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Effect of Hydrogen and Oxygen Equivalence Ratio on Deflagration-to-Detonation Transition in a Rocket Pre-Detonator

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This paper presents optimized detonation through experimentation of varying equivalence ratios to find the most reliable fill fraction that results in detonation. This study aims to create a reliable pre-detonation system to further research in areas including, but not limited to rotating detonation engines and liquid rocket engines. In order to isolate equivalence ratio data set, regulated pressure of gaseous hydrogen (fuel) and oxygen (oxidizer) are set at a constant 150 psi throughout the study. Utilizing solenoid valves and Arduino controls mounted on a mobile test stand with a 0.25" outer diameter, 12" long tube, spark ignition delay, fill fraction, and equivalence ratios were tailored for optimization. Equivalence ratios ranging from 0.2 to 1.5 between fuel and oxidizer were utilized in order to create successful detonations at the lowest possible fill fraction. The results of the experimentation process determined that 0.5 equivalence ratio is the optimal for producing detonations. Although an equivalence of 0.5 proved to be most successful, little to no negative impact until a significant deviation from the ratio was observed. Equivalence ratios higher than 0.7 were much less reliable, showing that it is better to increase the flow of oxidizer over fuel if the optimal ratio of 0.5 cannot be achieved. Observations from this study can be used to influence the integration of reliable predetonation systems for use in liquid and rotating detonation engines.

I. Nomenclature

ER = equivalence ratio
τ = spark delay
L = tube length
D = outer diameter of tube
FF = fill fraction
P = pressure
H_2 = hydrogen
O_2 = *oxygen*
Decibels = *dB*

II. Introduction

The motivation for this paper is to develop rotating detonation engine technology. Chemical propulsion research at Oklahoma State University has been primarily focused on experimenting with already existing technologies. Rotating detonation rocket engines are still at a low technology readiness level, and experimenting with them would yield data

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that few other universities have. The data gathered by this research will help further the development of other technologies outside of detonation-based propulsion. One possibility is an ignition system that could be implemented in other types of rocket engine technologies. This data will also allow for the study of shockwaves themselves, and the relationship between shockwaves and combustion. The method used for collecting this data is by testing both individual parameters for producing detonations. First is finding an effective equivalence ratio of the hydrogen fuel and pure oxygen oxidizer through direct trial and error. Second is then reducing the fill fraction to find the shortest length of tubing required to sustain detonation. Spark timing is part of the baseline testing to find an effective starting point for the previously described equivalence ratio and fill fraction. Both of these data points will then be sorted into a table, and then input into a series of graphs to visualize the results and identify trends in performance. One objective of this paper is to provide data for detonations inside a pre-detonator system through direct experimentation of different variables, including initial conditions of the combustion chamber of the system. This objective will lead to achieving the main objective of the paper and allow for further research to be conducted. The main objective of this paper is to find the most effective conditions that lead to detonation. This objective will allow for the best utilization of this technology. The data provided will be centered around the effects of equivalence ratio and fill fraction on the detonation. This paper will not be providing applications of this technology, only the effectiveness and parameters needed to produce detonations.

III. Background and Theory

A. Detonation and Its Significance

Detonation is a supersonic combustion process characterized by a coupled shock wave and reaction front propagating through a reactive medium. Unlike deflagration, which occurs at subsonic speed, detonation consists of an immediate pressure rise and self-sustained shock-induced combustion (Zuniga).

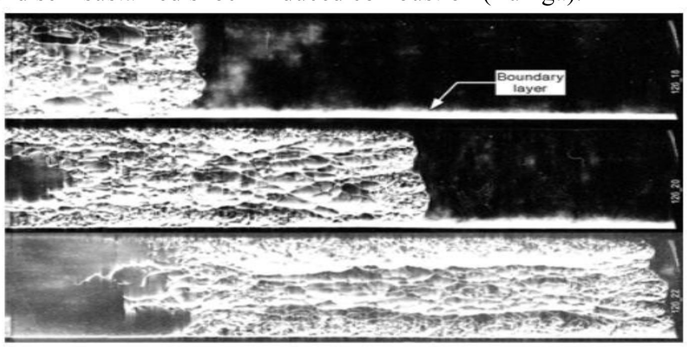

Fig. 1 Detonation Shockwave Fig. 1 shows a real example of a detonation shockwave (Kuznetsov).

B. Deflagration-to-Detonation

The transition from deflagration-to-detonation (DDT) is critical for the development of detonation-based propulsion systems. This transition occurs when a subsonic wave sustained by a chemical reaction (deflagration,) eventually reaches a self-sustained detonation state through turbulence, shock reflections, and confinement effects. DDT is achieved through three phases: initial flame propagation, shock formation, and shock-flame interaction which leads to detonation onset. The detonation itself depends on several factors, this paper focuses on the effects of equivalence ratio, fill fraction, and spark delay. These factors influence energy release and shock wave formation, which are critical for achieving DDT (Zhang et al.).

IV. Methodology

A. Physical setup

The pre-detonation equipment is designed to test the variables in creating detonation. Two solenoid valves control the flow of Hydrogen and Oxygen. A four-way segment connects the fuel and oxygen tubes directly opposite each other. Both are delivered with solenoid valves. Perpendicular to the fuel and oxidizer tubes, and opposite each other, are a threaded and unthreaded side, with a spark plug in the threaded channel, and the detonation tube in the fourth and final channel. The sparkplug is connected to a general-purpose ignition coil. The solenoid valves and ignition coil are controlled by a standard Arduino unit slotted into a breadboard, with timing control modules connected between it and the valves.

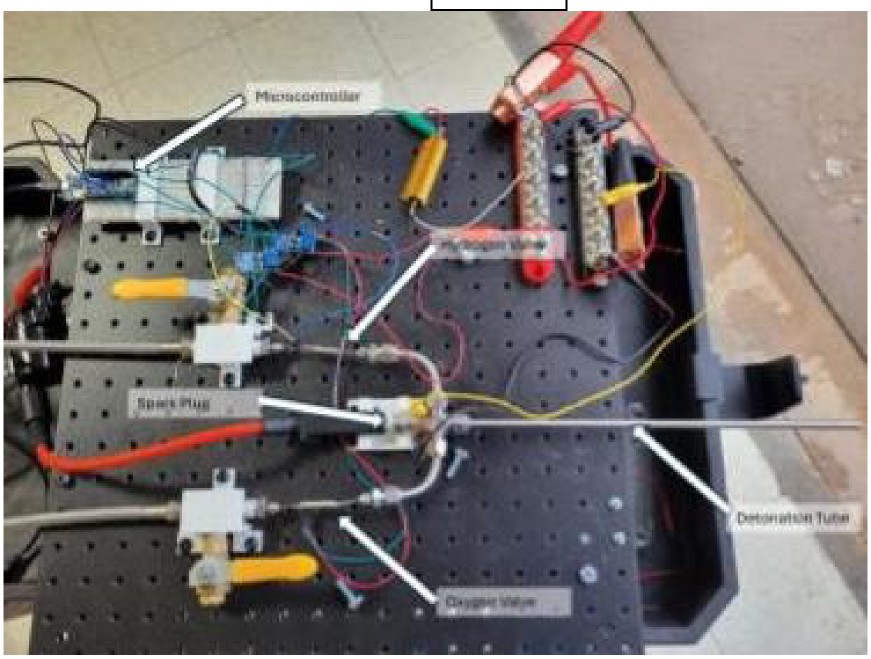

Fig. 2 Pre-Det Rig

The image above shows a top-down view of the equipment.

C. **Software setup**

The Arduino unit is equipped with a small memory bank allowing for the code used to run experiments to be stored locally. After inputting the initial conditions, i.e., the choice of fuel and oxidizer and regulated pressure, the user is prompted the choice between a complete test or spark troubleshooting, followed by equivalence ratio, then fill fraction, number of consecutive tests, and then finally the desired spark delay. Once the fuel, oxidizer, and pressures are entered, the code will save those values until the restart button is pressed or until the computer running Arduino IDE is disconnected. This allows tests to be more easily repeatable and reduces the number of inputs required to test variables.

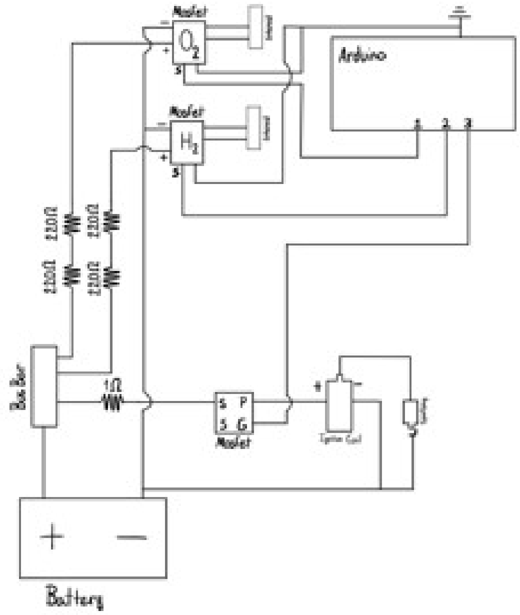

Fig. 3 Pre-Det Circuit Diagram

As seen above, the Arduino unit was our control unit for this experiment.

D. **Experimentation**

The primary objective of this study was to investigate the effect of equivalence ratio and fill fraction on the successful transition from deflagration to detonation (DDT). The experiment was designed to determine optimal conditions for detonation events in the pre-detonator system. Several parameters were manipulated, including equivalence ratio of fuel and oxidizer, fill fraction, and spark delay, for optimization. The code is set up to flutter the valves to promote better mixing of the fuel and oxidizer mixture during tests, but a spark delay of 9 full seconds nearly guarantees complete mixing.

E. **Auditory Verification of Detonation Events**

Due to limitations in equipment, the occurrence of detonation was verified through auditory methods rather than instrumentation. During each experiment, detonation attempts were carefully observed for the sound generated by the detonation event. Specifically, a successful detonation was verified when a high-decibel shockwave was produced. Auditory verification relied on the human sense of hearing to distinguish the success of combustion events in producing a detonation. Detonation was scored as follows: -1 for no audible sound, 0 for a faint sound, indicating a partial combustion or deflagration event, and 1 for a loud and distinct crack, corresponding to a successful detonation event.

F. **Testing Procedure**

The experimentation process involved conducting ten detonation attempts for each combination of equivalence ratio and fill fraction. The equivalence ratios varied from 0.2 to 1.5, and the fill fractions ranged from 0.2 to 1.5. Each test was designed to identify the optimal range for both parameters. For each test, the solenoid valves were activated to allow for a controlled flow of hydrogen and oxygen into the pre-detonator system. The oxygen valve was open and closed in extremely rapid succession to help promote mixing, however the chosen spark delay of 9 seconds mostly eliminates the mixing variance. The fuel and oxidizer were mixed at the set equivalence ratio and fill fraction, and the spark timing was adjusted to initiate ignition. After the ignition was triggered, the detonation event was monitored and scored based on the criteria above.

V. Results and Discussion

A. **Equipment Limitations**

One of the significant issues encountered during the experimentation process was the frequent failure of spark plugs. After approximately 10 to 15 tests, condensation began to accumulate on the spark plug, leading to no spark being generated. This issue necessitated having 2 to 3 extra sparkplugs on standby to swap out and dry and clean the one most recently used. Spark plug failure compromised the consistency and reliability of the ignition process, which meant that some data points had to be retested throughout the data collection process. Given the critical role of the spark plug in initiating the detonation, this issue directly impacted the ability to obtain consistent and reliable results. Future experiments should focus on using more robust ignition systems that are resistant to condensation. Practical solutions include heating the spark plugs to prevent condensation, a tertiary valve aimed directly at the cathodes of the sparkplug, or utilizing ignition systems that do not rely on exposed spark plugs, such as laser ignition systems.

B. **Inconsistent Experimental Setup**

The experimental setup itself was plagued by inconsistencies that significantly affected the results. Factors such as the physical positioning of the ignition system, fuel and oxidizer delivery, and the adjustment of spark timing led to unreliable performance across trials. These inconsistencies contributed to the difficulty in achieving repeatable detonations and impacted the validity of the results. To improve future setups, it would be beneficial to use automated and precise control systems for spark timing, fuel, and oxidizer delivery. Utilizing sensors for real-time monitoring of system conditions (e.g., pressure, temperature) and incorporating feedback mechanisms would reduce human error and improve the repeatability of the tests. Also, spark timing proved to be a key aspect of reliable detonation, as delaying ignition for too long can lead to pressurization leaving the detonation tube, greatly hindering the ability for detonation to occur. Further experimentation will prioritize spark timing before manipulating equivalence ratios and fill fractions to ensure data is reliable and accurate.

C. **Auditory Verification and its Limitations**

As discussed in the methodology section, the verification of detonation success was based on auditory methods. This approach, while feasible for a preliminary study, had inherent limitations. During some of the detonations, the acoustic shockwave was so intense that it caused discomfort and hearing damage, raising concerns about the safety of using this method. Additionally, the reliability of auditory detection is questionable as it is subject to the observer's sensitivity, ambient noise, and the distance from the detonation tube. Not to mention the fact that if the observer puts hearing protection on, their ability to determine if a detonation occurred is hindered. These factors introduced variability into the results, making it challenging to confirm detonation events reliably. To improve the verification process, it is strongly recommended to use objective instrumentation, such as pressure sensors or high-speed cameras, to confirm detonation events. Acoustic sensors would also provide more accurate data for sound intensity, and pressure transducers could measure the shockwave characteristics directly.

D. **Data Analysis and Results**

Detonation success varied significantly across different ERs and FFs. At ER=0.2, detonation failed at lower FFs (<0.5). As seen in the figure below, detonation occurred more frequently as FF increased, with the most detonation reliability occurring around 0.8 to 1.2 FF.

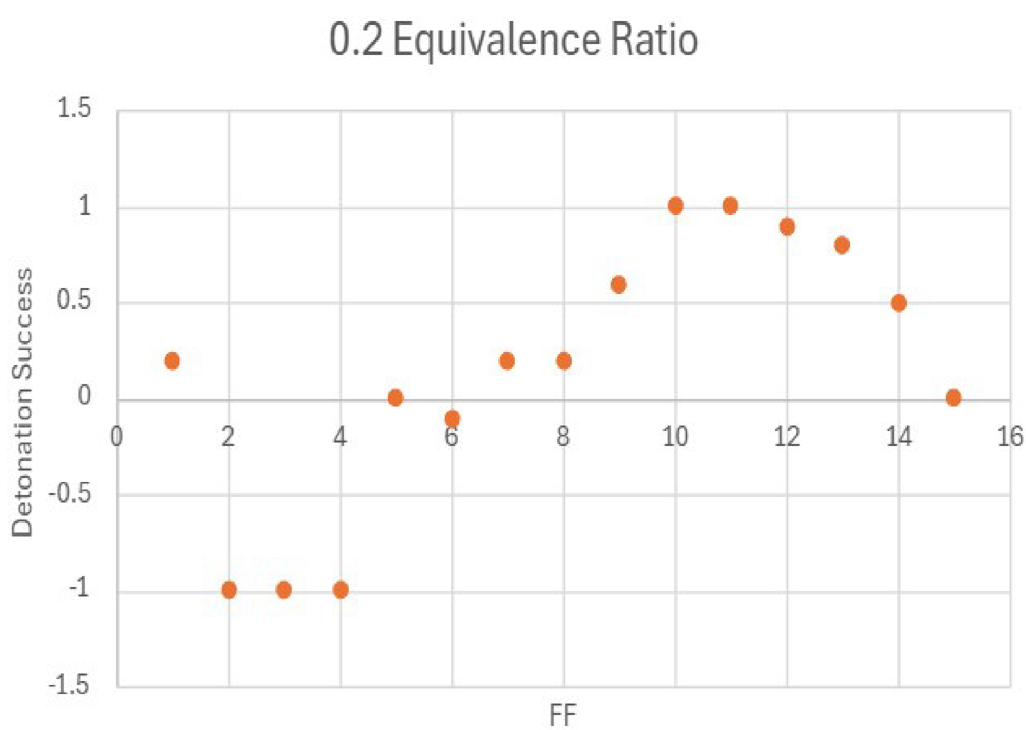

Fig. 4 Detonations at 0.2 ER

For ER = 0.2, detonation was consistently successful across most FF values, with only a few failures at very low FF. This indicates that ER = 0.2 is close to an optimal detonation regime, where the fill fraction at this smaller scale has a bigger impact than at higher ER values. This is due to the raw amount of fuel compared to oxidizer can influence the resulting ER physically in the tube, rather than in the code. However, the stability of this mixture, and the ones up to an ER of 0.5, makes it a strong candidate for future testing. The table of data does not cover an FF of less than 0.2, so the error in the graph is due to the system, rather than the results itself, so it along with the similar data points at 0.1 FF can be disregarded on this and the following graphs.

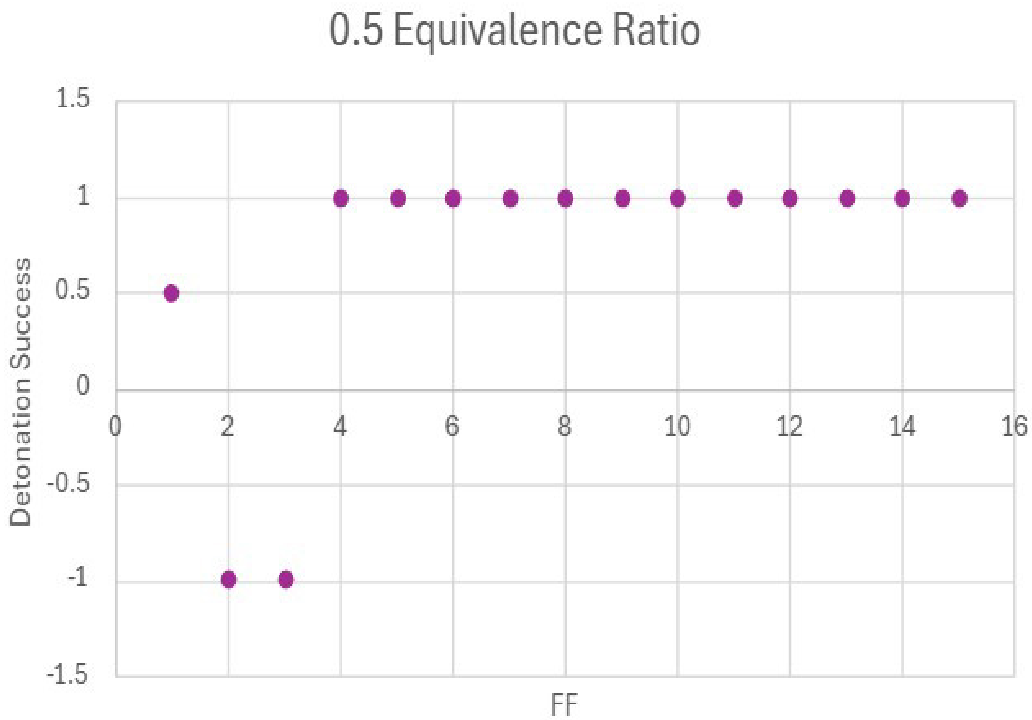

Fig. 5 Detonations at 0.5 ER

A 0.5 equivalence ratio gave some the best results, with 12 out of 15 trials being successful detonations. Fill fractions at this ER should remain above 0.4.

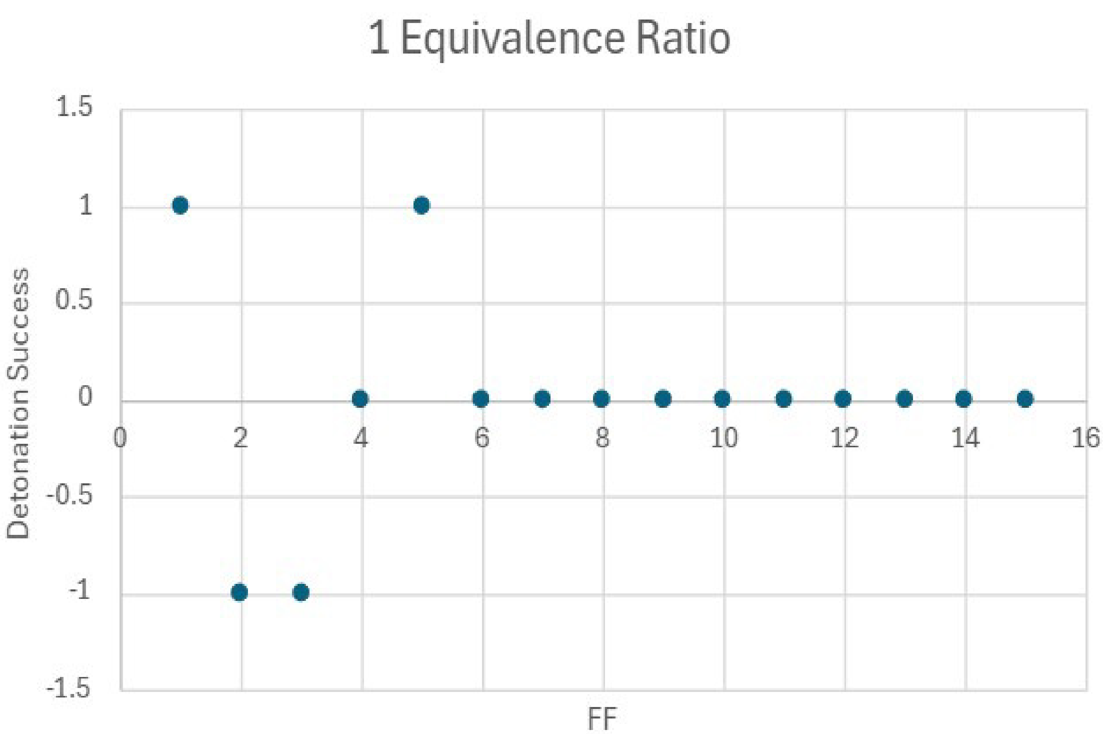

Fig. 6 Detonations at 1 ER

At an ER of 1, most of the tests resulted in partial combustion or a deflagration. This is most likely due to the increase in cell size due to a higher ER.

VI. Conclusion

Detonation success varied significantly across different equivalence ratios (ER) and fill fractions (FF), highlighting key areas where our methodology introduced inconsistencies. At ER = 0.2, detonation failed at low fill fractions (FF < 0.5), but success improved as FF increased. Peak detonation reliability was observed around FF = 0.8 to 1.2, this suggests that extremely lean mixtures provide inadequate fill fraction to sustain detonation at the pressures in the data set, and that higher FF is unlikely to disrupt the process. In contrast, at ER = 0.5, detonation was consistently successful across most FF values, with only occasional failures at very low FF. This indicates that ER = 0.5 is close to an optimal detonation regime, where fill fraction has minimal impact on performance. This ER proved to be the most reliable. However, at ER = 1.0, detonation was inconsistent at low FF values (FF < 0.4), alternating between success and failure. Beyond FF = 0.4, detonation generally stabilized, though it never reached the reliability observed at ER = 0.5. This suggests that fuel-rich mixtures require careful FF control to maintain stable detonation. One major issue in our methodology was the 9000 ms spark delay, which likely contributed to experimental inconsistencies. This delay was chosen without sufficient consideration for its impact on chamber conditions. Given that our initial chamber pressure was set at 150 psi, it is highly probable that, after 9000 ms, pressure had significantly decayed due to gas leakage, cooling, or premature mixing with residual gases. As a result, the test conditions at the moment of ignition were not consistent with our intended experimental setup. This oversight means that our data on ER and FF dependence is inherently unreliable, as the baseline chamber conditions were not adequately controlled. To improve the reliability of future experiments, establishing an optimal spark delay should be the first priority before systematically varying ER and FF. A shorter, well-characterized spark delay will ensure that ignition occurs at the intended 150 psi condition, allowing for more meaningful comparisons between different mixture parameters. Additionally, integrating pressure sensors to track real-time chamber conditions would provide insight into how pressure decays over time, enabling more precise timing adjustments. Overall, while our data suggests that ER = 0.5 with a fill fraction between 0.5 and 1.2 is the most reliable, these findings remain tentative until we refine our ignition timing strategy and utilize instrumentation to reliably verify detonation.

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