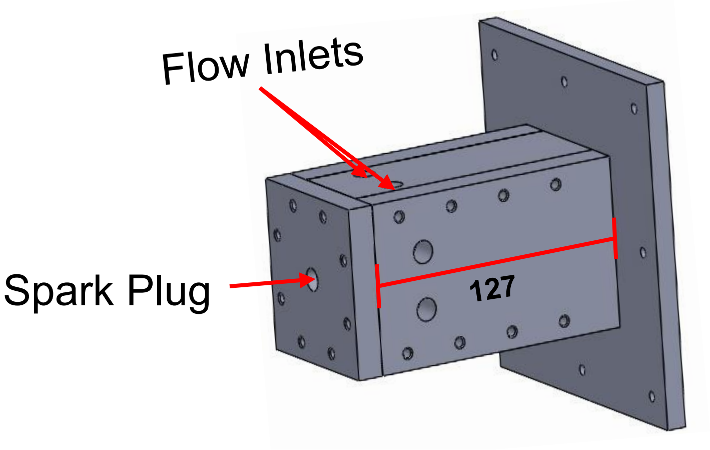

Figure 2: Experimental Facility

This experiment took place at the University of Central Florida Propulsion and Energy Research Lab (PERL). The experiment was conducted in a short, square-tube channel that opened into a fume hood. The entrance to the channel has a spark plug to ignite the fuel as well as eight tubes connected around the spark plug to move the fuel into the channel. Figure 1 depicts the original design CAD that was formulated using SolidWorks. This design was the machined completely out of acrylic and allowed for immediate viewing of the ignition process. After testing this section out, it was decided to use a similar section that is a test section at the beginning of the normal channel used for DDT, shown in figure 1, with fused silica windows that allowed optical diagnostics of the burning fuel immediately as the fuel reacted with the flame. The windows are thick to withstand detonation pressures. This component was determined to give a clearer image than the new component machined and was thus used.

For the experiment, we begin by opening the fuel and oxidizer lines to the designated flow rates for the condition of interest. The fuel delivery is regulated by three Dwyer VFA-4 flow meters. All gasses entering the flowmeters were set to 50 psi to maintain a safe environment and prevent pressure induced detonations. Once the gasses exit the flowmeters, the oxidizers and fuel were mixed through a multitude of reinforced polyurethane tubes that lead directly into inputs in the beginning of the facility to create an even mixture. The channel is then filled for a period of time, to allow the gas to fill the volume of the channel. A pulse/delay generator controls the rest of the experiment. When the facility is ready, a relay-powered fast-acting solenoid valve receives a signal and exhausts the incoming mixture so that back pressure does not rise and to prevent ignition within the oxidizer-fuel delivery system. A short delay later, a pulse width signal is sent to a power supply in order to trigger the spark plug in the beginning of the

facility. At ignition, a flame forms and begins propagating throughout the facility. I recorded

and observed the flame at this early stage of propagation.

We have analyzed the flame optically through schlieren images and chemiluminescence. schlieren diagnostics allow a broad flame velocity to be resolved. The images for the experiment were be recorded through a Photron SA1 camera. The capture rate was set to 16 kHz. For schlieren, a powerful light focused to its focal point was reflected by two large mirrors and a small one, then recorded by the camera as a density gradient in order to gather data. chemiluminescence involved the same procedure of recording the flame without the need for the mirrors or light. For chemiluminescence, the testing chamber was recorded directly at a capture rate of 20 kHz. The recordings of both processes were analyzed using the PFV viewer and Excel.

For this experiment, we will analyze hydrogen at various equivalence. Hydrogen was chosen for this experiment as hydrogen is known to have higher laminar flame speeds, thinner laminar flame thickness, and lower activation energy than other DDT prone fuels. We will be looking at the speed, position, and shape of the flame and seeing the changes in these variables when different equivalence ratios of hydrogen are tested in the same manner. [25]

# RESULTS AND DISCUSSION

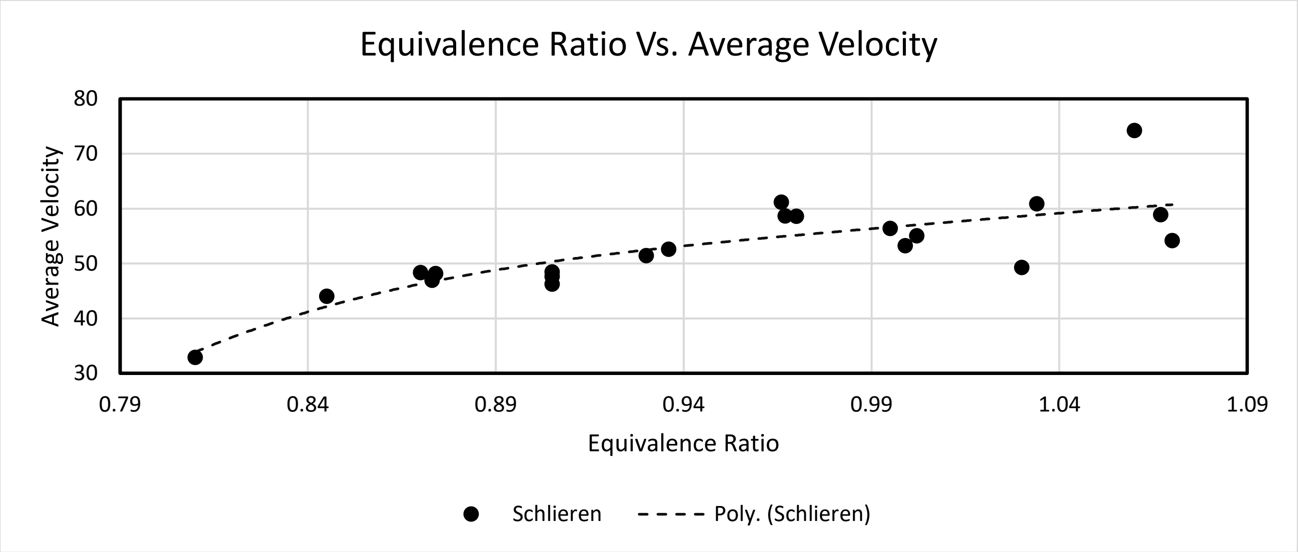

*Figure 3: Equivalence Ratio Vs. Average Velocity for Schlieren*

The goal of this experiment was the analysis of the resulting flame shape, instabilities and the speeds of the ignition and deflagration of flames and the check for general trends that occur with DDT flames. The results of the testing demonstrated that flames with higher equivalence ratios were more elongated and top biased than flames with lower equivalence ratios. This bias could be caused due to the rising of the hydrogen-air mixture. The longer flames produced at higher equivalence ratios have a greater surface area and in turn can consume fuel faster leading to DDT that is stronger and faster than the flames at lower equivalence ratio. This trend is demonstrated when comparing the flame speed to equivalence ratio, as the equivalence ratio increases, the flame speed increases as well.

It was shown through chemiluminescence imaging that flames at higher equivalence ratios also occasionally produced broken flames. These broken flames were longer and had a greater surface area than other flames. Although the instabilities found in the flames caused the average speed of the flame to be slower than cases without such instabilities, these broken flames were much longer than the other flames and had an even larger surface area meaning that these flames would be able to produce even stronger, faster detonations than the other flames.

It was determined that flame speeds of the hydrogen – air mixture increased at higher equivalence ratios until a maximum point of around 1.04 equivalence ratio before the speeds began to decrease again as shown in Figure 2. This increase in velocity is caused by the ratio of fuel to oxidizer increasing to an ideal point where the oxidizer and fuel are balanced properly. The decrease in velocity happens when the amount of fuel is too great relative to the amount of oxidizer and the flame is not able to consume the fuel as quickly to grow.

When comparing the lean flames of equivalence ratios 0.8-0.95 to the rich flames of equivalence ratios over 1.06, it is clear to see the trends depicted above. Figure 3 shows the comparison of flame lengths of a lean flame (top) and a rich flame (bottom) and demonstrates the difference in lengths of the flames.

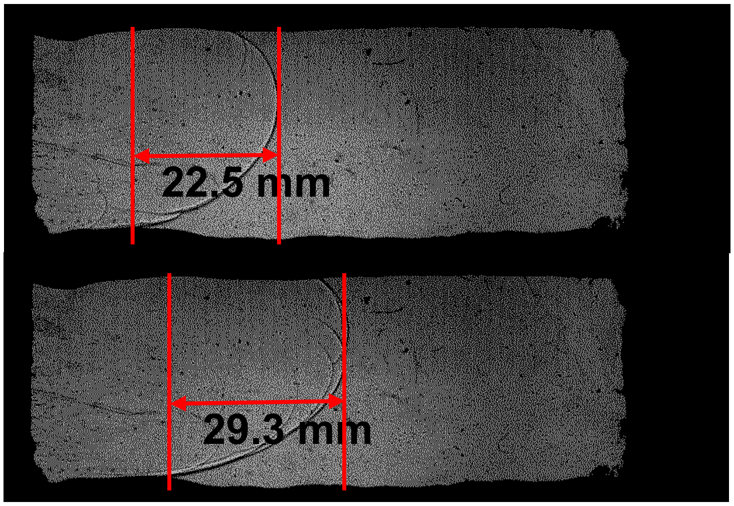

*Figure 4: Flame Length Comparison*

When comparing the leanest trial of this experiment, to a stoichiametric trial (equivalence ratio of 0.95 – 1.06), to the richest trial by using both schlieren and chemiluminescence overlapped to better show flame trends, the trends described become even more apparent. Figure 5 shows the comparison of these cases and clearly demonstrates how the richer flames tend to be more elongated and top biased as well as have more instabilities. The richest trial itself is actually shown to be a broken flame. These broken flames created even more elongated flames and presented the top bias clearly. These instabilities, as shown in figure 6 increase the surface area of the flame leading to detonations that are even stronger and faster.

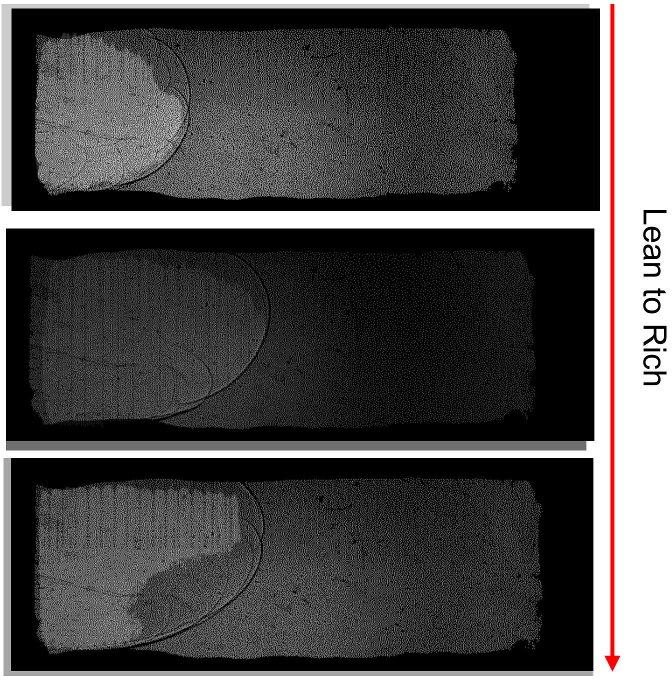

*Figure 6: Leanest to Richest Flame Comparison*

*Figure 5: Unstable Flame*

# CONCLUSION

The experiment observes the first four inches of the process of DDT of hydrogen air was observed under different equivalence ratios and captured with schlieren and chemiluminescence imaging techniques. The research shows that flame speed generally tends to be higher under higher equivalence ratios. The experiment has also shown that flames in higher equivalence ratios tended to be more elongated and were occasionally broken and distorted. These flames had more boundary layer effects, and are in turn better prepared for DDT, giving way to stronger detonations and faster DDT in the process that occurs after the observed area for this experiment. Future work will utilize different fuels, such as Methane, Ethylene, and Propane along with hydrogen through chemiluminescence and schlieren recoding techniques in order to further deepen the understanding of DDT. By analyzing this data and noting the trends depicted in flame shape, instabilities formed, and shape, it will be possible to better understand the origins of the DDT process and use this knowledge for the safer storage of fuels prone to DDT, such as hydrogen, as well as the ability to better utilize the DDT process as a whole.

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