48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition
4 - 7 January 2010, Orlando, Florida

AIAA 2010-146

Testing of a Continuous Detonation Wave Engine with Swirled Injection

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Two different continuous detonation wave engines with swirl to improve mixing were developed. The reactants were ignited with an ordinary automotive spark plug. Mixing and detonation occurred in a common annular chamber in the first engine but occurred separately in the second. Deflagration-to-detonation transition could be observed in the first engine. The number of revolutions of the detonation wave was limited due to the inability of the supply to deliver sufficient flow. For the second engine, detonations were sustained for a longer duration. The data indicate that detonation was achieved with multiple detonation waves traveling in one direction. Adding an endcap raised the pressure in the detonation chamber.

I. Introduction

WHILE research in pulsed detonation engines (PDEs) and oblique detonation wave engines (ODWEs) has progressed considerably in the past decade, there has lately been interest in the continuous detonation wave engine (CDWE) concept, also known as the rotating detonation wave engine (RDWE).[1–23] CDWE testing was initiated by Voitsekhovskii[24] in Russia circa 1960 as a rotating instability in rocket motors (see also Clayton and Rogero[25]) and subsequently followed by Nicholls and coworkers in the United States.[26–28] Despite considerable effort, Nicholls and coworkers were unable to develop an engine that could initiate a detonation wave traveling in one direction around the annular chamber upon ignition. Instead, detonation waves would propagate in each direction from the ignition source and collide with each other on the opposite side of the annulus. Perhaps because of this outcome, no further studies were presented in the literature from the United States despite the increasing popularity of PDEs and ODWEs. Development has continued at a modest pace in Russia with the progress summarized by Bykovskii et al.;[13] see also Canteins.[16] According to Bykovskii et al.,[13] the quality of mixing between the fuel and oxidizer (assuming separate injection) is crucial towards creating and maintaining a detonation wave in the annulus. Once the mixing is sufficient, a rotating detonation wave can be maintained around the annulus using a variety of injection schemes and fuels. Minimum sizing constraints have additionally been empirically estimated based on the detonation cell size.

Although a detonation wave has been experimentally maintained in the annulus for hundreds or thousands of revolutions, it should be noted that the speed of the wave of 1 km/s or more, and the annulus diameters commonly used of about 100 mm thus far corroborate with run times of no more than about a second. Some of the earlier experiments appear to have been constrained by a low reservoir tank volume coupled with high

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fuel injection pressure. In more recent work, Lentsch et al. stated that the run-time limit of their CDWE is self-imposed to 0.25–1.9 s due to thermal considerations.[18] It then appears that there are four major design hurdles to overcome for RDWE development: initiation of the detonation wave in one repeatable direction around the annulus, sufficient fuel/oxidizer injection, sufficient fuel/oxidizer mixing, and thermal considerations (that is, preventing auto-ignition).

The problem of starting the detonation wave in one direction around the CDWE annulus is the first that must be overcome to result in a feasible engine. The ignition source and the fuel injection method are factors in this process. In their annular engine experiments, Nicholls and Cullen used 72 impinging injector pairs with orifice diameters of 0.017 and 0.024 in. for fuel and oxygen, respectively.[26] The injectors were mounted on the outer wall of the annulus. A diaphragm was placed next to a spark plug ignition system to ensure the detonation wave would propagate in one direction, but these efforts were not successful. Fuel injection was also originally established through a series of impinging orifices by Bykovskii and Mitrofanov where their sizes are comparable to the abovementioned diameters.[23] However, the orifices were usually placed near the bottom of the annular combustor with many impingement strategies reported.[13] Ignition is usually begun from a specially mounted channel located in the outer wall or a central insert, and the initiation of a rotating detonation wave is obtained. Similar designs by Wolanski et al. and Canteins (each incorporating transducers along the annulus) clearly showed the detonation wave traveling around, but its pressure and speed often decreased within the first half-second of the experiment.[16,19] Canteins, in particular, showed that the pressure peaks were unstable during initiation but quickly stabilized into a pattern that resembles a rotating detonation wave.

This paper reports on the design of two rotating detonation wave engines in which the reactants are swirled. In the first, designated CDE001, the reactants were mixed and ignited in a common chamber. In the second, designated CDE002, the reactants were premixed before entering the detonation chamber.

II. Engine Design with Swirled Injection

Although recent tests have significantly added to the knowledge of the CDWE, many improvements must be made before it may be feasible to integrate with an aerospace vehicle. Small fuel orifices are often used with injector manifolds in rocket engines,[29] but the pressure losses across these orifices may not be suitable for airbreathing CDWEs. Another issue to address is to ensure that the detonation wave rotates stably. Finally, it is desirable to ensure that the detonation be sustained. Swirled injection was considered because it can control the direction of the annular fuel flow and may induce a detonation wave in one direction.

A. Engine with Swirled Hydrogen Injection

In the first engine, designated CDE001, fuel is swirled into a chamber serving the purposes of both mixing and detonation. Figure 1 shows a schematic of CDWE initiation with swirled flow injectors. Initially, the fuel (either hydrogen or propane) and oxygen are injected through the inner and outer walls of an annular chamber, respectively. The reactants mix and pass a flush-mounted spark plug and fill the annulus. Before the mixture completes a rotation, it is ignited by the spark plug and a detonation wave proceeds counterclockwise in the figure. A fresh mixture fills the chamber just before the detonation wave completes a second rotation. As shown in Fig. 1, the detonation wave will pass the injectors before the chamber is again entirely filled. Therefore, more than one injector pair may be needed, although the number must be limited to perhaps 1–10 before timing with the single ignition spark plug becomes too difficult.

For this design, between one and four injection ports with openings of 1 cm^2 and spaced at 90 deg increments can be used. A diagram of the engine is shown in Fig. 2, where the injectors not used may be filled with a high temperature ceramic seal. Only one set of injection ports are used for the present work. Ignition is initiated with a flush-mounted automotive spark plug (Bosch Platinum +4). Six water-cooled pressure transducers (PCB model 111A24) are mounted at 45 deg increments to measure the detonation wave rotation. The center of the annulus contains a separate check valve for each fuel port. Table 1 lists

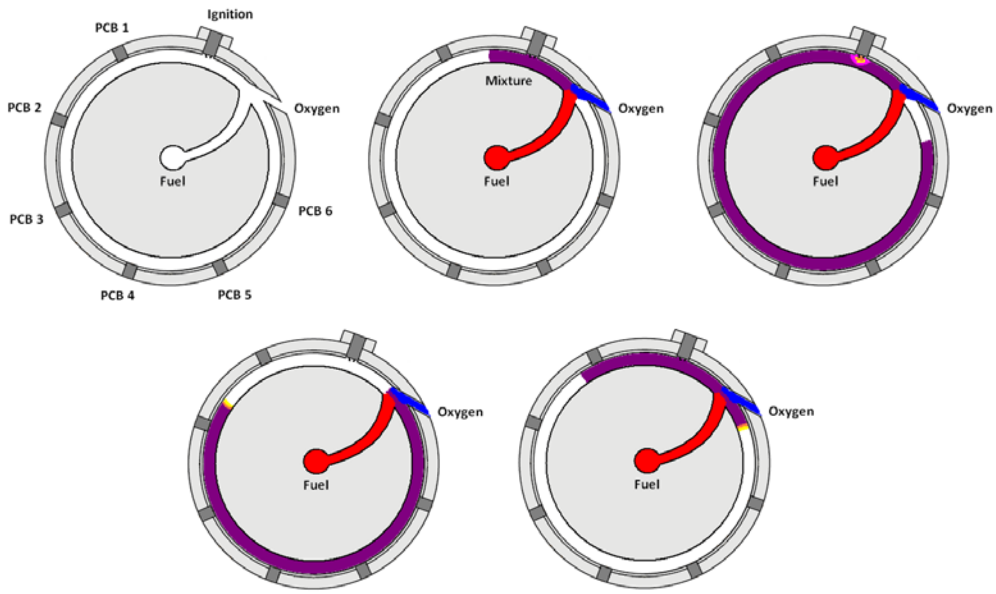


Figure 1. Schematic of the initiation cycle of the swirled-flow RDWE.

the main dimensions of the engine, including the frequency of a single CJ wave rotating within the engine. Figure 3 is a photograph of it prior to mounting. In addition to the pressure transducers, the core of the engine around the fuel ports and check valves is also watercooled. An aerospike nozzle was mated to the annulus.

Table 1. Main geometry of the RDWE

Component	Measurement
Outer annulus diameter	24.1 cm (9.5 in.)
Channel width	1.27 cm (0.5 in.)
Channel height	6.99 cm (2.75 in.)
Transducer separation	45 deg spacing (9.47 cm, 3.73 in.)
Oxygen injector orifice area	0.62 cm^2 (0.1 in.^{2})
Fuel injector orifice area	0.9 cm^2 (0.14 in.^{2})
f, CJ C_3H_8-O_2 mix	3100 Hz
f, CJ H_2–O_2 mix	3750 Hz

B. Engine with Swirled Oxygen Injection

As will be discussed later, the inability to sustain detonations in CDE001 pointed to the need to develop a smaller engine with larger ports, the latter also being able to reduce pressure losses. This engine is designated CDE002. A cutaway schematic of the CDWE is shown in Fig. 4(a). The engine is 15.24 cm in diameter $\times$ 17.8 cm in length (6 $\times$ 7 in.), which includes a watercooled jacket around the detonation chamber. Most of the engine is made of stainless steel. The inner piece of the detonation chamber is made of brass.

Oxygen enters a mixing chamber from a centerline pipe, 2.54 cm (1 in.) in diameter and is set into a swirling direction by seven swirl vanes (Fig. 5). The vanes are 2.54 cm (1 in.) long and the exit gap between them is 0.64 cm (0.25 in.) The hydrogen port has a 1.27 cm (0.5 in.) diameter and is visible in Fig. 4(b).

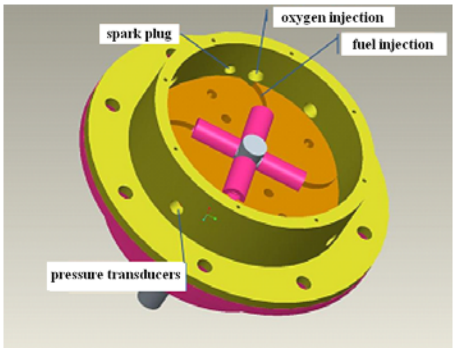


Figure 2. Computer-generated image of the CDWE annular chamber and central injection ports.

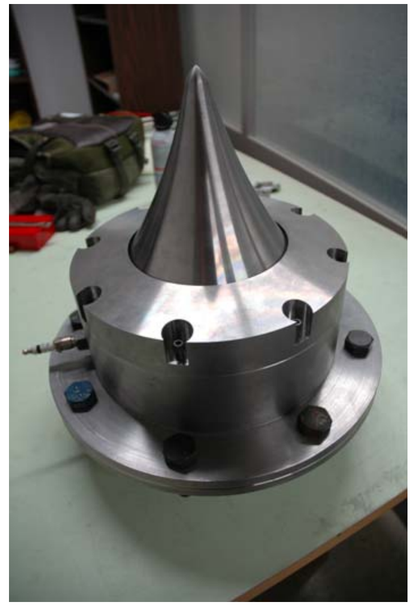


Figure 3. Photograph of the CDWE with the annular aerospike nozzle before mounting.

The hydrogen enters a plenum chamber and exits an annular opening with inside and outside diameters of 7.85 and 9.76 cm (3.09 and 3.45 in.) respectively. Such a simple design enables the mixing chamber to be filled with hydrogen with less loss compared to injection via a large array of small holes. The hydrogen enters the mixing chamber in the axial direction and mixes with the swirling oxygen. This arrangement ensures good mixing. Note that the rationale for having a mixing chamber is to keep the mixing process separate from the detonation to ensure reliable detonations. As a safety feature, a thermocouple is inserted into the mixing chamber to indicate if burning occurs within the mixing chamber, whereby the test will be terminated. The thermocouple is not visible in Fig. 4. The equivalence ratio of the mixture is controlled by the supply pressures. At present, no flow meters have been installed.

The detonation chamber is an annulus with inner and outer diameters of 7.87 and 8.76 cm (3.1 and 3.45 in.) respectively, and a length of 12.7 cm (5 in.). The chamber is made of brass. Toward the end is an optional cap. The end constricts the exit annulus to have inner and outer radii of 7.87 and 8.13 cm (3.1 and 3.2 in.).

The detonation chamber is equipped with two circumferential rows of instrumentation located at 7.0 and 3.18 cm (2.75 and 1.25 in.) from the exit of the detonation chamber. The transducers are all water-cooled PCB model 111A24. In the first row are three transducers arranged at 90 deg from each other and labeled P2, P4 and P6. At the fourth location is a flush-mounted Bosch Platinum +4 automotive spark plug. The second row of transducers are mounted at 90 deg from each other and aligned with the first row. The transducer and spark plug arrangements are shown in Fig. 6. Figure 6(a) also shows water-cooling ports and jackets.

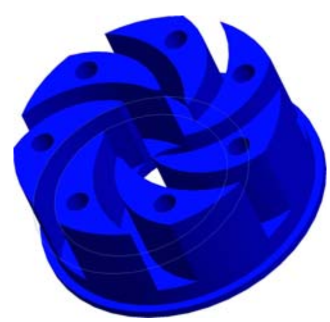
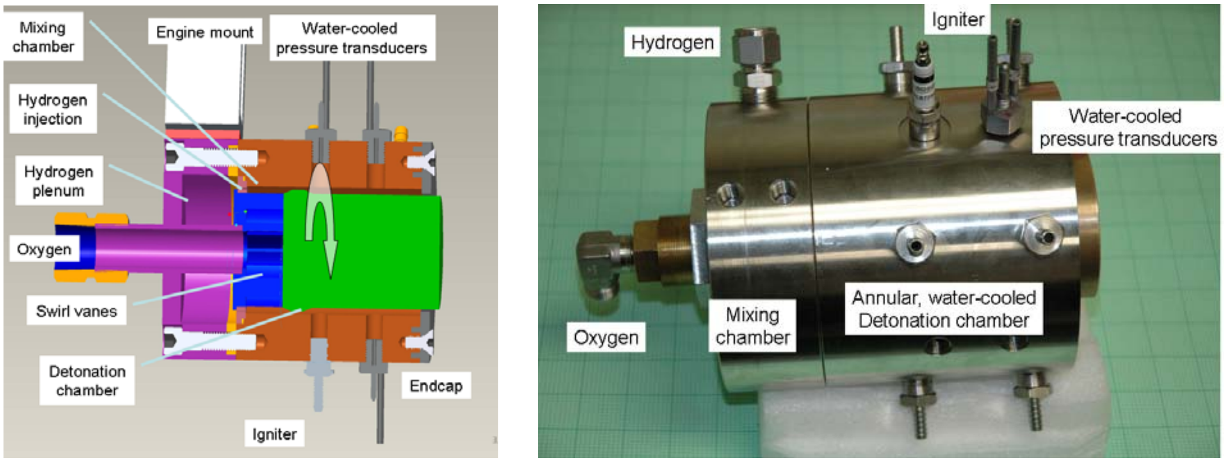


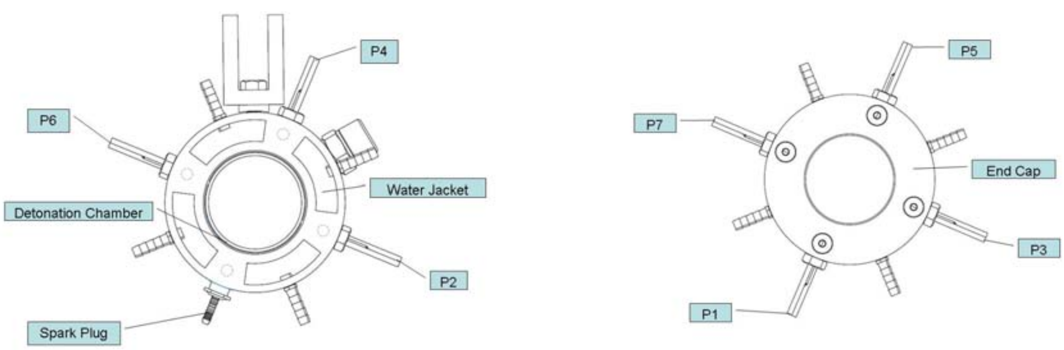
Figure 5. Swirl vanes.



(a) Photograph of engine.

(b) Cutaway schematic of engine.

Figure 4. CDWE with swirl.



(a) First row of pressure transducers (P2, P4, P6) and spark plug.

(b) Second row of pressure transducers (P1, P3, P5, P7).

Figure 6. Pressure transducer layout.

III. Experimental Results and Analysis

A. Engine CDE001

Propane and hydrogen were both made available for use with this engine. They were both considered since the pressure ratio of the detonation wave is almost doubled with propane when compared to hydrogen. This allows for some parametric studies of the detonation wave pressure influence on the injector performance where the injector pressure remains fairly constant. Experiments were begun with one set of injectors with the intention of continually opening more injector pairs to increase the engine performance.

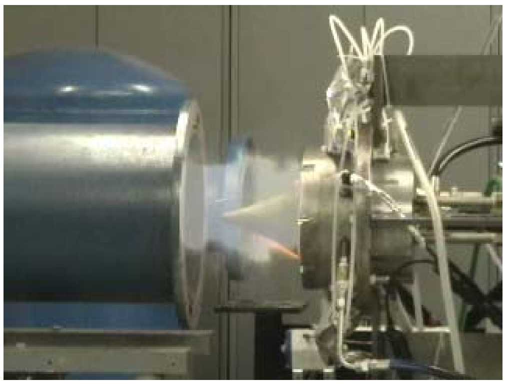
The first set of experiments were conducted using one pair of ports and propane for fuel. The fuel/air ratio was adjusted to nearly stoichiometric by varying the propane pressure until the engine produced a clear flame. The detonation process was initiated by opening pneumatic gate valves for the fuel and oxygen to enter the annulus, after which the spark plug ignited the mixture. Consequently, the timing sequence of the fuel injection and ignition is crucial. With too long of an ignition delay, the mixture fills the annulus, and the spark induces detonation waves in both direction from the source that cancel with each other on the opposite side of the annulus. After some trial and error, the timing issue was resolved and a detonation wave was created in the annulus traveling in a counterclockwise direction referenced to Fig. 1. A sequence of images of a typical run is shown in Fig. 7. Figure 7(a) shows a detonation which then broke down into "choked deflagration" as shown in Figs. 7(b) and 7(c). Finally, only a subsonic deflagration occurred as shown in Fig. 7(d).

Figure 8 shows the resulting pressure transducer data from a hydrogen/oxygen test. The supply pressures for hydrogen and oxygen are 1 and 3.45 MPa (150 and 500 psia) respectively. The sampling rate was set to a fairly low value of 100 kS/s in this case. The data clearly shows that the detonation wave is traveling in one direction past transducer PCB 4 which is located opposite of the spark plug. Using hydrogen, test runs that recorded 2–3 rotations of a detonation wave were typical over a large range of equivalence ratios. Generally, the tests with hydrogen fuel resulted in a better defined detonation wave when compared with propane. The timing window for successful ignition is less than 20 ms. The detonation wave speed measured between transducers 3–5 is within 5 percent of the stoichiometric CJ speed. Although the detonation wave reaches a CJ state, the speed is significantly reduced after the wave passes the fuel and oxygen ports. It is possible that the detonation wave interrupted the flow of hydrogen or oxygen long enough for it to die out. An apparent transition to detonation can be seen in the figure as well whereby the time of passage between PCB1 and PCB2 appears longer than that between the subsequent transducer pairs. Further, it is noteworthy that the detonation wave can make multiple rotations in the annulus with the relatively large injector areas.

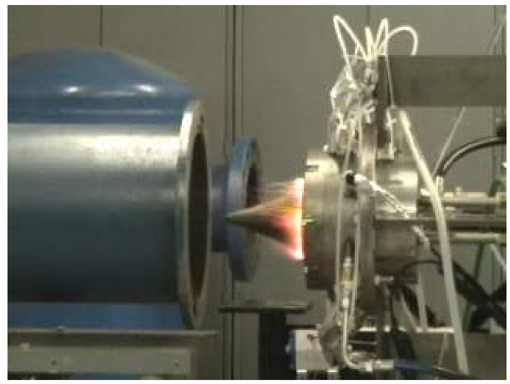
B. Engine CDE002

CDE002 uses oxygen and hydrogen and was meant to demonstrate the feasibility of sustaining rotating detonation waves without the use of a predetonator as well as various other improvements over what have been reported in the literature. Figure 10 shows an example of a test firing. In this example, the engine was run without the endcap. The photograph shows the cooling tubes clearly. The contraction of the exhaust plume is similar to that of Ref. 18.

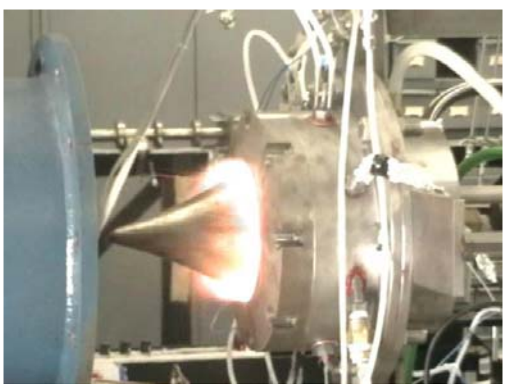
Tests were performed with and without the endcap and with different equivalence ratios. Only two sample results will be discussed here. The first set of results is for 345 kPa (50 psia) hydrogen and 1.38 MPa (200 psia) oxygen without the endcap. Figures 11(a) and 11(b) show oscillatory pressure data which also decayed rapidly with time. The trend is similar to that of Lentsch[18] except that the current results show large negative readings. These readings are nonphysical and may be attributed to transducer characteristics. (In addition, transducer 7 appears to be malfunctioning.) Figure 11(c) shows an enlargement of the first 2 ms of the upstream transducers. The pressure oscillations are evident but do not display the typical detonation wave profile of a sharp rise in pressure followed by a Taylor rarefaction, a phenomenon also observed by others.[16,18]



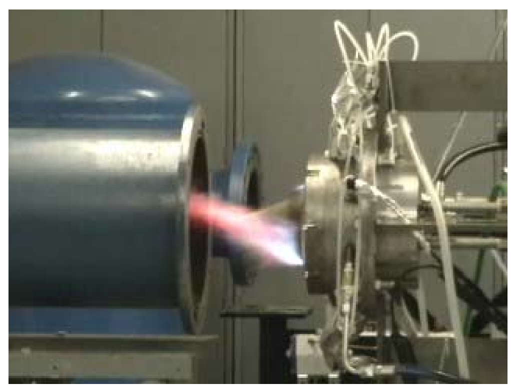
(a) Detonation of hydrogen/oxygen mixture.



(b) Choked deflagration of fuel-rich propane/oxygen mixture.



(c) Side view of Fig. 7(b).



(d) Deflagration of hydrogen/oxygen mixture.

Figure 7. Images of CDE001 tests.

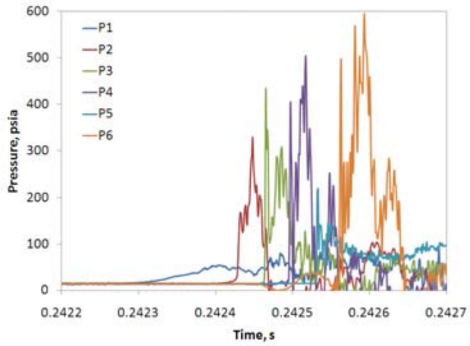


Figure 8. Pressure transducer readings from a hydrogen/oxygen test that shows the swirled fuel injection technique inducing a detonation wave in one direction around the annulus.

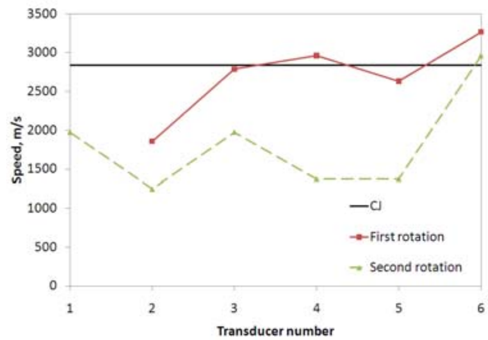


Figure 9. Wave diagram from a hydrogen/oxygen test showing an initial CJ detonation speed which degrades as the wave passes by the injector pair.

In order to understand the pressure signals further, the data were bandpassed with a Butterworth filter with cutoff frequencies of 2 and 50 kHz. The filtered data are shown in Fig. 11(d) and its spectrum is shown in Fig. 11(e). The spectrum indicates a peak at 15.6 kHz. This frequency translates to a wave speed of 4083 m/s (13 400 ft/s) which is larger than the Chapman–Jouguet detonation velocity of 2836 m/s (9304 ft/s). Due to this result, it appears that there is more than one detonation wave revolving around the chamber.[16,18] Note that the data from transducers 2 or 4 yield the same frequency peak and are omitted here for brevity.

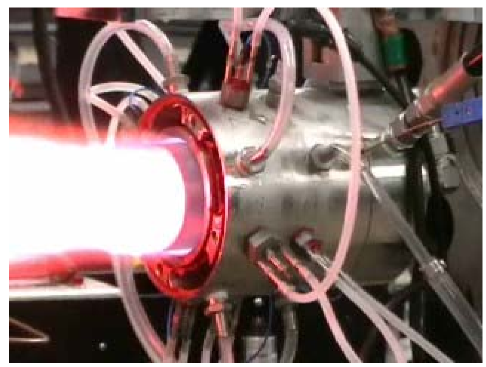
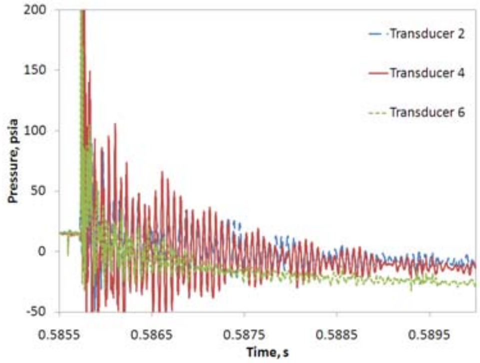


Figure 10. Photograph of a test firing.

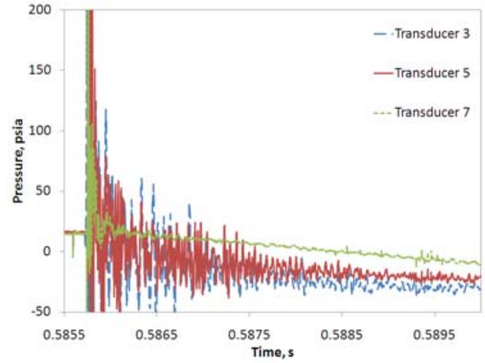
An example of test results with the endcap attached is shown in Fig. 12. This test was performed with hydrogen supplied at 345 kPa (50 psia) and oxygen at 2.76 MPa (400 psia). The first row of transducers showed trends similar to those of Fig. 11. The second row shows higher pressures due to the presence of the endcap. The pressure fluctuations are found to be 13.67 kHz.

A summary plot of the frequency of detonation waves as a function of equivalence ratio for endcap on and off is shown in Fig. 13. The frequency with the endcap on generally trends lower than with the endcap off. However, no definite trends can be made regarding the data which appear to be weakly dependent on the equivalence ratio. This result is similar to that of Canteins[16] who showed a weak dependence of the wave speed on the equivalence ratio.

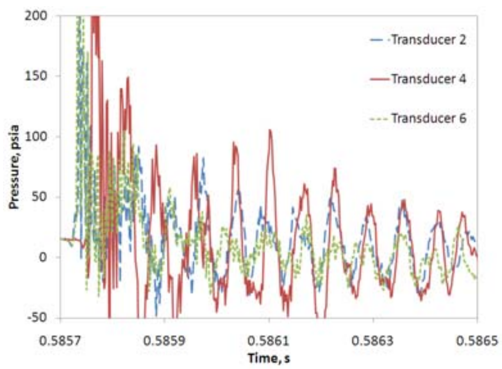
Finally, a sample dataset from the thermocouple in the mixing chamber is plotted in Fig. 14. This thermocouple was meant to detect if a backfire occurs and apparently there was none. Inspection of the engine after the test campaign also revealed that it was not damaged. The temperature data showed that the temperature rose continuously during the nearly 1 s of test. This indicates that the present cooling scheme needs to be improved even for the mixing chamber.



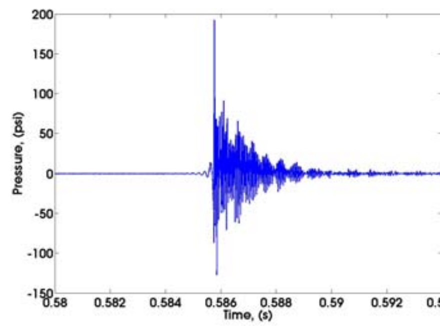
(a) Upstream transducers.



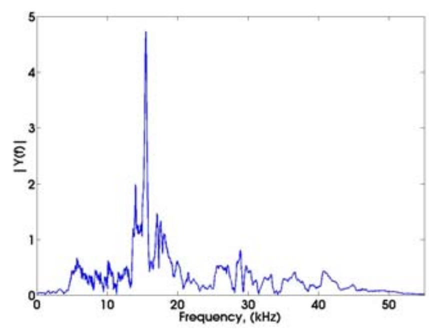
(b) Downstream transducers.



(c) Enlargement of the first 2 ms for the upstream transducers.

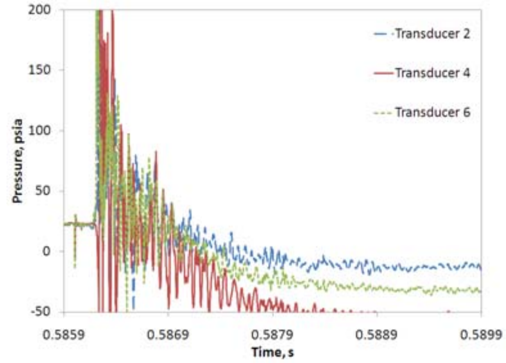


(d) Filtered data of P4.

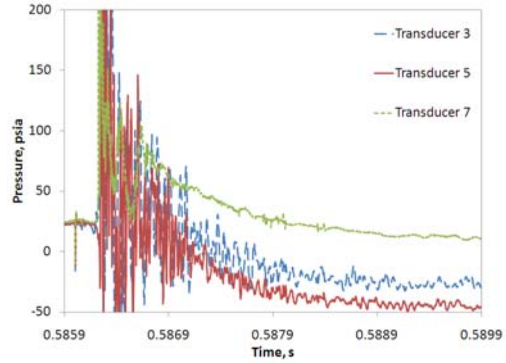


(e) Fourier transform of filtered data.

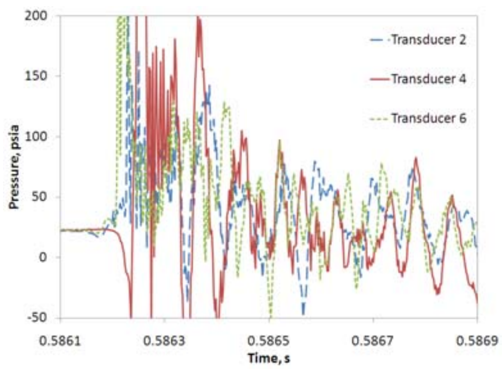
Figure 11. Pressure transducer data of a test without endcap with 345 kPa (50 psia) hydrogen and 1.38 MPa (200 psia) oxygen.



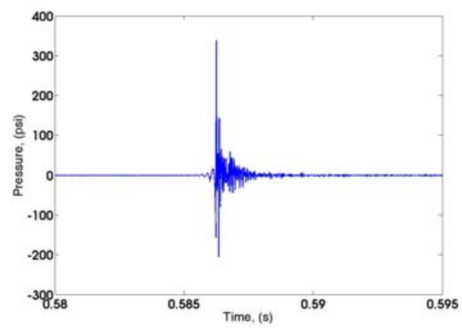
(a) Upstream transducers.



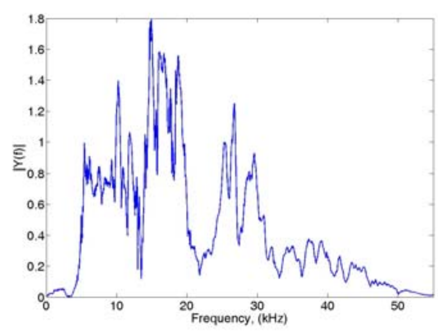
(b) Downstream transducers.



(c) Enlargement of the first 2 ms for the upstream transducers.



(d) Filtered data of P4.



(e) Fourier transform of filtered data.

Figure 12. Pressure transducer data of a test with endcap with 345 kPa (50 psia) hydrogen and 2.76 MPa (400 psia) oxygen.

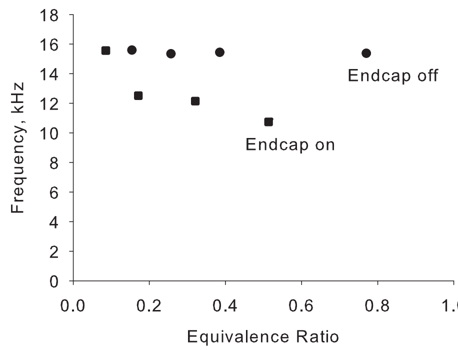


Figure 13. Frequency of detonation waves as a function of equivalence ratio.

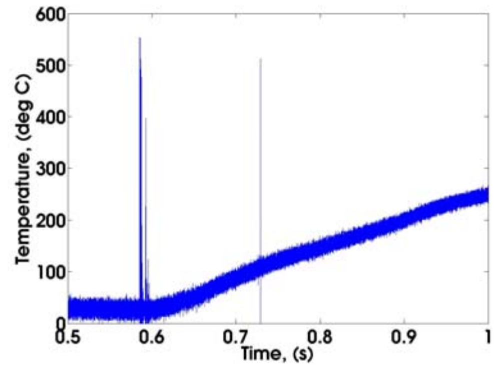


Figure 14. Temperature in mixing chamber during a test.

IV. Conclusions

Two rotating detonation engines using gaseous fuels and oxygen were developed and tested, with emphasis on swirling the reactants to improve mixing. In one configuration, the mixing occurred in the detonation chamber. In the second configuration, the reactants were mixed in a chamber and detonated in another. There is limited evidence that multiple waves were formed in the detonation chamber. There is limited evidence that the present cooling scheme is insufficient to handle the heating rates even in the mixing chamber.

No predetonator was used for both configurations. There was also no need for a deflagration-to-detonation device with detonation transition occurring naturally as the wave rotates around the annulus. Moreover, it was demonstrated that the detonation could occur safely with premixed reactants. It can also be concluded that swirl played an important role in ensuring stability of the rotating detonation wave.

Some major deficiencies were revealed in this study, however. The most important is the inability to capture the pressure magnitudes properly. It was thought that this may be due to transducer limitations and, therefore, other transducers will be tried in the future. Also, there were no proper measurements of reactant flow rates and performance parameters such as thrust and impulse. These, too, will be addressed in the future. Further instrumentation in the detonation chamber will be included to help in understanding the performance of the engine. High-speed flow visualizations are also contemplated.

Acknowledgments

This work was partly supported by a Louis Stokes Alliance for Minority Participation Scholarship awarded to NLD.

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