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Muhammad Amri Mazlan

High Speed Reacting Flow Laboratory, School of Mechanical Engineering, Universiti Teknologi Malaysia

Mohd Fairus Mohd Yasin

High Speed Reacting Flow Laboratory, School of Mechanical Engineering, Universiti Teknologi Malaysia

Aminuddin Saat

High Speed Reacting Flow Laboratory, School of Mechanical Engineering, Universiti Teknologi Malaysia

Mazlan Abdul Wahid

High Speed Reacting Flow Laboratory, School of Mechanical Engineering, Universiti Teknologi Malaysia

他

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Initiation Characteristics of Rotating Supersonic Combustion Engine

Muhammad Amri Mazlan¹, Mohd Fairus Mohd Yasin¹, Aminuddin Saat¹, Mazlan Abdul Wahid^{1,*}, Ahmad Dairobi Ghazali¹, Mohammad Nurizat Rahman¹

¹High Speed Reacting Flow Laboratory, School of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

*Author to whom correspondence should be addressed:

E-mail: mazlan@utm.my

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Abstract: A rotating supersonic combustion engine (RSCE) is tested with various initiator tube positions along the combustion chamber to determine its impact on the ignition process. The type of fuel used is methane with oxygen as the oxidizer. The initiation of RSCE is assessed for near-stoichiometric methane-oxygen mixture to slightly rich mixture. Successful initiation of rotating supersonic combustion in the RSCE was obtained when the position of the initiator tube is located higher end of the combustion chamber that indicates a proper mixing of reactants. The mixing of reactants improves further up the annulus chamber of the RSCE.

Keywords: evergreen; rotating detonation engine; pre-detonator; supersonic combustion

1. Introduction and background

In the time of dwindling fuel resources, heavy emphasis are being put on sustainability and improving efficiency^{1,2}. Organizations throughout the world are focusing on obtaining methods to reduce the consumption of fuel³. Exploration of more efficient and potentially revolutionary engine technologies are done to overcome the matter⁴. Among those other technologies are supersonic combustion engines. Supersonic combustion or in other word detonation, is utilize by detonation engine, acting as a method of compression⁵ which is normally done by a compressor in traditional turbine engine. Without the requirement of a compressor the engine is lighter in weight producing a higher power to weight ratio which reduces fuel consumption⁶. It is also a promising technology to improve efficiency on gas turbine systems. Currently, rotating supersonic combustion engine (RSCE) or most commonly called as rotating detonation engine (RDE) has been extensively studied experimentally, numerically and theoretically⁷⁻⁹.

Several methods have been used to initiate the RSCE in which initiator tube or commonly called pre-detonator are frequently employed^{10,11}. The reason for this is that initiator tube have a higher success and repetition rate for initiation of RSCE^{12,13}. The only downside is that it requires a long straight tube to enhance deflagration-to-detonation transition (DDT) process before the annulus chamber of the engine.

A requirement of combustion process other than

ignition source is good mixing of fuel and oxidizer. Mixing of the reactants must happen rapidly and at a short distance, especially for supersonic combustion. Due to the high flow rates of RSCE, mixing are one of the problem to tackle. Based on literature, injector configuration commonly have lineups of impinging micro nozzles or narrow slots that inject fuel and oxidizer separately into the combustion chamber^{14,15}. With these arrangements it apparently was capable of mixing the reactants. The only concern is that, in what position thus the reactants starts to mix inside the combustion chamber. This position is the best position to attach the initiator tube to obtain a high repeatability of successful RSCE initiation.

To have a better understanding regarding the initiation of rotating supersonic wave in RSCE related to the position of the initiator tube, a series of experiments were carried out which will be presented in this paper. The focus will be on initiating the detonation process by varying the initiator tube at different positions along the combustion chamber. The primary major issue of RSCE is the ignition of fuel-oxidizer mixture and steadiness of the supersonic wave. Pressure transducer installed in the system is used as a tool to analyze the detonation wave initiation process. In this study, mixture of hydrogen and oxygen is used as the reactant in the ignition tube while for the engine, mixture of methane-oxygen is used. An automotive spark plug is used as the spark source inside the initiator tube.

2. Method and experimental setup

The current study is conducted in the engine test room at High Speed Reacting Flow Laboratory (HiREF), School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia. For this study, an initiator tube with shchelkin spiral and automotive spark plug is used to ignite and accelerate the combustion wave to detonation wave for the initiation of rotating detonation wave in the combustion chamber of the RSCE. This setup simplify the ignition system. The experimental setup of RSCE which mainly consist of the combustion chamber, ignition system, fuel and oxidizer supply system, and data acquisition (DAQ) system is shown in Fig. 1.

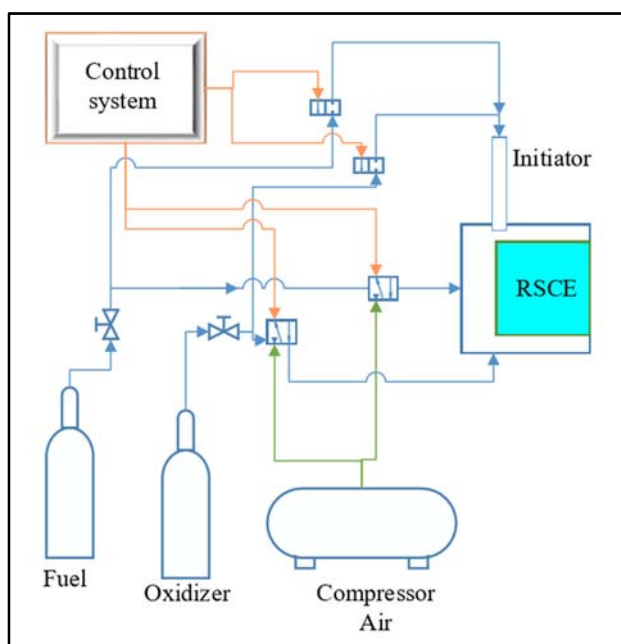


Fig. 1: Schematic diagram of experiment.

Reactants are supplied in form of gaseous, methane for fuel, and oxygen as the oxidant. Both the fuel and oxidizer are separately fed into two different plenum chambers situated behind the annulus chamber. The reactants are then spouted through micro nozzles and slot into the annulus chamber. Combination of pressure regulators and flow meters inserted at the feed lines are used to control the flow rates of the reactants. Magnetic valves and pneumatic valves controlled by the Arduino software are used to instantly turn on and off the fuel and oxidant flows respectively. For safety reason, manual shutoff valves are also include in case of any failure to the automatic valves.

The supplied reactants are mixed and combusted simultaneously in the annulus chamber which indicates the mixing is required to happen within a short period of time. This makes the effect of mixing one of the vital importance for rotating detonation initiation. The RSCE used in this study is configured for radially outward fuel injection and axial oxidizer injection. A total of 80 holes with diameter of 0.7 mm are equally arrange on the

surface of the internal body to spout out methane. As for oxygen, slot-orifice impinging injection method with width of 1 mm is applied to the system. Detailed view for the injection of both reactive is shown in Fig. 2. The annulus combustion chamber is designed to have a gap of 4 mm width, similar to the internal diameter of the ignition tube. To have this, the overall design have an inner diameter of 38 mm, and an outer diameter of 46 mm, with an axial length of 60 mm. The modular design of the engine can accommodate adjustments to the position of the initiator tube along the combustion chamber. These positions are labeled P1, P2, and P3 as shown in Fig. 2. P1, P2 and P3 is located 10 mm, 30 mm and 50 mm respectively from the fuel injectors. These positions is based on the level of mixing between the reactants run by simulation as shown in Fig. 3. It is seen that mixing of reactants is improving as it flows further up the annulus chamber. All form of tests are perform at ambient condition with temperature of 302 K and pressure of 1 atm.

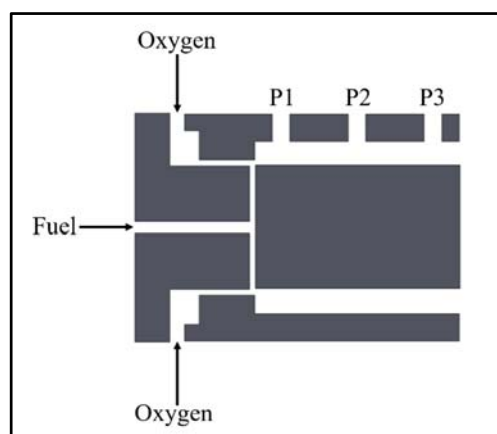


Fig. 2: Schematic of RSDE.

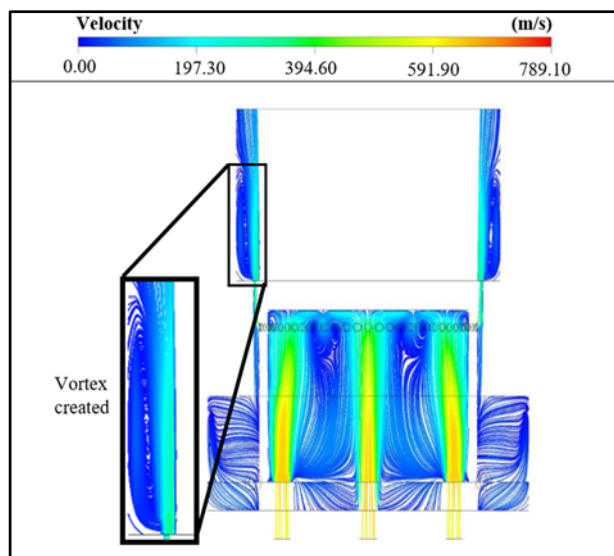


Fig. 3: Simulation for mixing of reactants.

Main instruments such as piezo resistive pressure transducers and a data acquisition card are combine to create a data acquisition system. Pressure transducers of

high frequency respond, 100 kHz, are used to capture the propagation of detonation wave in the RSCE. All the pressure data captured by transducers is recorded by the data acquisition card, which is connected to the controlling computer. The sensitive pressure transducer are coated by an adapter with water cooling system to prevent damage from the product of supersonic combustion. Due to the high temperature, the engine was also run for short duration of time which is the common practice of many studies related to supersonic combustion^{16–19}), and for this particular study at 1s.

The important breakthrough of this study is to determine the position of initiator tube along the combustion chamber in which will be easiest to initiate a continuous supersonic combustion or detonation wave in the annulus chamber of the RSCE. Experiments run throughout the study follow the time sequence shown in Fig. 4. The sequence begins with the filling of reactive mixture for both the initiator and the RSCE. It end with the shutting off of data capturing by PCB sensors.

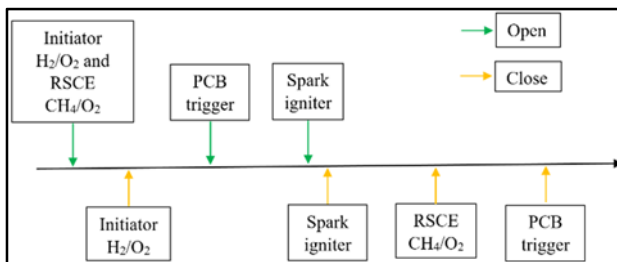


Fig. 4: Time sequence of the experiment.

3. Results and Discussion

As mentioned earlier, the RSCE in this study uses an ignition tube (or most commonly called pre-detonator²⁰) to initiate the ignition process. The tube is 200 mm (7.87 in.) long with an inner diameter of 4 mm (0.16 in.). The initiation process of rotating detonation wave in the annulus chamber is affected by the position of the initiator tube. The position of initiator tube for this experiment can be varied along the combustion chamber of the RSCE which is designed with three slots for the initiator tube.

A particular test case is run multiple times for each of the initiator tube position. The equivalence ratio for the tests are slightly fuel-lean condition. Although, a slightly fuel-rich condition can increase the success rate of supersonic combustion initiation^{21,22}), but for this particular study, it is best to use reactants with equivalence ratio of lower success rate to determine the best possible position for initiator tube. From these tests, result from the initiator tube at position P3 results with the highest rate at 60% of successful initiation and transition to steady detonation operation compared to the other position. The success rate of rotating supersonic combustion initiation are shown in Fig. 5 in form of percentage for each initiator position.

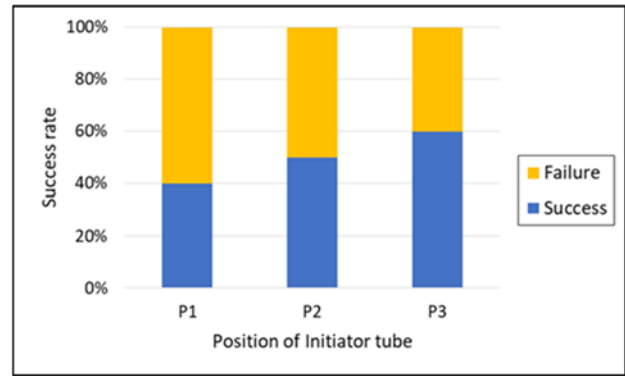


Fig. 5: Initiation success rate of rotating supersonic combustion wave

Pressure profile capture by pressure transducer are observed to determine whether the initiation of supersonic combustion is successful or not. In Fig. 6, a sample of successful initiation obtained from this study are shown. Instrumentation characteristic of thermal drift can be observed from the descending trend of pressure profile, which is often caused by high heat transfer. This high heat transfer within a short period of time is often a good sign of successful detonation²³). A closer examination at the pressure profile, it provides a view of the actual pressure peaks due to supersonic combustion or in other word, detonation. Each spike in pressure can be clearly defined and is evidence detonation wave propagating around the annulus chamber. The first spike in pressure profile indicate the capture of energy spark release from the spark igniter. After the release of spark, a supersonic combustion spike of 9 bar is observed in the pressure profile. This indicate the deflagration-to-detonation transition (DDT) occurred in the initiator tube that is filled with a higher reactive mixture (H_2 and O_2) compared to reactive mixture filled into the annular combustion chamber (CH_4 and O_2). The rotating supersonic combustion propagate continuously in the CH_4 and O_2 mixture with an average pressure spikes of 5 bar.

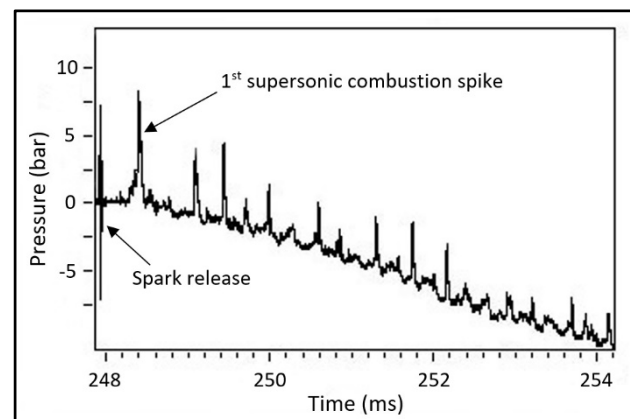


Fig. 6: Pressure profile of success in supersonic combustion initiation.

In Fig. 7, a sample of failure initiation obtained from this study are shown. After the first supersonic

combustion spike, two minor spike is observed. This is due to the multi counter combustion waves that oppose each other after exiting the initiator tube. Even though the pressure of supersonic combustion wave supplied from the initiator tube (10 bar) is higher compared to the test of successful initiation (9 bar), but due to the counter waves, the following propagating waves failed to proceed in the mode of supersonic combustion as no supersonic combustion spike are observed in the annulus chamber. But still instrumentation characteristic of thermal drift is observed which indicate the condition of the combustion waves are in the range of near to DDT region.

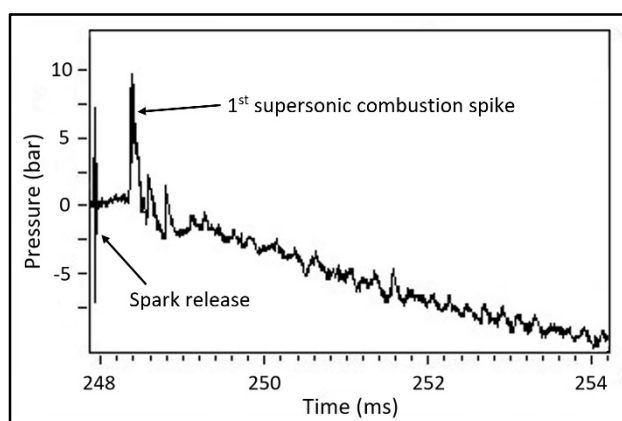


Fig. 7: Pressure profile of failure in supersonic combustion initiation.

4. Conclusion

The rotating supersonic combustion engine supplied with methane and oxygen through micro nozzles and slot orifice impinging injection method was studied in this paper, using an ignition tube with an automotive spark plug to ignite the engine. From this study, it is shown that the mixing of reactants improves further up the annulus chamber. Even with equivalence ratio of lower success rate for supersonic combustion, initiator tube in position P3 which is near the open end is still able to successfully initiate rotating supersonic wave in the engine. To further improve mixing of reactants, studies such as ^{24,25} which uses technique of wall mounted cavity could be implemented in the annulus combustion chamber.

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Abbreviation

RSCE	rotating supersonic combustion engine
RDE	rotating detonation engine
CH ₄	methane

H ₂	hydrogen
O ₂	oxygen
DDT	deflagration to detonation transition

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