Ignition Characteristics of Supersonic Combustion

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Abstract. Detonation may be initiated by two different modes, direct initiation or deflagration-to-detonation transition (DDT). Direct initiation can occur by a strong source such as using exploding wire or high-voltage discharge jets. Nevertheless, this method required a significant amount of energy in order to ensure that the generated blast wave will not separate and decay. A good alternative to direct initiation is Pre-detonator initiation, it depends on initiate the detonation in an ancillary small tube connected to the main tube then the detonation waves propagate to achieve detonation in the main tube. The pre-detonator is one of the most used methods to initiate the detonation due to the high reliability and design simplicity. This article is used to present a short review on experimental studies of supersonic combustion using various types of pre-detonator together with preliminary experimental work on single supersonic combustion experiment by using methane-oxygen and propane-oxygen mixtures. From this initial work, it is shows that equivalence ratio of Propane-Oxygen mixture at 0.6 shows smaller size of the supersonic combustion wave front as compared to the Methane-Oxygen mixture at 0.6 and 0.8.

1.0 Introduction
It is worth to mention that, Detonation Engines has gained significant attention from many researchers in the field of aerospace propulsion due to its high thermal efficiency and simple design compared to other deflagration based propulsion systems. There are two main ignition methods that can initiate a detonation,[1-3] direct initiation, and deflagration-to-detonation transition. In Direct initiation, a strong source (e.g.: a solid explosive; exploding wire) discharges a large amount of energy that couples with the shock wave and creates a detonation wave. However, this approach required a significant amount of energy in order to ensure stable and continuous detonation. A Pre-detonator is considered as one of the most reliable approaches of direct initiation, it depends on initiate the detonation in an auxiliary small tube connected to the main combustor then the detonation waves propagate to the main tube. The second method DDT requires less energy than direct initiation to generate a detonation. The transition from deflagration to detonation is achieved by using obstacles in the path of the combustion wave in order to accelerate deflagration wave velocity to a C-J velocity. Nevertheless, the pre-detonator is most widely used in experiments to initiate the rotating detonation wave due to its high reliability and simplicity.

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A study in 2011[4] pointed out that the reliability of using the pre-detonator initiation is about 95 percent, which makes it the most simple detonation initiation method. A pre-detonator initiates a detonation directly in the combustor, which removing the necessity for a DDT device, as a result, increasing the thrust and efficiency. However, Practical pre-detonators have not been developed enough because it is difficult to maintain a detonation while diffracting from one geometry to the other. Many Studies focus on detonation transition from a small tube into an unconstrained space. Experimental evidence revealed that there is a critical diameter based on the cell width of a detonation. Successful detonation propagation into an unconstrained area can be obtained if the tube diameter is larger than the critical diameter (d_c). For circular tubes, critical diameter d_c is 13 detonation cell widths. For Rectangular channel with an aspect ratio of one requires 10 cell widths [5].

In Rotating Detonation Engine(RDE) experiments, the pre-detonator tube is sometimes set apart from the chamber by a diaphragm to solve timing mechanism problem during the filling process [6, 7], though this is an impractical method for operational use. More recently, using timed sparks was investigated to initiate a detonation wave [8, 9]. Kindrachki et al. [10] found that the automotive spark plug had only 40% repeatability rate for a methane/oxygen mixture in the combustion annulus. However, in the same engine, the repeatability could be increased to 95% by using a pre-detonator and breakable diaphragm. But the diaphragm should be replaced before the next ignition, and it was not convenient to start the engine again. Miller et al. [11] performed some tests to evaluate the development of detonation wave with the schlieren apparatus. They discovered that there was no a strong relation between the inclination of the pre-detonator tube entering the channel and the successful detonation transition. The wave would decouple immediately after coming from the pre-detonator, and the reflected wave off the bottom plate could reiniate the detonation wave.

Jan at Warsaw University of Technology [12], investigated detonation in a heterogeneous mixture of kerosene and oxidizer in RDE. Propagation of detonation was not achieved with the mixture of liquid kerosene and air for ambient temperatures because of problems with proper fragmentation and evaporation of liquid fuel at room temperature. It was suggested that air and fuel need to be pre-heated. Liu [13] found that the exhausting process of the combustion products in the pre-detonator can cause a time interval from the ignition to the establishment of the detonation. Yuhui Wang et al. [14] investigated experimentally the phenomenon of multiple detonation waves in RDE. The ignition system consists of a spark plug, and a pre-detonator. Hydrogen and oxygen mixture have been used in the pre-detonator, to be ignited by the spark plug. A single detonation wave formed when there was an axial flow of reactants into the combustor, while when there was both axial flow from the head of the combustor and tangential flow from the pre-detonator after DDT, Multiple RDWs formed. Chao Wang conducted an experimental facility in order to demonstrate the feasibility of air-breathing continuous rotating detonation. A pre-detonator tangent to the detonation combustor was used to initiate the mixture of hydrogen-air. H2 and O2 are chosen as the fuel and the oxidizer for the pre-detonator. The results showed successful detonation propagation with a velocity of 1280 m/s [15]. Lei Peng et al. [16] initiated successfully a steady detonation wave in RDE by using gaseous H2-Air mixtures ignited by an automotive spark plug with 30 MJ energy. The igniter is vertically installed and the head of the igniter is inserted into the annular combustion chamber to make the direct initiation more convenient. However, the initiation effect and repeatability have not been reported in a systematic form. Three groups of experiments have been carried out with different equivalent ratio and mass flow rate In order to verify the ignition repeatability. After 20 times for each experiment case, the rate of success was 75%, 90%, and 94%, respectively.

Yang [17] experimentally investigated three ignition methods included using a normal spark plug, high-energy spark plug, and pre detonator. The experiments have shown that there is a delay between the initial ignition and the onset of propagating detonation wave. These delays have been observed to be random but using pre-detonator generally shortening the time to initiate the detonation wave. Zhiwu Wang
et al. performed experimental work on pulse detonation engine using kerosene-air to investigate three ignition methods, including spark ignition, hot jet, and pre-detonator. The results revealed that the pre-detonator ignition method achieved the shortest detonation initiation time among the three methods of (2–3 ms) and DDT distance was shortened to just about 700 mm [18]. Lim D et al. [19] investigated the extent of plenum penetration from “one-shot” detonation events from a pre-detonator. The study pointed out that there was a leakage of very strong shock waves into the air plenum due to the blast wave from the pre-detonator. A. St. George et al. [20] conducted an experimental study to assess the performance of a tangentially-injecting initiator tube of a rotating detonation combustor. The results showed that the maximum energy deposition is achieved for a rich Hydrogen–Oxygen mixture, which provides twice the energy deposition of the highest performing Ethylene–Oxygen mixture.

Baoxing Li et al. in 2018 [21], analyzed the initiation and propagation characteristics of rotating detonation wave in RDE. A pre-detonator is used as the ignition device, which is tangentially connected to the annular combustor. Hydrogen and Oxygen are separately spouted into the pre-detonator and ignited by the spark plug and AShchelkin spiral used to facilitate the DDT process. It was clear that the equivalence ratio has a great effect on the initiation process of RDW, with the increase of the equivalence ratio, the formation time of detonation wave decreases rapidly. Zhuang Ma et al. [22] presented experimental research on the ignition, quenching, re-initiation and the stabilization process in hydrogen-air RDE with an array of injection holes. The ignition system consists of a spark plug, an ignition loop, and a pre-detonator. The pre-detonator is also filled with hydrogen and air, and it includes a spiral for flame acceleration. The detonation wave was not initiated in the combustion chamber at once, then after a period of delay time, a weak detonation wave formed. The weak detonation wave cannot exist stably, but it becomes a coexistence of detonation with deflagration.

M.L. Fotia et al. [23] in 2018 tested the RDE in a direct connect configuration in order to identify the impact of different geometric and flow parameters on the ignition processes. The ignition process is initiated by a pre-detonator, with a tube diameter of 6.35mm and a length of 152.4mm. The detonation ignition process was affected by two factors related to the pre-detonator. The first factor was the amount of chemical energy deposited through the combustion of the detonative mixture, while the second was the shock wave coupling mechanics between the detonation channel and the pre-detonator tube connected to the outer diameter of the channel. The results showed that as long as a minimum amount of energy is introduced into the combustion channel, ignition will occur leading to the same end combustion state. The end combustion state is steady operation with only acoustic waves present and can be seen for the 25, 50 and 75 ms fill times. Given this insensitivity once over a minimum pre-detonator fill time, an interval of 50 ms was used. The initiation of the rotating detonation wave in the channel is not achieved through direct coupling to the pre-detonator detonation wave, which lowers the sensitivity of successful initiation to pre-detonator backpressure conditions, in essence removing the relative cell size constraints between the pre-detonator tube and combustor mixtures. Practically, changes in chamber backpressure affect the required minimum pre-detonator fill times; nevertheless, the choice of 50 ms can greatly compensate for any such variation of this minimum and sets the amount of chemical energy deposited.

Ethylene-air mixtures were used by Yuhui Wang et al. [24] to obtain rotating detonation waves. Ethylene and oxygen were used in the pre-detonator to initiate the detonation. The results revealed successful detonation propagation. The study suggested that the combustor outlet may be an appropriate position for the pre-detonator in order to avoid the interaction between the reactants and high-temperature products. Yuhui Wang and Jialing Le in 2019 conducted an experiment to study hollow and annular RDE combustors using hydrogen and air. A high-energy spark plug with an ignition frequency of 28 Hz was used to ignite the hydrogen–oxygen mixture, and it is mounted at the head of the pre-detonator, which is tangentially connected to the detonation channel. The hollow combustor produced high-speed rotating detonation waves with speeds exceeding 94% of the CJ speeds; however, the annular combustor produced
low-speed detonation waves with speeds around 60% of the CJ speeds. The study pointed out that the pre-detonator weakens the RDW and causes detonation instabilities periodically and suggested that blocking off the pre-detonator outlet after ignition may have a good effect on the RDW stability by removing the flow coupling between the pre-detonator and combustor [25].

As a summary, there are many experimental works that have been conducted in order to initiate supersonic combustion in detonation engines. Table 1 below includes a summary of the previous works which indicates the Pre-detonation type as well as the Fuel-Oxidizer mixture that used to initiate detonation. In the present work, the study of pre-detonation has been proposed where various pre-detonation methods and Fuel-Oxidizer mixtures have been presented.

| Researcher                         | Pre-detonation type                      | Ignition mixture          |
|-----------------------------------|-----------------------------------------|---------------------------|
| Kindracki et. al. [10]            | Automotive spark plug and a pre-detonator| Methane-Oxygen            |
| Miller et al. [11]                | Inclined pre-detonator                  | Hydrogen-Air              |
| Jan [12]                          | Pre-detonator                           | Acetylene - Oxygen        |
| Liu [13]                          | Pre-detonator                           | Hydrogen-Air              |
| Yuhui Wang et al. [14]            | Spark plug and a Pre-detonator.         | Hydrogen-Oxygen           |
| Chao Wang [15]                    | Pre-detonator                           | Hydrogen-Oxygen           |
| Lei Peng et al. [16]              | Automotive spark plug                   | Hydrogen-Air              |
| Yang [17]                         | Normal spark plug- High energy spark plug - Pre-detonator | Hydrogen-Air |
| Zhiwu Wang et al. [18]            | Spark ignition- Hot jet- Pre-detonator  | Kerosene- Air             |
| Lin D et al. [19]                 | Pre-detonator                           | Hydrogen-Oxygen           |
| A. St. George et al. [20]         | Tangentially-injecting initiator tube   | Rich Hydrogen–Oxygen mixture |
| Baoxing Li et al. [21]            | Pre-detonator, Spark plug and Shchelkin spiral | Hydrogen-Oxygen |
| Zhuang Ma et al. [22]             | Spark plug, an ignition loop, and a pre-detonator | Hydrogen-Air |
| M.L. Fotia et al. [23]            | Pre-detonator                           | Hydrogen-Oxygen           |
| Yuhui Wang et al. [24]            | Pre-detonator                           | Ethylene-Oxygen           |
| Yuhui Wang, and Jialing Le [25]   | A high-energy spark plug and pre-detonator | Hydrogen-Oxygen |

2. Experimental Setup
A recent study [26] has been conducted by using Schlieren technique photography in the present laboratory. Flame propagation through a single pulse supersonic combustion tube with test section was studied experimentally. The supersonic combustion tube which is 3 meter long has three section (Section A, B and C). A 1.5 meter orifice plate is installed from Section A to B to generate an accelerating turbulence for the laminar combustion wave. Two types of fuel gases were used which are Methane and Propane with Oxygen as oxidizer. The motivation for this research mainly comes from the initiative in designing and developing of Rotating Supersonic Combustion Engine (RSCE). The experimental setup is
shown in Figure 1. The facility was conducted to visualize the image of the shock wave for the different hydrocarbon mixtures. The light source used for this Schlieren setup is Nitecore LED light source (260 lumens). Six inch diameter lenses are used for both the collimating and focusing lenses. Angle of light entering the camera act as a knife edge which is to cut off any refracted light connected with the combustion event before it is focused and imaged on top of an imaging screen.

3. Results and Discussions

The results were divided into two parts which are results of Schlieren images of reacting shock wave for methane-oxygen and propane-oxygen mixtures and experimental results of Champan-Jouguet pressure, velocity and Mach number under different equivalence ratios for methane-oxygen and propane-oxygen mixtures.

Figure 2(a), 2(b) and 2(c) showed the curvature of the leading supersonic combustion wave front that has been captured by using high speed camera. The results showed that the shock front image for propane-oxygen is the thinnest compared to methane-oxygen mixture at various equivalent ratios. Nevertheless for
methane-oxygen mixtures, the thickness of the shock front image for equivalent ratio at 0.6 was bigger compared to the equivalent ratio at 0.8. Based on the experiments results, it shown that, the more reactive the hydrocarbon mixture, the smaller the Schlieren shock front image that will be produce by the combustion mixture. Propane-oxygen mixture is more reactive than both of methane-oxygen experiments due to the high calorific value of propane which is 101000 kJ/kg compared to methane which is 39820 kJ/kg [26].

Time duration from ignition to edge for Schlieren shock front image for propane-oxygen mixture also was the longest (16.034 ms) compared to methane-oxygen at \( \Phi = 0.6 \) and \( \Phi = 0.8 \) which are (15.893 ms) and (14.923 ms) respectively. From the time taken, it shows that the velocity for propane-oxygen is lower compared to methane-oxygen because of the density for propane which is denser compared to methane. It can be clearly seen that the higher the density of the hydrocarbon, the lower the velocity of the combustion mixtures.

The experimental results obtain were compared with the numerical result by using Chemical Equilibrium with Applications (CEA) software. The calculated results of supersonic combustion pressure and velocity revealed only percentage errors of 10% as compared to the CEA results. The Propane-Oxygen mixture at \( \Phi = 0.6 \) showed smaller size of the supersonic combustion wave front as compared to the Methane-Oxygen mixture as shown in Table 2.

| Fuel          | Equivalence ratio (\( \Phi \)) | Pressure (Bar) | Velocity (m/s) | Mach Number |
|---------------|-------------------------------|----------------|----------------|-------------|
| Methane, CH₄  | 0.6                           | 26.86          | 2183.4         | 6.16        |
| Propane, C₃H₈| 0.6                           | 31.23          | 2145.9         | 6.09        |

4. Conclusion
In general, in order to obtain a successful ignition of supersonic combustion, several factors must be considered. These factors may be drawn:

1. Fuel cell size is one of the main conditions that must be taken into consideration, as it determines the critical diameter based on the cell width of a detonation. Thus, successful detonation propagation can be obtained if the tube diameter is larger than the critical diameter.

2. The equivalence ratio has a great effect on the initiation process and the formation time of the detonation wave. However, it varies depending on the fuel and the oxidizer as some studies achieved a successful detonation by lean mixture, while others obtained it by using a slightly rich mixture.

3. The amount of chemical energy deposited through the combustion of the detonative mixture in the pre-detonator.

4. Adapting the sudden change in the geometry is a significant factor to obtain a successful transmission from the pre-detonator into the combustor.

5. The transverse wave structure must be considered in the design of the pre-detonator for a stable propagating detonation wave.
6. Selecting an appropriate position for the pre-detonator is a critical factor to avoid the interaction between the reactants and high-temperature products.

7. Estimating the exhausting process should be considered as some studies pointed out that the combustion products in the pre-detonator can lead to a time interval from the ignition to the stabilizing of the detonation.

8. In case of using a liquid mixture a pre-heating process for air and fuel is essential to avoid problems such as fragmentation and evaporation of liquid fuel.

As preliminary works, the experimental setup for the gaseous supersonic combustion experiments was established and completely installed in the present laboratory. The experiments of hydrocarbon mixture in the supersonic combustion tube were successfully conducted by using methane-oxygen and propane-oxygen mixtures at equivalence ratio of 0.6 and 0.8. For visualization purpose, the Schlieren technique was set up in the current rig and the images of reacting shock is successfully recorded. It is shown that the size of the supersonic combustion wave front of Propane-Oxygen mixture at ratio of 0.6 was smaller as compared to the Methane-Oxygen mixture at 0.6 and 0.8. The experimental calculations of supersonic combustion pressure and velocity were within the percentage errors of 10% as compared to the numerical calculations obtained from CEA software.

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