Experimental study of a pulse detonation rocket with Shchelkin spiral

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1 Introduction

There is much recent interest in the development of propulsion systems using high-frequency pulsed detonations [1]. An important technical challenge remains the ability to achieve consistent, repetitive detonations in a short distance. The direct initiation of detonation requires an inordinate amount of energy while a deflagration-to-detonation transition (DDT) occurs at lower energies but requires excessive length for aerospace propulsion applications.

For propulsion applications, the large energy requirement poses practical problems such as an energy source may not be readily available in a compact and lightweight package. Consideration therefore turns to an acceptable DDT length since it has been found that as long as transition occurs within the length of the detonation tube, the specific impulse obtained is the same as that from direct initiation [2]. The trade-off between energy and DDT length (or time) is crucial. A weak source would result in a long transition that causes problems associated with length, such as reduction in cycle frequency, mixing, and engine weight. Most single-shot experiments do have transition lengths that are too excessive (0.7–2 m) to be practical.

One way of reducing the DDT length is to place obstacles in the detonation chamber such as orifices, channels, or spirals. It appears that some sort of DDT enhancement device may be needed for a practical PDE to be feasible. However, only a few reports exist on using these devices in a pulsed operation mode [3]. Most research has been done on single shot facilities. This investigation explored the behavior of a Shchelkin spiral in a pulsed detonation engine. It is expected that the rapid cycle requirements absent in single shot experiments will be affected by this obstacle.

2 Experimental setup

The experiments were carried with a high frequency pulse detonation rocket (PDR) facility. This facility utilizes a mechanical rotary valve injection system for three gas species (fuel, oxidizer, and purge). The propellants are detonated by a high current, electric arc discharge. Near stoichiometric ratios were calibrated with the aid of two critical flow nozzles; one for fuel and one for oxidizer. Only a brief description of the experiment is provided; for more details, refer to [4].

2.1 Detonation chamber

The detonation engine is constructed of steel tubing of various lengths that can accommodate pressure transducers, thermocouples, heat flux gauges or photodetectors as required. The Shchelkin spiral experimental setup is shown in Fig. 1. The spiral has a pitch of 15 degrees and wire diameter of 9.53 mm. The blockage ratio, the area of the obstruction to the area of the clean cross-section, for the spiral was about 0.21, relatively small when compared to other DDT experimental studies [3]. A special in-house ignition system capable of delivering 3–20 J at up to 200 Hz is used. For the experiments, an energy of about 18 J/pulse was used.

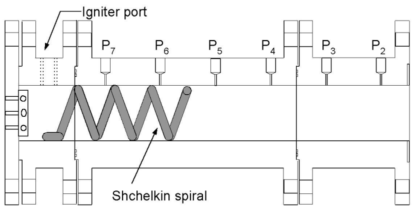


Fig. 1. Detonation chamber configuration: internal and external diameters of 7.62 and 15.2 cm respectively, length = 7.62, 15.2 or 30.5 cm; igniter located 3.81 cm from end wall, transducer P_7 located 7.62 cm from igniter and transducers thereafter are spaced at 7.62 cm intervals, P_1 (not shown) measures atmospheric pressure

2.2 Gas injection system

The problem of injecting a stoichiometric mixture into an intermittent detonation device is more involved than the partial pressure method used when charging up a single shot detonation experiment. Two critical flow nozzles (FlowDyne Corp., Fort Worth, Texas) were used in metering the oxygen and fuel flow rates. The calibration procedures are not reported for brevity.

The fuel and oxygen sources were kept at a distance from each other as well as the PDR for safety reasons. Flash arrestors were also installed about 15 m upstream of the mass flow meters to further ensure safety. The reactants were delivered to the detonation chamber via a mechanical rotary valve injection system. This valve was designed and fabricated in house for fuel injection, oxygen injection, and purging purposes. Gases were injected from the side opposite the drive gear and then distributed from three ports in a radial fashion from the internal rotating shaft. The three valves are mounted to the engine via a trapezoid-shaped manifold as seen in Fig. 2.

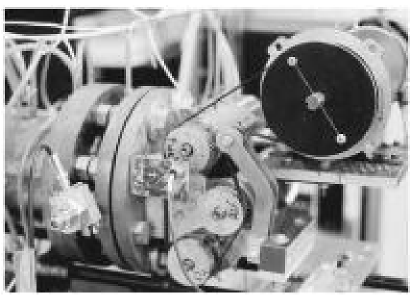


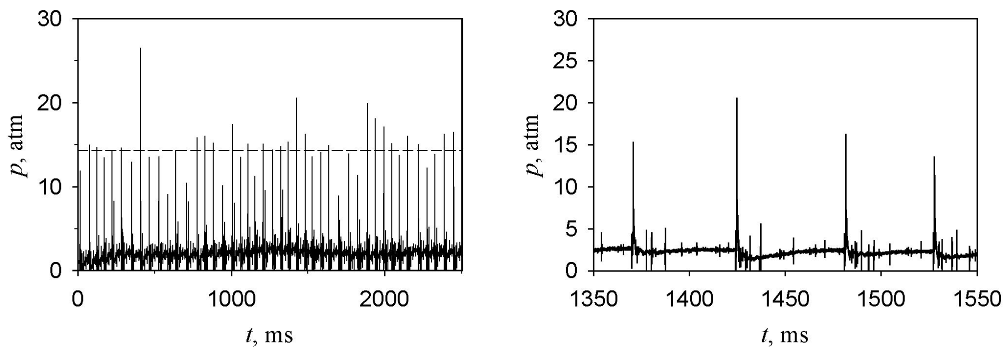
Fig. 2. Rotary valve assembly

This injection block directed the propellant and purge flows into the engine. The propellant gases are then forced into a swirling motion by an injection disk mounted on the end wall inside the detonation tube to enhance mixing, Fig. 1. Due to the present drive gear radius and friction of the rotating system, the 0.5 hp electric motor was only capable of driving the system up to a cycle frequency of 20 Hz.

2.3 Test conditions and data acquisition

Experiments were conducted for configurations with a Shchelkin spiral at frequencies of 4.4, 6.9, 14.4 and 20 Hz using a stoichiometric propane/oxygen mixture at room conditions of 1 atm and 20 °C. The clean configuration was used at 6.9 Hz only. Six PCB pressure transducers were used in the experiments. The data at 14.4 and 20 Hz operation were acquired simultaneously by 12 bit digitizers at 100 kHz/channel. The data were sampled with a temporal resolution of 10 μs to fill the 512 ksample memory module, but this sampling rate seriously handicapped the ability to resolve pressure peaks. Experiments at 4.4 and 6.9 Hz used 1 MHz/channel digitizers with a temporal resolution of 1 μs. In conjunction with a 2.048 Msample memory module, only 250 ms worth of data can be acquired. The large data files created were not fully analyzed. The dilemma encountered here is the need for high temporal resolution vis-a-vis limited storage and the data reduction effort.

The pressure transducers were water-cooled and recessed in the mounting ports to protect them. However, this procedure damped out the pressure peak. Previous work has suggested that the wave speed, using a time-of-flight (TOF) method, remains a good indicator of DDT, instead of relying on pressure peaks [6]. The TOF method, when used with the 1 MHz digitizers, yielded a resolution of 2 μs for velocities of 2000 m/s or an error of 5%. TOF data at 4.4 and 6.9 Hz were obtained with 1 MHz digitizers, while those at 14.4 and 20 Hz were obtained with 100 kHz digitizers.



a. 2.5 s record

b. Enlargement showing a number of consecutive pulses

Fig. 3. Pressure record of transducer 6

3 Results

The ability of the test rig to obtain repetitive cycles is shown in Fig. 3a, which shows a 2.5 s window of data, obtained a few seconds after starting the test. Note that transducer No. 6 lies within the Shchelkin spiral. The data were acquired at a sampling frequency of 100 kHz/channel due to memory constraints. This was adequate for a cycle-to-cycle repeatability experiment of relative long sampling duration. Cycle-to-cycle repeatability shows significant overpressure levels of around 14.3 atm on average, albeit lower than the Chapman–Jouguet (CJ) level. (The CJ pressure obtained from the NASA CEA code [7] is 35 atm for a stoichiometric oxygen/propane mixture at standard conditions.) The lower experimental value of peak pressure is partly due to the difficulty in resolving the peak and was also thought to be due to poor mixing. The latter difficulty will be discussed later. A narrow time window showing a number of consecutive pulses can be found in Fig. 3b. The enlargement shows that the characteristic shape of the pulses appear similar and comparable to those obtained by other investigators of single-shot detonation waves, namely, that the steep pressure rise is followed by a gentle expansion to subambient.

Sample pressure profiles obtained at 6.9 Hz are shown in Fig. 4 for a clean configuration and one with a Shchelkin spiral. The pressure profiles of the clean configuration (Fig. 4a) showed poor performance. The wave appears to accelerate and transition to a detonation profile but failed before reaching the open end. Amongst the numerous runs, not one achieved detonation within the detonation tube, with the wave in general barely reaching 30% of the CJ level. A reason for the poor performance may be poor mixing of the reactants. At 6.9 Hz, a window of about 40 ms (the time after the injection valve closed to the time of ignition) is available for mixing. The swirling disc used to enhance mixing may not be creating the desired level of turbulence to completely mix the reactants in such a short period.

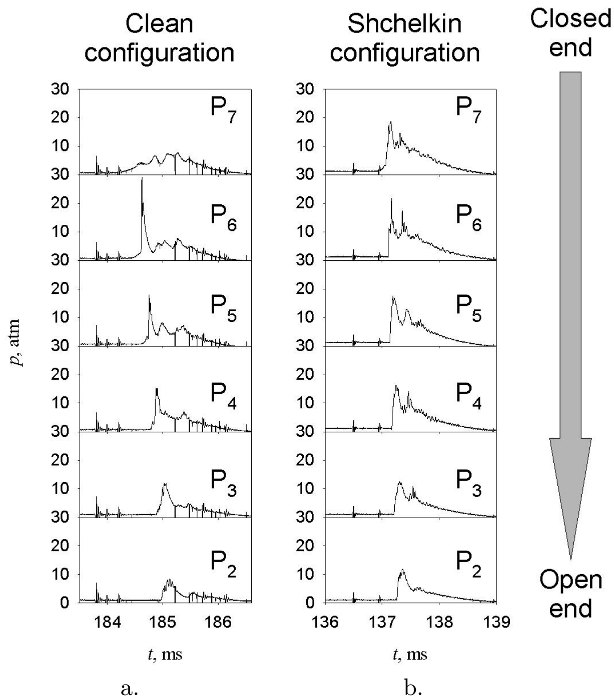


Fig. 4. Pressure profiles at 6.9 Hz cycle frequency

In comparison, the wave evolution with the Shchelkin spiral showed more promise in reducing the DDT length. In the presented results, the profiles for P4–P6 showed a distinct pressure spike characteristic of a detonation wave. While the transducers were unable to obtain the peak pressure value, the wave propagation velocity appeared to be a good indicator of DDT. The propagation velocity for different waves for the two configurations is plotted in Fig. 5. The figure shows that the clean configuration achieves a subcritical detonation that reaches about twice the sonic velocity whereas, with the Shchelkin spiral, the wave consistently reaches the CJ velocity in a short distance near the end of the spiral. This velocity lasts briefly, however.

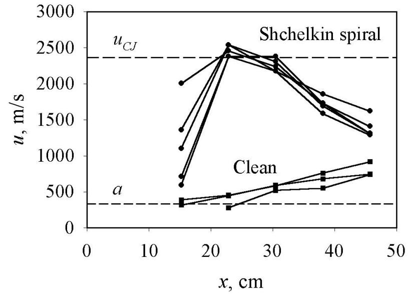


Fig. 5. Wave velocity at 6.9 Hz cycle frequency for clean and Shchelkin spiral configuration

To undersand why the experimental results did not show a sustained CJ velocity, the different cycle tests were compared. Samples of single pulses were chosen from the runs for comparison in Fig. 6. The figure shows a progressive decline in the ability to sustain a CJ velocity as the cycle frequency is increased. For example, at 4.4 Hz, the wave accelerates and maintains itself whereas at 20 Hz the wave reached only a subcritical state. It is believed that the lower frequency allowed more time for injection and mixing to provide the better performance. Figure 7 also shows that the present configuration may actually be longer than necessary for developing a compact pulsed detonation device. Given proper injection and mixing, the Shchelkin spiral configuration yields a CJ velocity in a length of about 20 cm from the closed end. Further experiments with closer transducer spacing are needed to provide a better length estimate.

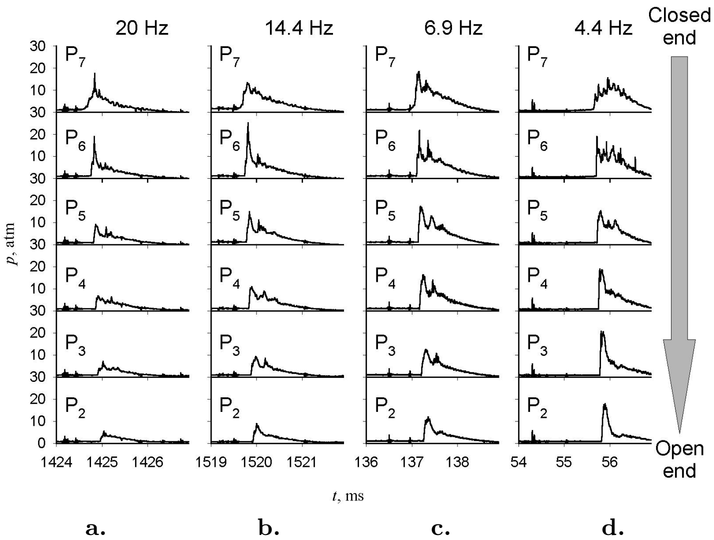


Fig. 6. Single pulse propagation comparison at various frequencies for the Shchelkin spiral configuration

4 Conclusions

Experiments were performed in a pulse detonation rocket facility using a stoichiometric propane/oxygen mixture at ambient conditions. The experiments showed that detona-

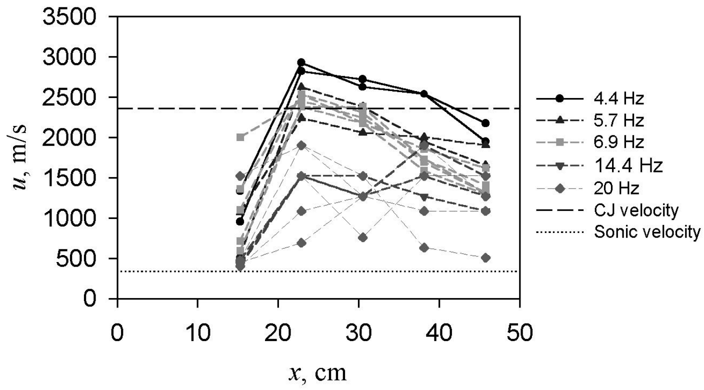


Fig. 7. Wave propagation for Shchelkin spiral configuration at various frequencies

tions could be obtained in a short distance of 11–17 cm for modest cycle frequencies of 4–7 Hz with a Shchelkin spiral installed. At higher frequencies, 14–20 Hz, only strong intermittent overpressures are observed. Each pressure profile yielded weak pre-compressions followed closely with a relatively strong overpressure peak that quickly deteriorated after passing the Shchelkin spiral. Average velocity plots are consistent with this diminishing of the wave front as velocity falls off towards the end of the chamber, never reaching the CJ level. This is possibly due to improper filling and mixing of the detonation chamber from cycle to cycle.

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