Some perspectives on pulse detonation propulsion systems

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1 Introduction

Pulse detonation engines and rockets (PDE/Rs) can potentially revolutionize airbreathing and rocket propulsion [1–6]. While the PDE concept is over five decades old, it has recently enjoyed renewed interest, due mostly to theoretical and computational studies indicating high cycle efficiencies. When modeled by a constant volume, Humphrey cycle, the detonation engine is found to be superior to that of existing constant pressure, Brayton cycles, with claims of as much as 10–40% improvement in specific impulse [4,7–9]. The constant volume process is derived from the Zeldovich–von Neumann–Döring (ZND) model of the detonation wave as a high strength shock wave, followed by a region of chemical reaction and a subsequent isentropic rarefaction. Amongst other advantages of the PDE is simplicity, where the PDE is easy to manufacture and requires few moving parts, with the possibility of eliminating high-pressure pumps in rocket applications, or reducing turbomachinery stages in air-breathing propulsion systems.

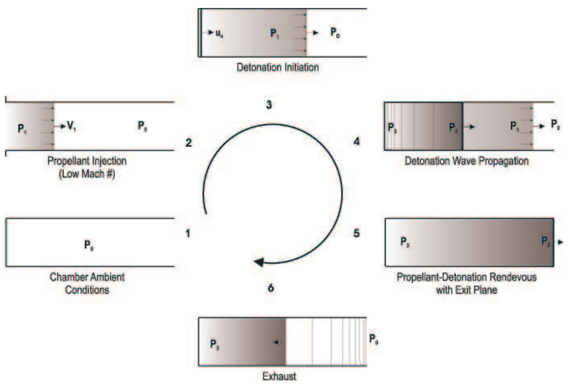


Fig. 1. Schematic of pulse detonation engine cycle

Each PDE cycle consists of several interdependent processes, namely, filling of the chamber with a fresh fuel–oxidizer mixture, detonation initiation, propagation of detonation waves and expansion of burned gases to reduce the chamber pressure to the refill level, Fig. 1. Presently, there is good understanding of the phenomenology of these processes, particularly in gases. Rapid progress has recently being made toward achieving repetitive detonations with claims of around 100 Hz.

There are various ways of incorporating pulse detonation devices into a propulsion system [10], with much interest centering on high-speed flight [11] and space access [12–14]. The military application for unmanned vehicles and missiles is of interest as well [15]. Other than the basic airbreathing PDE that relies on the inlet ram or a pulse detonation rocket that utilizes an onboard oxidizer, a combined cycle engine integrates a pulse detonation device with a ramjet or scramjet, as via an ejector. A multimode concept can be devised where a PDE and a PDR share largely the same hardware but cannot be operated simultaneously. Finally, a proposed hybrid system for commercial aviation utilizes a pulse detonation augmentor in the bypass flow of a turbofan [16]. While there are many concepts, none of these, as far as the authors are aware, have reached flight demonstration. Thus, much work remains to be done. This paper summarizes work that has been performed at the University of Texas at Arlington over the past decade.

2 Experimental techniques

Major components of the facility are a detonation chamber, a rotary valve injection system for three gas species (fuel, oxidizer and purge), an electric igniter and a gas supply system. Gaseous fuels used included hydrogen, methane and propane and oxidizers included air and oxygen. The purge gas is air. Most of the results reported here pertains to propane and oxygen. Only highlights of the experimental apparatus are provided.

2.1 Detonation chamber

The detonation engine is constructed from lengths of flanged steel pipe with inside and outside diameters of 7.62 and 15.24 cm respectively, and with lengths of 7.62, 15.24 and 30.48 cm. Rubber O-rings seal the pipe segments. Each segment can accept instrumentation, such as pressure transducers, thermocouples, heat flux gauges, or photo-detectors. The 30.48 cm sections allow for four equally spaced instrumentation ports along the tube. Sections of 15.24 cm allow two ports, and 7.62 cm sections allow one port. Another 7.62 cm section was used to support the mounting of the arc-plug igniter. A photograph of the test rig is shown in Fig. 2a. The water-cooled pressure transducers are clearly seen at the top of the tube. On the right is a mechanical valve system. In this configuration, sections were assembled to the injection end-plate to yield a total chamber length of 53.34 cm.

Direct initiation of detonation requires a large amount of energy [17] while DDT occurs at lower energies, although the latter requires excessive length for aerospace propulsion. One way of shortening the DDT length is to place obstacles in the detonation tube, such as orifices, channels or spirals. Shortening the DDT length translates to reducing the transition time, a factor that is important to obtaining high cycle frequencies [18]. Our recent approach uses a Shchelkin spiral, as shown schematically in Fig. 2b. A 20.32 cm long spiral with a 15° pitch and 9.53 mm diameter was placed in the detonation chamber. 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 compared to other DDT studies [19].

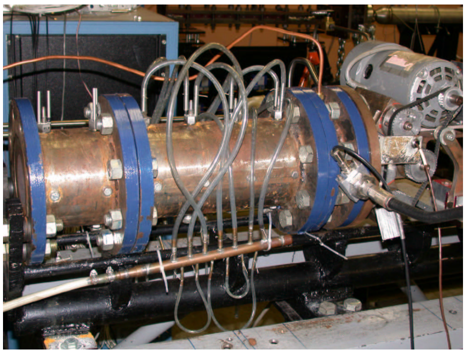
2.2 Ignition system

The Shchelkin spiral is used with an energetic, high frequency electric igniter, similar to a triggered spark gap device. Compared to other forms of energetic ignition, such as shocks, explosives and lasers, the adopted method was the most practical. Figure 3 shows the discharge energy decreasing from over 20 J at low frequencies to 5 J at 200 Hz.

3 Results and discussion

3.1 Effect of pressure

Single-shot detonations led to a practical understanding of gaseous fuel detonations in a stoichiometric oxyhydrogen mixture [20,21]. Pressure histories for the base PDE config-

a. 

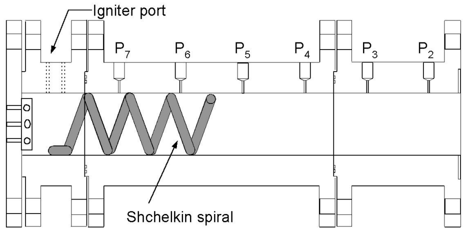
b. 

Fig. 2. Pulse detonation test rig. **a.** Photograph, flow from right to left; **b.** Schematic of detonation chamber with Shchelkin spiral

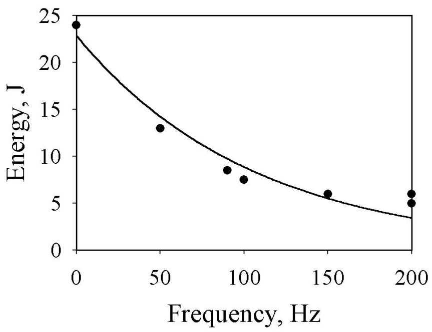


Fig. 3. Arc discharge measurements

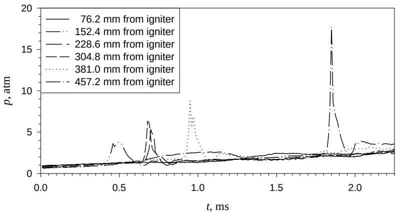
uration at initial pressures of 0.5, 1.0 and 2.0 atm are shown in Fig. 4. The corresponding wave speeds based on time-of-flight measurements are compared with theoretical Chapman–Jouguet (CJ) velocities calculated by the NASA Chemical Equilibrium Code [22] in Fig. 5. (In Fig. 5, the horizontal bars represent the spacing between the transducers.) Figure 5 shows that initial reactant pressures above 1 atm are needed to sustain a detonation wave for the configuration used.

3.2 Ignition energy and enhancement devices

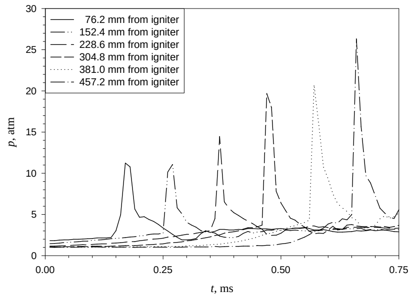
Figure 6 shows that the energy levels available produced a sub-critical CJ wave instead of a deflagration. However, this range of energy levels was insufficient to materially affect the initial detonation wave speed. Instead, Shchelkin spirals, wire rings, orifice plates, centerbodies or nozzles promoted transition, Fig. 7. Subsequent experiments were performed with Shchelkin spirals as the enhancement device of choice using a stoichiometric oxygen–propane mixture at 1 atm [23]. The results were consistent with single-shot data in that the Shchelkin spiral reduced the DDT length. A summary plot is shown in Fig. 8. The transition lengths for oxyhydrogen and oxygen–propane mixtures with Shchelkin spiral are comparable at around 20 cm and appear feasible for practical use.

3.3 Nozzle

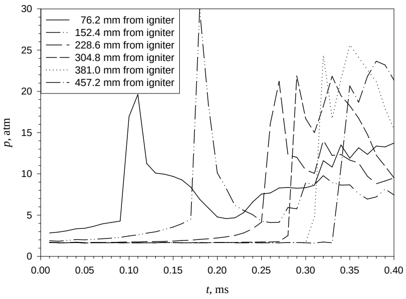
The effect of a nozzle on detonations in a stoichiometric propane–oxygen mixtures at 1 atm are shown in a single-shot result in Fig. 9. A higher wave speed was obtained for the



a. 0.5 atm



b. 1 atm



c. 2 atm ←

Fig. 4. Pressure traces for a stoichiometric H_2/O_2 mixture in 76.2 mm diameter tube at different initial pressures

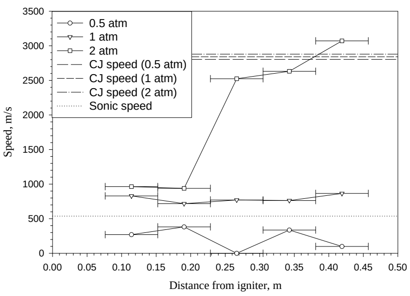


Fig. 5. Wave velocities for a stoichiometric H_2/O_2 mixture at different initial pressures.

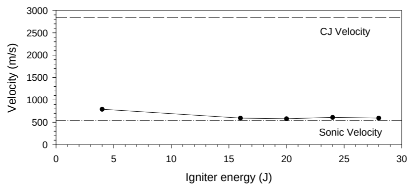


Fig. 6. Wave speed for different ignition energies for a stoichiometric H_2/O_2 mixture at 1 atm (single-shot experiment).

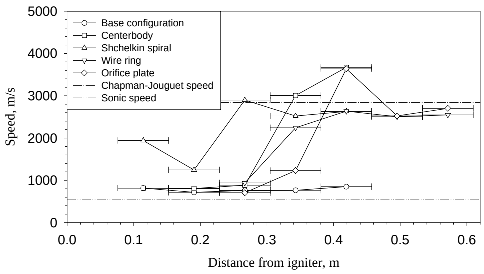


Fig. 7. Effect of enhancement devices on wave velocity for stoichiometric H_2/O_2 mixtures at an initial pressure of one atm (single-shot experiment)

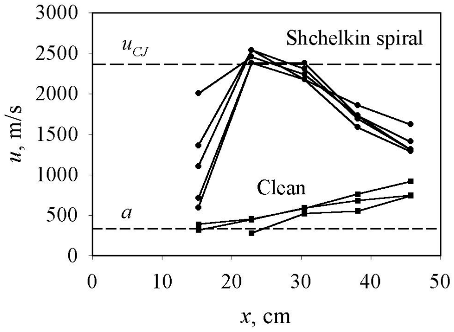


Fig. 8. Wave velocity at 6.9 Hz cycle frequency for clean and Shchelkin spiral configuration (stoichiometric oxygen–propane mixture at 1 atm initial conditions

annular configurations. The nozzle appeared to improve performance in that, with the exception of the cylindrical configuration with the 14.24° nozzle, the wave speed did not fall off near the exit as it did for the configurations without the nozzle. Figure 10 shows pressures near the nozzle exit for one complete blowdown cycle for the cylindrical and annular configurations. The traces are similar, and although the nozzle appeared to have a beneficial effect in reducing DDT distance, the nozzle does not appear to significantly affect the blowdown process. The chamber pressure equilibrated to atmospheric in 18–20 ms in both cases.

A numerical method [24] was used to simulate the detonation of stoichiometric oxyhydrogen, initially at standard conditions, along a tube with and without a simple convergent-divergent nozzle. Figure 11a shows the wave propagation to the right under an ambient pressure of 1 atm. The wavefront barely reaches halfway down the tube 1.6 ms after initiation. However, Fig. 11b shows that the wave would have exited the tube at about 1.2 ms when the ambient pressure is 0.1 atm. Figure 12 shows that a convergent-divergent nozzle at the exit of the tube slows the wave arising from the pressure buildup. The results suggest that a variable geometry nozzle may be needed to produce an appropriate level of back pressure.

4 Single-path multimode pulse detonation propulsion concept

The above summary of experimental and numerical studies into pulse detonation led to the conceptual design of a PDR-based multi-mode, single flow path propulsion system [25–27]. The various modes, as depicted schematically in Fig. 13 are

1. An ejector-augmented PDR for take off to moderate supersonic Mach numbers
2. A pulsed normal detonation wave mode at combustion chamber Mach number $M_{cc} < M_{CJ}$
3. An oblique detonation wave mode of operation when $M_{cc} > M_{CJ}$
4. A pure PDR mode of operation at high altitude.

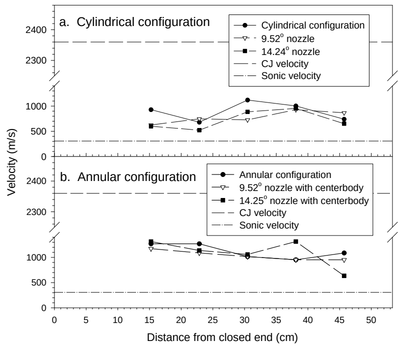


Fig. 9. Effect of nozzle on detonation wave propagation in a stoichiometric propane-oxygen mixture at 1 atm initial pressure (single-shot without Shchelkin spiral)

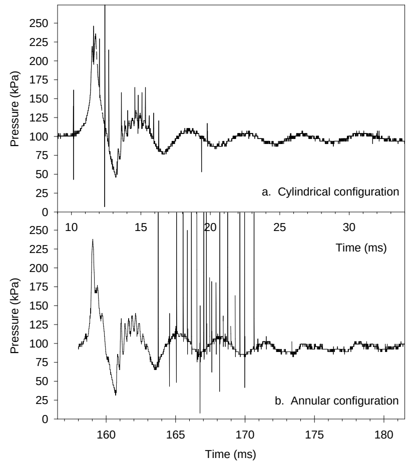
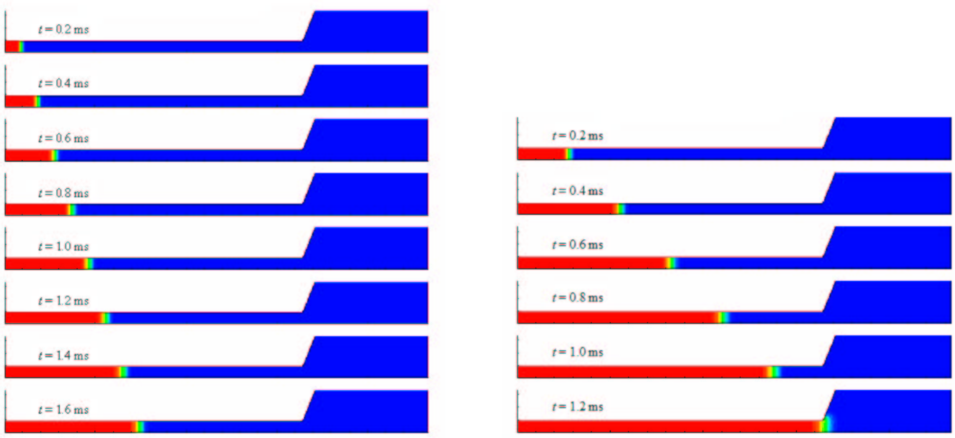


Fig. 10. Pressure traces near nozzle exit (single-shot experiment with stoichiometric oxygen–propane mixture at 1 atm initial conditions without Shchelkin spiral)



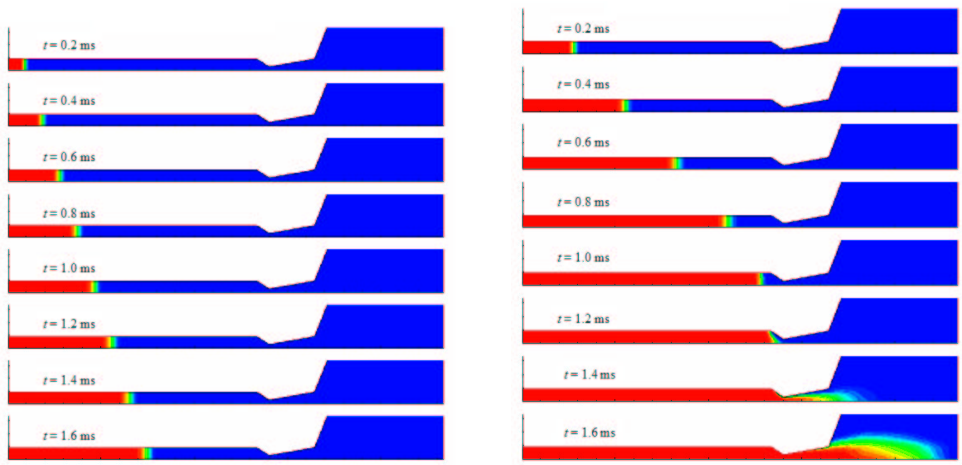
a. Ambient pressure = 1 atm

b. Ambient pressure = 0.1 atm

Fig. 11. Hydrogen concentration plots of wave propagation in a straight tube filled initially with a stoichiometric oxyhydrogen mixture at standard conditions

4.1 Mode 1: ejector augmented pulsed detonation rocket

The ejector augmented PDR has the ability of enhancing thrust and specific impulse at low speeds beyond that provided by conventional rockets, by adding momentum due to the increased air entrainment [28], as opposed to steady-state devices based on ejector rockets [29,30]. Preliminary estimates of thrust enhancements due to a pulsed core flow were reported in [26]. The specific impulse of the ejector augmented PDR was approximately 100% higher than that of a steady-state device of the same dimensions.



a. Ambient pressure = 1 atm   **b.** Ambient pressure = 0.1 atm

Fig. 12. Hydrogen concentration plots of wave propagation in a tube with a convergent-divergent nozzle filled initially with a stoichiometric oxyhydrogen mixture at standard conditions

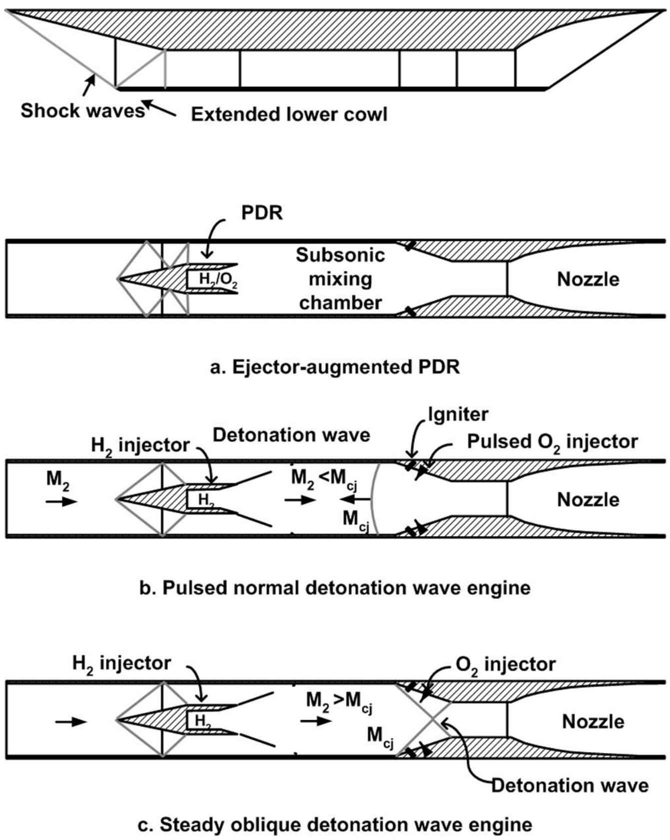


Fig. 13. A single-path, multimode pulse detonation propulsion concept

4.2 Mode 2: upstream traveling detonation wave engine

This mode is a crucial part of the present design. In this mode, fuel is injected in a pulsating manner in a supersonic combustion chamber flow upstream of a wedge to support a detonation wave expanding upstream and downstream. An example of this complicated unsteady flow process is shown in Fig. 14 where the chamber flow of stoichiometric oxy-hydrogen ahead of the wedge is at Mach 3. Detonation is initiated at the leading edge of this region. The detonation wave progresses upstream, as shown in the figure, until the fuel is consumed. At this point, the wave recedes and is eventually exhausted from the nozzle. The residence time of the detonation wave within the combustion chamber determines the usable frequencies of this mode. The frequency increases with M_{cc}. Moreover, apart from the Mach number limit in the combustion chamber, the flow temperature is limited to prevent premature ignition. This temperature requirement restricts M_{cc} to about 5–6 based on a typical scramjet trajectory.

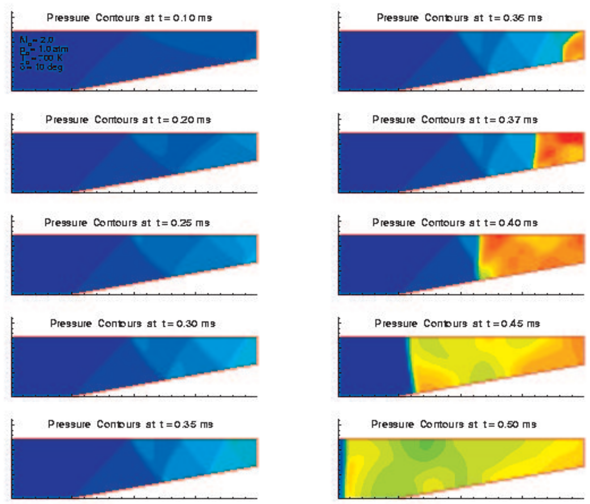


Fig. 14. Pressure contours showing shock initiation of unsteady detonation at low supersonic Mach numbers (flow from left to right)

4.3 Mode 3: oblique detonation wave engine

Once $M_{cc} = M_{CJ}$, the upstream propagating detonation wave becomes a standing wave and a steady mode of operation is established. When $M_{cc} > M_{CJ}$, the normal detonation wave transitions to a standing oblique wave that can be stabilized by a ramp at an appropriate angle to the flow. Prerequisites are that the fuel and air are mixed to near stoichiometric ratio, and that the condition for the instability of shock waves at the design ramp angle and Mach number be satisfied at one of the reflected shocks. This condition is given approximately by

$$q/(C_pT) > \left[\left(M_{N1}^2 - 1\right)^2\right] \Big/ \left[2\left(\gamma+1\right)M_{N1}^2\right]$$

where q is the heat release during the chemical reaction, M_{N1} is the incoming Mach number normal to the shock, γ is the ratio of specific heats of the mixture, C_p is the specific heat at constant pressure and T is the incoming flow static temperature.

4.4 Mode 4: pure pulsed detonation rocket

A pure PDR is used in the upper atmosphere. Multiple PDRs are operated so as to provide a smooth transfer of thrust to the flight vehicle. The challenges in the pure rocket mode center around the demands of high altitude operation of Mode 4. High pressure filling of a detonation tube may requires the use of end valves or other mechanisms to prevent losses. Beneficial effects of convergent-divergent nozzles fitted to the end of the detonation tube have been observed computationally, as discussed above.

5 Conclusions

Experimental and numerical studies on the development of pulsed detonation propulsion systems were reviewed. The review emphasized the gasdynamics aspects of such systems. The review showed that extremely complex unsteady interactions between physics and chemistry exist, not all of which have been well understood. Progress toward reducing the DDT length through a combination of Shchelkin spiral, high ignition energy and optimizing the detonation tube dimensions was discussed. The experimental studies were complemented by numerical studies that led to the design of a multi-mode, single-path detonation-based propulsion system for space access.

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