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Development of Rotating Supersonic Combustion Engine with Swirling Air-Fuel Injection

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Abstract. Rotating Supersonic Combustion Engine (RSCE) has the benefit of high-frequency operation, high thrust density for future generation engine. However, RSCE that is developed is still at infancy stage which requires further refined study especially in determining best mixing scheme. Therefore, the objective of this study is to develop and to test the new mixing scheme of RSCE using swirl injection system. The research also involves the investigation of the RSCE engine using supersonic combustion ignition system with various fuel-air injection configurations on the overall engine performance. This paper discussed about the engine and its ignition development using various configuration of swirl air-fuel injection system to achieve successful operation of rotating supersonic combustion engine.

INTRODUCTION

In nowadays dwindling fuel resources, there is great emphasis on sustainability and improving efficiency. In order to help achieve the aim, government and industry are focusing on finding ways to reduce fuel consumption. Scientist and engineers are exploring into more efficient and potentially revolutionary engine technologies which among others Rotating Supersonic Combustion Engine (RSCE) or most commonly called as Rotating Detonation Engine (RDE). Is was reported that RSCE has been identified as to be one of the major future game changers for aviation in terms of improving its environmental performance in order to achieve the target of 75% reduction in CO2 emissions per passenger-kilometer and a 90% reduction in NOX emissions [1-7]. RSCE is a revolutionary technology in industrial turbine generators as well as aircraft and aerospace propulsion that promises significant fuel saving and reduction in exhaust pollutants. RSCE which utilizes supersonic combustion or called detonation as a compression method is a promising technology to improve efficiency on gas turbine systems. The efficiency gain comes from a rapid, constant volume detonation, rather than the ordinary deflagration flame currently used in the majority of energy conversion

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systems [4-7]. In traditional combustion processes, such as those used in current both ground-based and aircraft gas turbine engines, heat release occurs at constant pressure.

To make significant improvement to the performance of gas turbine engines, there is a need to look at more innovative cycles rather than conventional Brayton cycle and RSCE is the potential candidate. RSCE is a futuristic and more efficient engine that need to be developed that could save the world hundreds of millions of dollars in fuel costs every year [8]. RSCE has great potential to replace jet engines in airplanes and the gas turbines that run power plants and ships. It offers a novel way to achieve high pressures compared to rotating blades that compresses air which involves complex and costly mechanism. In RSCE, fuel combustion generates shock wave that raises pressures up to levels 15 times those inside a conventional engine. An advantage of this approach is that it produces a constant stream of hot gases, which more closely resembles what normally seen in a conventional jet engine. RSCEs do not require complex valving and have detonation frequencies in the kilohertz range, providing smooth operation. These advantages have led to a significant increase in interest in RSCE technology in recent years [9 - 10].

The engine operates using supersonic detonation wave, a combustion process that occurs at constant volume. The constant volume combustion process that occur in RSCE releases energy much faster than deflagration combustion process that happen in normal gas turbine. The constant volume combustion process is an important feature contributed to the higher energy conversion efficiency in RSCE that reduce fuel consumption. Higher energy conversion efficiency means lesser use of fuel with less impact to the environmental pollution [1 - 4]. The technology is highly potential to be applied on hybrid gas turbine for the purpose of increasing its thermal efficiency. The fundamental concept of RSCE operation is the initiation of supersonic combustion wave that travel along the annulus combustion chamber [5]. Typical shape of RSCE combustion chamber is coaxial barrel shape. The supersonic combustion wave within the chamber is normally initiated using pre-detonator that joined extraneously to the chamber [6].

However, to make it reality many challenges still remain. So, this paper envisages on the design and development of RSCE for future, more efficient energy conversion system. The important element of control, performance evaluation, ignition as well as thermal management are important aspect to be investigated in order to ensure the viability of such novel technology. Focus will be on developing the RSCE, initiating the detonation process, controlling and maintaining stable combustion, performance evaluation and preventing excessive heat loading. Two primary major issues on RSCE are ignition of fuel-air mixture and steadiness of the supersonic wave. For successful initiation of supersonic combustion, adequate combustible air-fuel mixture must exist in the combustion zone. Mixing must happen quickly to maintain supersonic waves to be continuously spinning around the annulus chamber [5].

EXPERIMENTAL SETUP

The development of such engine requires the design and development of the engine, fuel-air mixing system, control and data acquisition system, ignition system, with appropriate cooling system. A modular RSCE combustion chamber was designed, fabricated and installed on the engine thrust stand located in the engine test room at High Speed Reacting Flow Laboratory (HiREF), School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia. Schematics of the RSCE experimental setup is shown in Figure 1.

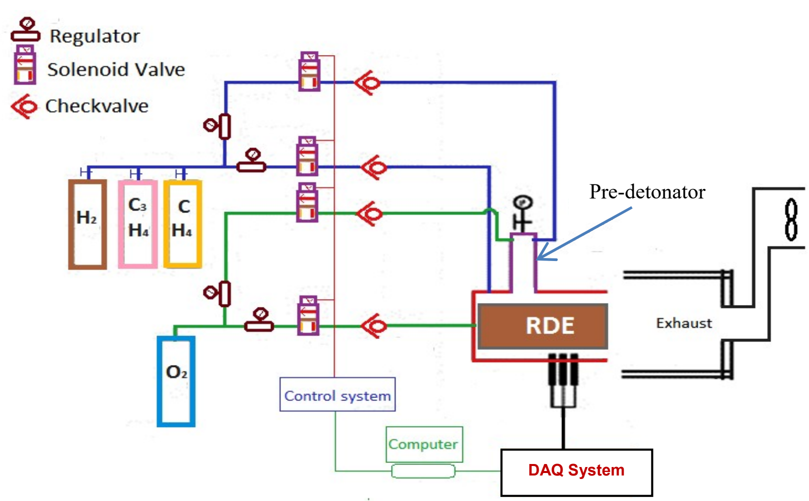

FIGURE 1. Schematic diagram for RSCE full setup at HiREF

The important breakthrough of the study is to run the engine successfully by producing supersonic combustion or detonation wave in the annulus of RSCE combustion chamber. The experiment will be conducted to determine the optimal configuration of RDE for successful operation. For that purpose a modular RSCE was built to have a platform on which the several critical variables of an RSCE could be changed and investigated independently. The critical variables are: oxidizer type, oxidizer injection geometry, fuel type, fuel injection geometry, and detonation channel width. However, in this study the focus will be mainly on the fuel-air mixing configuration and ignition of RSCE.

Various methods of data collection were used in this research. Visual data using standard speed and high-speed camera will be collected via cameras installed within the HiREF test cell. Low and high-speed pressure data will be collected using a LabView® software. The low speed data to be collected includes upstream (of the air sonic nozzle) static air pressure, fuel manifold pressure, and air manifold pressure. High-speed data will be collected from pressure transducers installed in the RSCE. All systems for the RDE were controlled remotely from the control room. The RSCE firing system is also housed in the control room. The control panel supplies power to the firing systems including the pre-detonator, fuel, and air. The control program sends various operational signals for opening and closing fuel-oxygen of pre-detonator valve and starting the ignition. The control system will also will also giving signal for the opening of fuel-air valve for the RSCE. Force generated will be quantified using load cell installed on the thrust wall of the RSCE. The gas flow rates to the test-section will be metered upstream of the feed manifolds through the use of sonic nozzles.

To determine type of combustion waves that propagated in the combustion chamber, pressure profile detection is required. The pressure detection is made through the use of a pressure transducer in an infinite tube pressure arrangement. This allows the greater than 1 MHz natural frequency of this transducer to be taken advantage of without exposing the sensitive transducer head directly to the detonating flow field. The characteristics of propagating combustion wave, such as the propagation patterns, propagation velocity could be analyzed using the recorded pressure profile. The high-frequency data acquisition system is important in order to capture the pressure variation due to combustion. Pressure detection system is composed of the NI digital acquisition system, dynamic piezoelectric pressure sensors, digital acquisition card, with sampling frequency of 1 MHz at minimum.

Another aspect that is important in the RSCE is ignition. Ignition of fuel-oxidizer in RSCE and the subsequent transition to steady detonating operation is a key component of the successful development of this technology. The examination of the behavior of back-pressured rotating detonation engine combustion chambers and the identification of the driving physical processes affecting ignition is the focus of this work. In a practical sense, the successful initiation of a rotating detonation engine is required to enable the study of the steady state operation of such devices under a wide range of fuel-oxidizer supply conditions. The initiation process of rotating detonation wave will be recorded and analyzed. Determination will be made also to see the dependability of RSCE on ignition for the same operating condition. Operating modes of the engine model need to be observed, namely failed initiation of the detonation, unstable detonation and continuous rotating detonation.

In RSCE combustion temperatures can rise as high as 2800K across the detonation wave. The continuous exposure to such elevated temperature may risk the integrity of the structural components of the engines. Consequently, heat management of the detonation engines is important aspect in the development of RSCE. In order to be able to design an appropriate cooling system for RDE, an accurate estimation of the heat load stands as an essential prerequisite. A rotating detonation combustor is characterized by an annular channel where combustible mixture is injected and ignited by a self-sustained spinning detonation front at supersonic speeds. However, practical implementation is currently constrained by important thermal management issues due to the high-speed flow and high temperature levels reached inside the combustor. The combustor walls are periodically swept by shock waves at several kilohertz, which results in extraordinary heat-flux levels that limit the operability of the combustor. RSCE was developed using modular concept with the ability to change its injection port configurations. There are three different ways of mixing the reactant inside the RSCE with main idea to generate swirl mixing scheme, such as shown in Figure 2. Top view for tangential swirling injection of RSCE oxidizer is shown Figure 3.

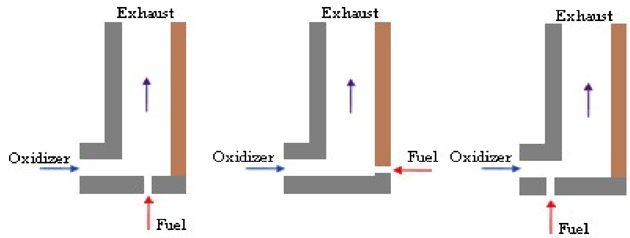

FIGURE 2. Three fuel-air mixing schemes

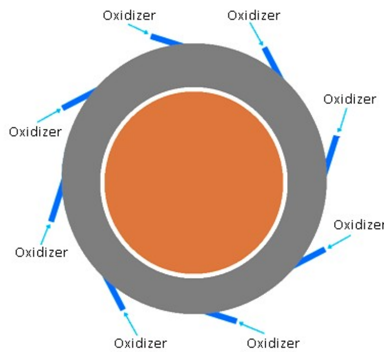

FIGURE 3. Top view of tangential swirling injection of RSCE oxidizer

RSCE was controlled using Arduino, an open-source hardware of single-board microcontrollers and microcontroller kits for building digital devices and interactive objects. The sequence is important to make sure RSCE will operate successfully. The timing sequence of the RSCE is shown in Figure 4. At zero second, the main supply valve at pre-detonator will be opened. After 0.9 second pre-detonator valve will be closed the while main supply for RSCE will remain open. Next, after 1 second period, the ignition will start to initiate the pre-detonator. The detonation wave from pre-detonator will in turn initiate the RSCE. The energy required to start the ignition was delivered from a discharge capacitor in the ignition circuit system.

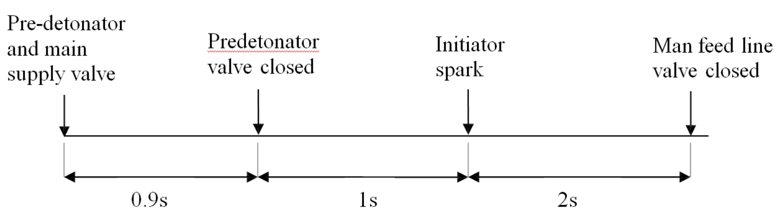

FIGURE 4. RSCE timing sequence

The pressure profile of propagating combustion waves in RSCE was measured using pressure transducers namely Kistler 211B300 Piezotron. The transducers were chosen due to their advantages to capture high-level, low impedance signal in terms of voltage analogue of the dynamic pressure input. The transducers is made of crystalline quartz as the sensing elements and a solid-state impedance converter. The sensitivity of this pressure transducer ranges from 1.156 mV/psi to 1.168 mV/psi. The pressure transducers were wall mounted equipped with cooling system to prevent over heating which may otherwise cause failure on the transducers. The maximum operating temperature of transducer was 1210oC. A data acquisition system was used to record the pressure signal from the transducers that is connected to the data acquisition (DAQ) system from National Instruments. The digital inputs were directly acquired while analogue inputs were conditioned as necessary and converted to digital signals for processing by the LabVIEW program [7 – 12].

RESULTS AND DISCUSSION

The most important data to determine the performance of RSCE is the pressure profile obtained from the installed pressure transducers both at the pre-detonator as well as the outer body of the RSCE. Pre-detonator is the key factor for detonation to occur inside the annulus shape of inside the RSCE combustion chamber. Acetylene–oxygen was used as reactive fuel inside the pre-detonator. After several testing and adjustment the selected equivalence ratio for pre-detonator is slightly rich, around 1.2. Figure 5 shows the typical pressure profile that achieved from the combustion of acetylene-oxygen combustion. The pressure curve shows the transition process from normal flame or deflagration till the supersonic combustion or detonation establishment. The supersonic combustion pressure as high as 16 bar was recorded in the pre-detonator. The supersonic combustion wave is characterized by sharp spike of pressure that occur in the pre-detonator and this

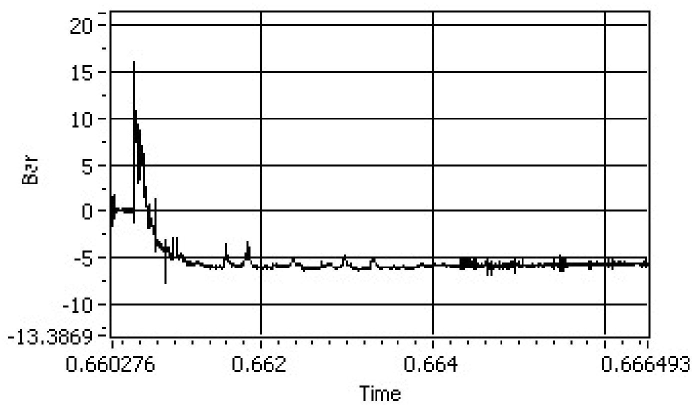

FIGURE 5. Supersonic combustion wave signal in pre-detonator

It is presumed that the highest detonation pressure will increase the probability to successfully initiate the RSCE. The supersonic combustion waves exiting the pre-detonator are expected to initiate the combustion in the RSCE. The expected result of running RSCE is shown on Figure 6. The frequency of RSCE expected will reach 1kHz based on result obtained by previous researcher [6].

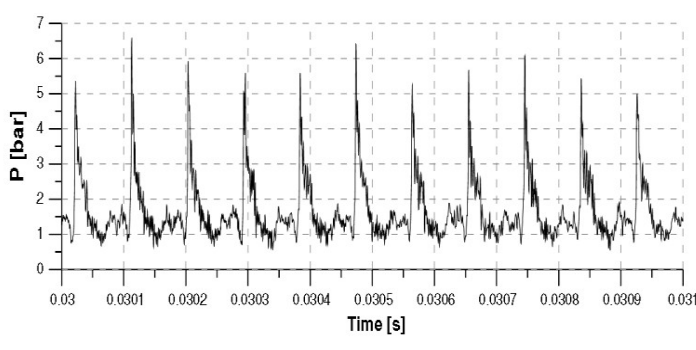

FIGURE 6. RSCE supersonic combustion pressure signal [6]

CONCLUSION

This paper dwell into the RSCE engine design, development and all necessary subcomponent to successfully run the engine. The most important aspect of constant combustion event to start in the RSCE is the sufficient supply fuel-air, their mixing schemes and ignition. This initial study has showed the successful pre-detonator initiation and the supersonic combustion wave propagation at the exit of pre-detonator to start the RSCE. Various configurations for the air-fuel inlet for RSCE has been fabricated and installed in the RSCE. The development of a swirl rotating supersonic combustion engine is described. This rig was designed to operate with oxygen and hydrogen as a main fuel. The developed experimental rig in the HiREF lab allows extensive investigation of the RSCE performance for various mixing strategy and equivalence ratio. The performance of RSCE is expected to show improved output in comparison to deflagrative combustion system that normally occurs in most nowadays combustion system.

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