

# Development of a Large Pulse Detonation Engine Demonstrator

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A test facility was designed and constructed to study pulse detonation engine (PDE) operations under a broad range of test parameters and to test and refine various subsystems and processes that are critical for a flight-weight PDE. The PDE combustor was designed to run on most common fuels, including kerosene, propane and hydrogen, with air or oxygen. A new ignition system was also built that features multiple low energy igniters located at the head manifold section of the engine, creating an impinging shock ignition when fired simultaneously. Instead of a separate initiator, an energetic mixture can be introduced in the ignition section to facilitate deflagration-to-detonation transition. The main sections of the combustor were fitted with fully enclosed water cooling passages. Kerosene fuel was preheated before mixing with preheated air in a mixing chamber. The fuel-air mixture and the purge air were injected into the engine at appropriate stages of the engine cycle using dual rotary valves, each having nine parallel ports. The fluid was injected into the combustor through ports located along the wall of the engine. The rotary valves were driven directly by a stepper motor. A pair of orifice plates were located downstream of the ignition zone for inducing deflagration-to-detonation transition. Dynamic pressure transducers and ion detectors were used for combustion diagnostics within the combustor. The various components of the engine were controlled via a data acquisition system, which was also used for monitoring the engine processes and for recording data.

## I. Introduction

DETONATION-based engines such as pulsed detonation engines (PDEs) have been proposed for revolutionary propulsion systems for a variety of aerospace vehicles and has seen intense activity over the past twenty-odd years.<sup>1,2</sup> Some of the potential advantages of a PDE include the higher thermodynamic efficiency of detonations compared to deflagrations, simplicity of manufacture and operation, a reduction of moving parts, operability over a broad speed range and flexibility in mounting on different platforms. A variety of configurations have been proposed but few of these have been demonstrated if at all.

Probably the main reason for the lack of practical examples is the difficulty in detonating the reactants which has remained the primary focus of much of the research and development effort. Since direct initiation of detonations requires a prohibitive amount of energy, these studies have generally focused on energy deposition of  $\mathcal{O}(0.1-1)$  J to achieve deflagration-to-detonation transition (DDT) in as short a distance as possible as this parameter affects the overall size and weight of the engine. Inroads have been made in developing an engineering understanding of DDT to the extent that there is sufficient confidence in detonating

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gaseous fuels with oxygen in a tube less than 1 m long. Many of these development efforts have been undertaken at the authors' laboratory, including ignition, pumping, data acquisition, thermal management, measurement techniques and systems integration into practical devices.<sup>3-5</sup>

An airbreathing engine capable of utilizing liquid fuels is of utmost importance in a number of applications and has been the subject of intense interest worldwide.<sup>6-16</sup> Liquid hydrocarbon (LHC) fuels have many advantages over gaseous fuels, such as high energy density, storability, portability and safety. However, LHCs are far more difficult to detonate than hydrogen or gaseous hydrocarbons, a problem compounded by using air instead of oxygen as oxidizer. The main governing parameter in determining detonability is the so-called detonation cell size  $\lambda$  which is large, of the order of cm, compared to mm for gaseous fuels in oxygen. A conclusion that can be drawn from the citations above is that the difficulty in detonating liquid fuels translates into a long DDT distance of  $\mathcal{O}(1)$  m. In addition, LHCs require a large amount of energy to ignite, even for such DDT lengths. Thus, much effort has been expended in methods to enhance detonability. These methods include

- DDT devices, similar to those used for gaseous fuels, such as Shchelkin spirals and orifice plates
- Flash vaporization which enables the advantage of easier detonation of a gaseous fuels to be exploited<sup>17</sup>
- Doping with free radicals by plasmas<sup>18-22</sup>
- High energy ignition
- Imploding shock to trigger the detonation<sup>23,24</sup>
- Predetonator where an energetic detonator, typically a gaseous fuel and oxygen mixture, is used to trigger detonation in the LHC/air mixture.<sup>10</sup>

All of the abovementioned methods have been demonstrated in single-shot experiments with energetic mixtures of oxygen and hydrogen or ethylene. Integrating them into a practical system is not a straightforward matter. The challenge is the careful integration with other critical aspects to ensure that the entire PDE cycle operates smoothly. Typical studies which have focused on ignition and DDT have not considered these critical aspects such as fuel/oxidizer mixing, injection and purging. Control of these processes is also not well addressed.

A conceptual approach to operating a PDE is shown in Fig. 1. A tube, closed at one end initially at ambient conditions (1) is filled with a reactive gaseous mixture from the closed end (2). As the reactants approach the exit, the igniter is activated in (3), from the closed end, thereby propagating a detonation wave. The detonation wave travels rapidly through the reactive mixture in (4) and exits the tube in (5). An exhaust stage occurs in (6) when an unsteady expansion travels into the tube. This expansion helps to cool and scavenge the tube but experience shows these may be inadequate to allow good mixing or prevent autoignition of the subsequent charge. Thus, the figure shows purge air being introduced into the detonation chamber. The cycle then repeats itself.

The cyclic operation of a PDE requires consideration of length and time scales. The entire cycle described above can be labeled a *unit process*<sup>25</sup> which can be conveniently displayed in a displacement-time diagram as shown in Fig. 2. This figure shows a unit process that is slightly different from that depicted in Fig. 1. For example, the ignition does not produce a detonation wave right away but shows a DDT. Further, the figure shows the purge process to occur after the exit of the detonation wave. On the other hand, one can envisage a purge process to be initiated earlier so that the purge air reaches the exit of the detonation chamber at the same time as the detonation wave.

From Fig. 2, the total time of the unit process is given simply by

$$t_{cyc} = t_{fill} + t_{ign+det} + t_{prop} + t_{purge} \quad (1)$$

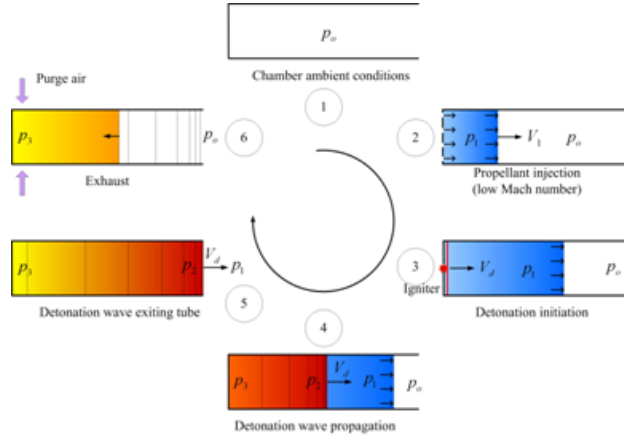


Figure 1. Stages in the operation of a pulse detonation engine.

where the subscripts *cyc*, *fill*, *ign+det*, *prop* and *purge* denote cycle, fill, ignition and detonation, wave propagation, and purge and exhaust respectively. The cycle frequency is therefore

$$f = 1/t_{cyc} \quad (2)$$

The ignition and detonation times are negligibly small compared to the other processes, as indicated in the figure. While Fig. 2 is not drawn to scale, it is obvious that other than the challenge of ensuring rapid DDT, high-frequency operation entails shortening the fill and purge events.

Following the development of a series of small PDEs, the development of a large PDE demonstrator was undertaken. The demonstrator was designed to serve as a testbed of various technologies. This paper describes the development of this large engine demonstrator. A companion paper describes the initial testing and further lessons learned.<sup>26</sup>

## II. Design Considerations

The requirements for the liquid-fueled PDE ground demonstrator are listed in Table 1. The overall approach is to develop and integrate various subsystems into a ground demonstrator. In the following subsections, a number of important issues and approaches in overcoming them are described.

### A. Liquid Fuel Detonation

The most critical of the items in Table 1 is the ability to detonate the fuel. Detonating liquid fuels rapidly and consistently proves to be a tricky problem<sup>6,10,13,27,28</sup> despite research into the detonation of liquid fuel droplets that has spanned over 50 years.<sup>29,30</sup> The primary difficulty for PDE applications is that extra time is required for liquid fuels in atomization and vitiation,<sup>31,32</sup> these processes potentially adding to the two most time-consuming portions of the PDE cycle, namely, the fill and the purge. Other problems include large initiation energy, longer ignition time than for gaseous fuels,<sup>33-38</sup> and a lengthy deflagration-to-detonation transition if the initiation energy is not high enough for direct initiation.

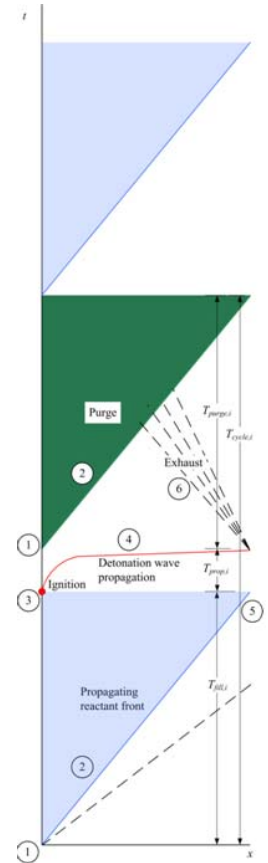


Figure 2. Wave diagram of a nonideal unit process for a pulse detonation engine.

**Table 1. Requirements for airbreathing liquid-fueled PDE ground demonstrator.**

Requirement	Purpose	Implementation
a. Liquid fuel	Operational requirement	Pressurized feed system; kerosene due to ready availability
b. Fuel atomization	Mixing with air	} Heated secondary mixing chamber(s), } high pressure diesel injectors
c. Fuel vitiation	Vaporize fuel	
d. Air	Simulate air breather	Compressed air; detonation tube sufficiently large to accommodate detonation cell size
e. Fuel-air mixture injection	Deliver reactants into detonation tube	Gas injectors
f. Rapid detonation	High frequency operation; short tube	Energetic ignition system; DDT devices
g. Cooling	Long duration	Pressurized water cooling jackets
h. Thrust	Performance	Load cell
i. Flow rates	Performance	Flow meters
j. Wave front measurement	Performance	Pressure transducers, ionization gauges, photodetectors, high-speed DAQ
k. Heating	Performance	Heat transfer gauges, thermocouples

Some studies into different techniques for using liquid fuels in a PDE include Refs. [6, 7, 9, 10, 13, 16, 39–43]. Recent ideas to overcome the difficulties in detonating liquid fuels make use of flash vaporization. The principle is to carry liquid fuel with its advantages of storability, high density and so forth, but to introduce the fuel as a vapor into the detonation tube. Flash vaporization appears to be successful for avoiding the difficulties of long ignition time and high ignition energy associated with liquid fuels.<sup>8, 11, 17, 44, 45</sup> An alternative approach involving catalytic or thermal cracking of liquid hydrocarbons<sup>14, 46–48</sup> was considered to be unnecessarily complicated.

The AFRL approach to pressurize and heat the liquid fuel prior to mixing with air is worth further study. This approach has the benefit of thermal management<sup>49</sup> and is considered here. The proposed approach independently heats the incoming air and the liquid fuel with the latter heated below its boiling point. Flash vaporization is then accomplished by injecting the liquid fuel into the hot air.

The discussion above assumes good mixing of fuel and air which is a challenging problem in itself and which is important for any combustion process. For detonations, fortunately, the “detonation bucket,” that is, the range of equivalence ratios for minimum initiation energy is quite broad [50, p. 360.] In other words, so long as the mixture is close to stoichiometric, it can be detonated with approximately the same amount of energy. Slightly uneven mixing may also be acceptable. However, since the initiation energy increases (rapidly for some mixtures), it is crucial to have the reactants to be as close to stoichiometric as possible.

## B. Ignition and DDT

High-frequency and reliable detonation requires the implementation of a number of techniques. Our previous studies indicate that the Shchelkin spiral remains the best candidate for reducing the DDT distance.<sup>3, 4</sup> However, the Shchelkin spiral may be prone to destruction from the high heat load. Thus, our proposed approach is to use orifice plates instead since these can be readily fabricated with internal cooling passages. The orifice plates also create wave reflections between themselves and with the closed end of the detonation tube. The reflections have been shown to shorten the DDT distance.<sup>51</sup>

It is also known that DDT is reduced with an increase in the ignition energy, short of the level required

for direct initiation. Our experience has shown that a high energy of over 1 J is desirable despite claims of detonation initiation with 50–500 mJ automotive spark plugs when the tradeoffs between DDT length, initiation energy and fuel/oxidizer type are considered. However, experience has also shown that high energy tends to wear away or even destroy the electrodes.<sup>5</sup> An approach that can impart adequate energy without destroying the igniters is to array them inward around the circumference of the detonation tube. In this way, the total energy delivered remains high. In addition, by arranging the igniters around the circumference of the detonation tube, a toroidal imploding wave is set up that can facilitate detonation.<sup>23,24,52</sup>

Plasma-assisted ignition and combustion concepts<sup>53</sup> have recently become popular for application to coal, alternate fuels, biofuels, heavy hydrocarbons<sup>22,54,55</sup> and scramjets.<sup>56,57</sup> These concepts have also been explored for reducing the ignition energy and DDT.<sup>58,59</sup> To further reduce ignition time and to promote DDT, we propose to incorporate plasma-assisted concepts. Incorporating a plasma source upstream of the ignition to provide free radicals is also a strategy that can be implemented to ensure reliable and consistent ignition.<sup>18,19,21,22</sup> Finally, instead of an explicit predetonator,<sup>10,20</sup> it may be possible to provide an enriched region in the igniter section.

### C. Tube Sizing

The diameter of the detonation tube is dictated by the detonation cell width  $\lambda$ , see Table 2. A convenient rule for the diameter required for successful detonation is that the tube diameter<sup>60</sup>

$$D > \lambda/\pi \quad (3)$$

Based on this consideration, the minimum tube diameter for the fuels of interest is about 20 mm (0.8 in.) for air operation.

Another criterion to be considered in sizing the tube is the thrust to be developed. A simple scaling law relates the PDE thrust to the frequency, cross-sectional area of the tube, number of tubes, initial pressure and the nozzle performance, namely,

$$T \sim pfAN \quad (4)$$

where  $p$  = initial pressure,  $f$  = frequency,  $A$  = cross-sectional area and  $N$  = number of tubes. Previous UTA tests yielded a 88 N (20 lbf) thrust using a tube with a 25 mm (1 in.) bore, operating at 10 Hz and using a stoichiometric propane/oxygen mixture initially at STP. Thus, for a 2.22 kN (500 lbf) requirement, a 100 mm (4 in.) tube is specified, in addition to increasing the operating frequency.

Other than specifying the diameter of the tube, the length of the tube also needs to be specified. Based on numerous studies on DDT of fuel/air mixtures, for example Ref. [28] on LHC/air detonation, a length of 1 m appears to be more than sufficient for the present.

### D. Fill and Purge

As mentioned in Section II.A and as depicted in Fig. 2, the two longest processes in the PDE cycle are the fill and the purge. The general practice in the past is to pump in the reactants or the purge air from the closed end, as shown schematically in Fig. 1. Given that the reactants enter the tube at  $\mathcal{O}(50)$  m/s, the time required to fill a 1 m long tube with reactants or to purge it will each take  $\mathcal{O}(20)$  ms if fed from the closed end. In other words, the cycle frequency is limited to 25 Hz at most. Higher flow rates may be feasible with high-pressure feed which adds to the pumping requirements and to flow losses.

Any other process such as mixing of the reactants and, for liquid fuels, any time required for vitiation and atomization time, only compounds the long filling time. Strategies to avoid additional time required for these two processes include premixing the reactants outside of the detonation tube, thereby delivering a detonable mixture directly, and to atomize the liquid fuel in the premixing process. The atomization process can be facilitated by heating the air and the fuel to flash vaporize the latter.<sup>17</sup> Introducing a vaporized liquid fuel also can potentially avoid difficulties encountered with direct injection.<sup>43</sup>

To overcome the slow, endwall fill process, sidewall injection is proposed. In this approach, a number of ports along the side of the tube are used to fill it with the premix and another set of ports diametrically opposite is used to purge. Each port has a pattern of nozzles to spread the appropriate gases into the detonation tube, with the pattern chosen to ensure that the tube is properly filled or purged.

Turning to purging, strictly speaking, it is an undesirable process. First, it requires additional components that add weight and volume. Secondly, it reduces the propulsive performance of the engine. However, experience has shown that the hot exhaust gases in the detonation tube may cause auto-ignition of the fresh reactants. This is such a critical issue that the complexity and performance penalty of purging is considered acceptable at present. Just as for filling, the purge time can be reduced by using sidewall ports. However, unlike filling, the purge time can be shortened so long as the detonation chamber is sufficiently cooled. Moreover, purging can commence even before the detonation wave exits the tube to further shorten this process.

### E. Thermal Stability and Cooling

Estimates of heat fluxes range from 0.6–2.5 MW/m<sup>2</sup>.<sup>62</sup> Hoke et al.<sup>63</sup> found that thermal equilibrium is reached in about 2 min. with an exhaust temperature of 815 °C (1500 °F), as was also observed by Panicker et al.<sup>5</sup> Long-duration PDE operation therefore requires that the detonation tube be actively cooled. This consideration is in addition to preventing auto-ignition and is to ensure survivability of the engine.

Another thermal stability consideration is auto-ignition of the reactants. A rule of thumb for auto-ignition is a temperature threshold of 700 K (1290 °F). With post-detonation temperatures exceeding 1000 K (1830 °F), there is every likelihood that a fresh mixture will auto-ignite deflagratively. Purging the detonation tube with a cool, inert gas such as air appears to be the best strategy for preventing auto-ignition as highlighted above.

### F. Controllability

Thus far, there are no known reports that addresses the control of PDEs. Nonetheless, various control strategies can be conceptualized, some bearing similarity to the automobile engine with its cyclic processes. For the proposed engine demonstrator, control is partly by computer and partly manual. This method ensures the focus is placed on the engine demonstrator development. Computer control is LabVIEW based and is driven off an encoder on one of the rotary valves.

**Table 2. Detonation cell widths for stoichiometric fuel/oxygen mixtures, adapted from [61].**

Fuel	$p$ , kPa	$T$ , K	$\lambda$ , mm
<i>Fuel/oxygen</i>			
Hydrogen (H <sub>2</sub> )	100	293	1.3
Methane (CH <sub>4</sub> )	100.3	293	4.5
Ethylene (C <sub>2</sub> H <sub>4</sub> )	50	293	0.8
Propane (C <sub>3</sub> H <sub>8</sub> )	50	293	2.5
Hexane (C <sub>6</sub> H <sub>14</sub> )	40	295	1.7
JP-10 (C <sub>10</sub> H <sub>16</sub> )	50	353	2
<i>Fuel/air</i>			
Hydrogen (H <sub>2</sub> )	100	295	10.9
Methane (CH <sub>4</sub> )	100	295	280
Acetylene (C <sub>2</sub> H <sub>2</sub> )	100	295	9
Ethylene (C <sub>2</sub> H <sub>4</sub> )	100	295	22.8
Propane (C <sub>3</sub> H <sub>8</sub> )	100	293	51.3
Benzene (C <sub>6</sub> H <sub>6</sub> )	100	373	126
Hexane (C <sub>6</sub> H <sub>14</sub> )	100	295	51.1
Octane (C <sub>8</sub> H <sub>18</sub> )	100	373	43
JP-10 (C <sub>10</sub> H <sub>16</sub> )	100	373	60.4
JP-10 (C <sub>10</sub> H <sub>16</sub> )	100	408	47
JP-10 (C <sub>10</sub> H <sub>16</sub> )	200	408	45
Decane (C <sub>10</sub> H <sub>22</sub> )	100	373	45
Jet A	100	373	42
JP-4	100	373	42

### III. Description

The conceptual design requires all of the challenges discussed above to be addressed adequately. The main features of the PDE design are mentioned below. The design of the PDE and associated equipment is done with the following points in mind:

- Modularity for ease of assembly and disassembly for inspection, repair or replacement
- Parts conform to industry standards to maximize the use of off-the-shelf components

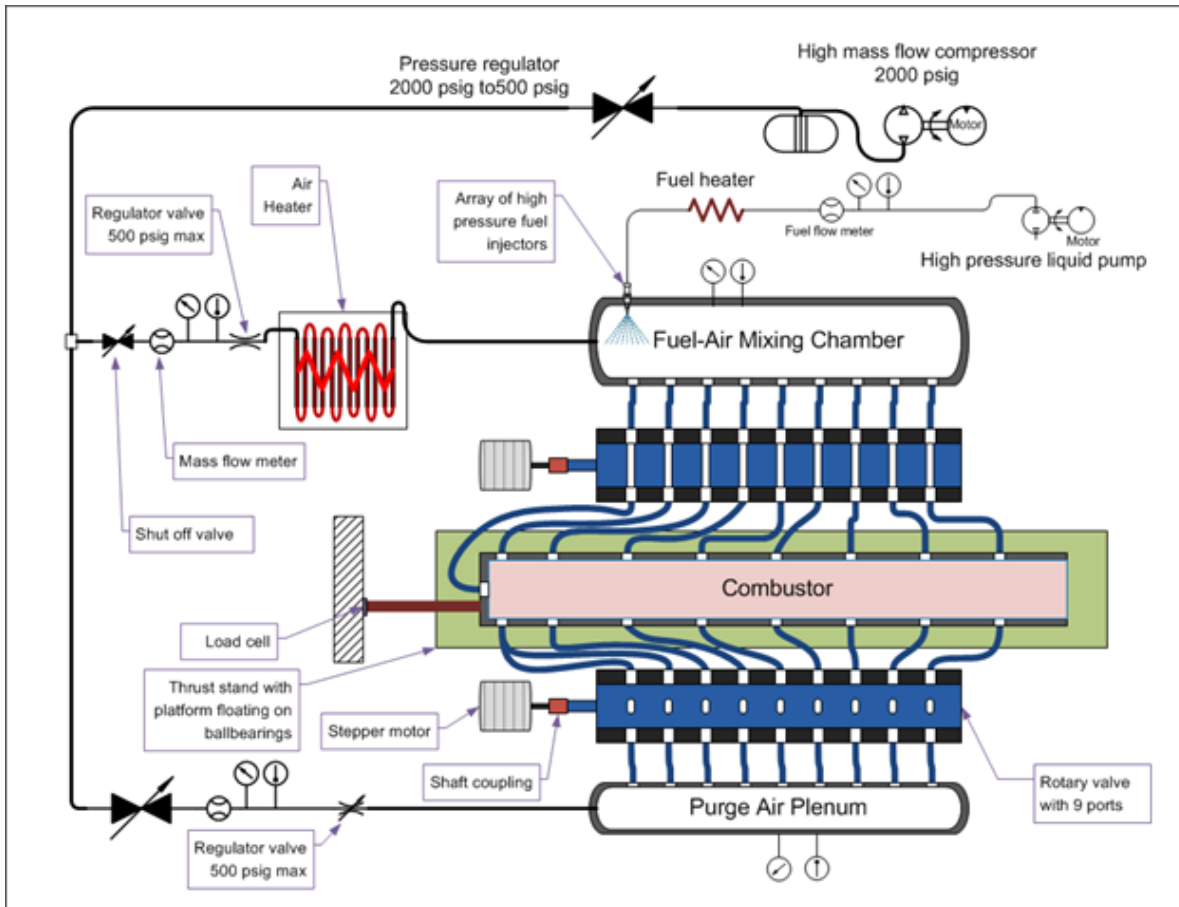


Figure 3. Schematic of the PDE test facility.

The PDE demonstrator facility is shown schematically in Fig. 3. The key component is the 1 m (40 in.) long detonation tube with an internal diameter of 101.6 mm (4 in.). This diameter, based on Eq. (3), is more than enough to accommodate the detonation cell size requirements of most of the hydrocarbon/air mixtures of interest. For design purposes, the operating frequency of the PDE ground demonstrator is set to 20 Hz. Fuel and air are delivered by means of two different valve systems. Fuel is injected using high-pressure diesel injectors while the fuel-air mixture and the purge air are delivered by means of rotary valve systems.

Air from a compressor at 14 MPa (2000 psi) is used for the ground demonstrator in lieu of an actual air induction system. The air entering the upper branch is heated. The liquid fuel is preheated and then injected into the hot air. This flash vaporization system was chosen to ensure that only gaseous fuel enters

the detonation chamber, thereby avoiding the difficulties of detonating a liquid fuel directly. The gaseous fuel/air mixture at about 2 atm is then fed through ports along the side of the detonation chamber. These ports are opened and closed by a rotating shaft, the so-called rotary valve system. After detonation, purge air from the lower branch is introduced into the detonation chamber by a similar rotary valve system. This air is used to scavenge and cool the chamber.

### A. Detonation Tube

The detonation tube, called combustor for short, has an internal diameter of 101.6 mm (4 in.) and an internal length of about 1 m (exactly 40 in.). This diameter is sufficiently large to accommodate the anticipated detonation cell size of hydrocarbon/air mixtures. Based on Eq. (4), such a tube is expected to develop 1.4 kN (320 lbf) of thrust using propane/oxygen operating at 10 Hz. Given that the thrust levels will be lower for a LHC/air mixture, the target thrust level of 2.2 kN (500 lbf) can be obtained by operating the engine at higher frequency, which is set to 20 Hz. All major sections are made of carbon steel with provision for eye bolts to help with the assembly.

A photograph of the combustor mounted on its thrust table is shown in Fig. 4. The major components of the combustor are the head manifold, shown without the end flange, the DDT section and the blowdown section. The large openings at the sides of the combustor are for introducing premixed reactants (partly hidden from view) and purge air.

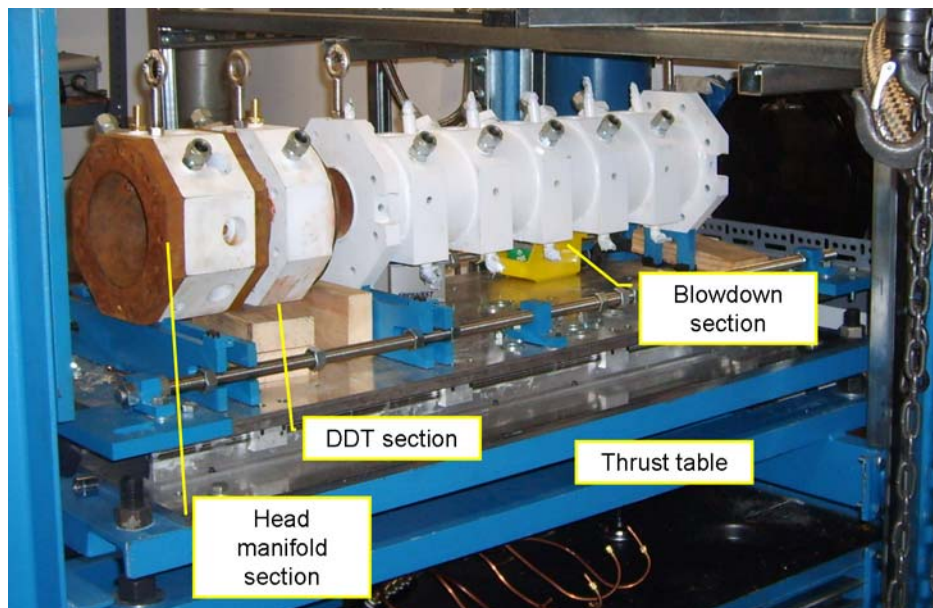


Figure 4. PDE combustor mounted on thrust table prior to final assembly.

The head manifold, as shown to the left in Fig. 4, has an octagonal cross-section, with each side being 101.6 mm (4 in.) wide, giving it an outer diameter of 238.8 mm (9.4 in.). It houses the primary ignition system consisting of eight standard automotive spark plug ports. The head manifold has a port for the fuel/air mixture and another for the purge air, visible at the top in the figure. The back end of the head manifold is sealed by an end flange which has eight ports for corona electrodes. The internal geometry of the head manifold is designed such that it has a large cavity to hold the corona electrodes and the spark plugs followed by a smaller diameter chamber that attaches to the rest of the combustor. Thus, the electrodes and the spark plugs are protected from shocks or detonation waves that emanate upstream from the detonation chamber. The head manifold has internal watercooling channels with an inlet and an outlet. The fuel/air



mixture injection port has a small perforated plate attached to its opening that allows the incoming fluid to be dispersed in multiple directions, thereby enabling the combustor to be uniformly filled with reactant.

The DDT section also has a similar octagonal cross-section as the head manifold, allowing them to be mated seamlessly together. The DDT section has an internal diameter of 101.6 mm (4 in.) and a length of 76.2 mm (3 in.). It is also internally water cooled by means of water channels. The DDT section holds an orifice plate at either end. The orifice plate at the upstream end has a 75 percent blockage ratio, while the downstream plate can have a blockage ratio from 0–75 percent. A 76.2 mm (3 in.) long Shchelkin spiral can be inserted into the DDT section by clamping against the orifice plates but was not implemented during initial testing. The orifice plates are copper-plated disks with internal watercooling passages.

The blowdown section is 736.6 mm (29 in.) long, also with octagonal flanges at either end with the same cross-sectional dimensions as the head manifold, thereby allowing the blowdown section to be bolted onto the DDT section. The large end-flanges can be used for ports for pressure transducers and other sensors, such as heat flux gauges, optical transducers, etc. The blowdown section also has four smaller flanges, spaced equidistant from each other, that have ports for housing transducers and for fluid delivery. The blowdown section is made of stainless steel with a copper paint applied to the outside. A jacket encloses the blowdown section to form a tube-in-tube heat exchanger.

## B. Rotary Valve Systems

The PDE demonstrator features two independently operated rotary valve systems, one for delivering the fuel/air mixture and the other for delivering purge air to the combustion chamber. These valve systems will prove to be the most troublesome components. The rotary valve housing and the rotors are made of steel. The rotor is driven by stepper motors. The design has nine ports. Each port has a 25.4 mm (1 in.) orifice, for housing 3/4-in. female NPT fittings. The rotary valve system is shown in Fig. 5 being bench tested with an electric motor. The figure shows the valve to have nine ports although only eight were used. Of the eight ports, seven are connected to the side of the combustor and one is connected to the head manifold. Note that the ports are elongated and this will be discussed later.

In the actual engine demonstrator, the rotary valves are driven by stepper motors which allow them to be computer controlled. As an added safety feature, a pneumatically operated, master shutoff valve, with additional spring return, is available. The shutoff valve for the fuel/air delivery system is normally shut while that for the purge air is normally open. Thus, if there is an unexpected flame out or if there is an electrical failure, the fuel/air valves will be shut while the purge air will be open, allowing the combustor to be scavenged. The rotor itself is sealed to the housing by a pair of graphite rods on each side of the housing and by rotary seals at the end.



Figure 5. Rotary valve being bench tested.

## C. Air Delivery System

The fuel/air mixture and the purge air are delivered by means of two different valve systems. Fuel is injected using high-pressure diesel injectors while the fuel/air mixture and the purge air are delivered by means of rotary valve systems (described in Section IIB).

Figure 6 is a diagram showing the air and gas delivery system. Air is delivered from an existing 14 MPa (2000 psig) compressor via a 25 mm (1 in.) ID pipe and first regulated to 4.5 MPa (650 psig) before being finally regulated down to 620 kPa (75 psig). A 50 mm (2 in.) ID pipe is used for the lower pressure lines. Two accumulators are used to dampen fluctuations and accommodate varying air demands. Within the air delivery system are the usual pressure gauges and flow meters. Calculations indicate that air at 75 psig can be used to feed the engine for it to operate at up to 50 Hz.

The air is split into two lines at point (9) in Fig. 6, one for the purge and the other for mixing with fuel, respectively on the top and at the bottom of the figure. The mixing air line is preheated by a propane heater. It was originally planned to use an electric heater but that turned out to be costly. The mixing air line will be heated to 100–200 °C (212–392 °F). Heating the air assists in flash vaporization of the liquid fuel. Pressure relief and pneumatic shutoff valves downstream of both lines are some of the safety features. The purging air line is similar to the mixing air line. In this case, air at 620 kPa (75 psig) enters a plenum which then feeds the air via a rotary valve to the combustor. As for the fuel/air premix, eight ports are used to feed purge air to the combustor, seven through sidewall ports and one through the end flange at the head manifold.

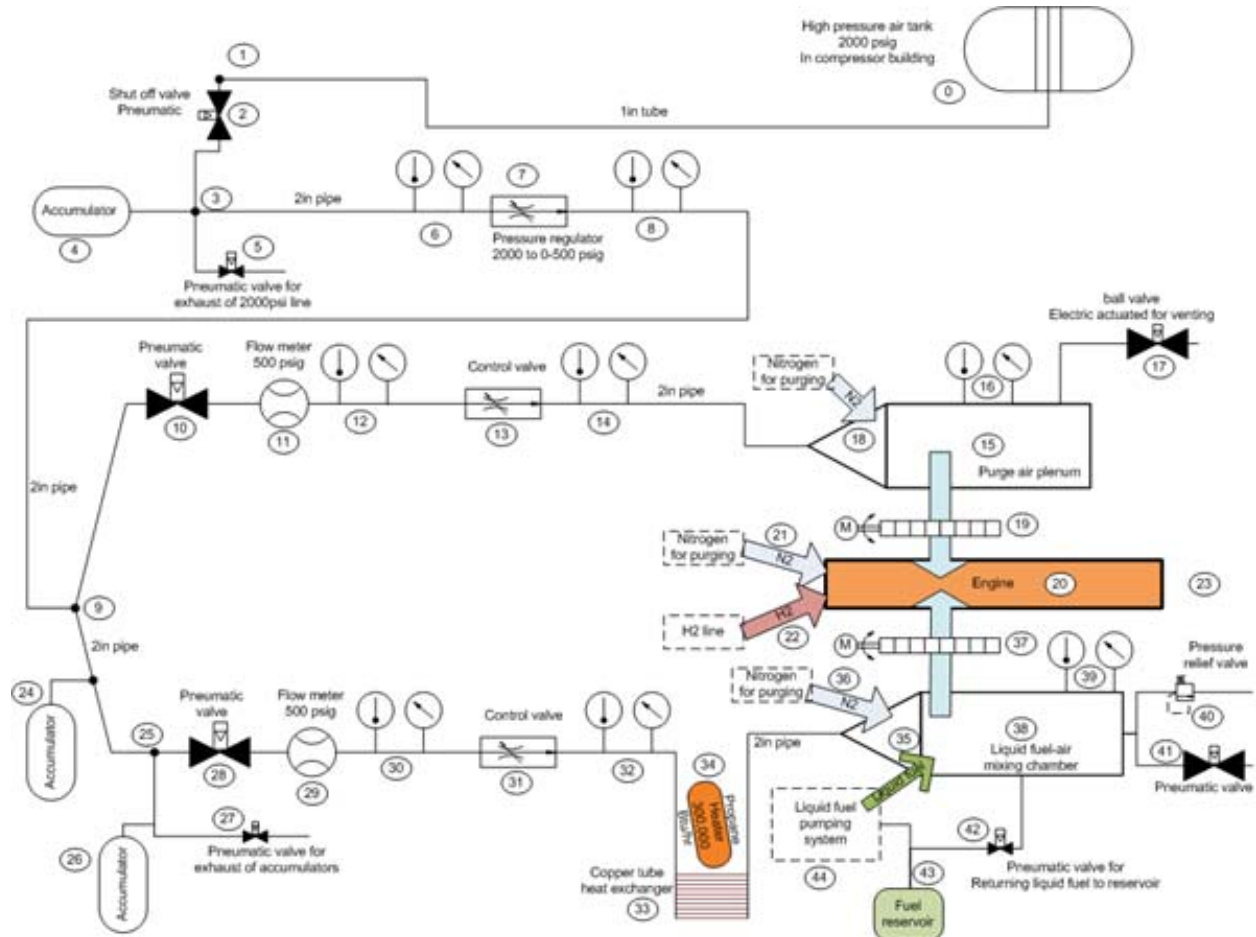


Figure 6. Air and gas supply.

#### D. Gas Delivery System

Figure 6 also shows nitrogen at (18), (21) and (36), supplied from 15 MPa (2200 psi) bottles, for purging and inerting the detonation engine core, the purge air plenum and the fuel/air mixing chamber. Nitrogen is used for purging these chambers at the end of hot firing. It is also used to extinguish any flames that may inadvertently be ignited should a backfire occur in the purge air plenum or the fuel/air mixing chamber. A hydrogen line (22) is available to provide local enrichment at the ignition location. Other energetic materials

can also be introduced here to facilitate detonation.

### E. Fuel Delivery System

Kerosene was used for the experiments although other gaseous and liquid fuels can be used as well. A 41 MPa (6000 psi) nitrogen bottle, shown in the left of the schematic in Fig. 7, is used to pressurize a fuel bottle with a 41.6 liter (11 US gal) capacity to 17.2 MPa (2500 psi). The fuel is delivered at a pressure of 200–400 kPa (15–45) psig and a temperature of 210 °C (410 °F). The heater is a simple glycerin/water bath. The heated fuel is injected into the fuel–air mixing chamber by an array of 12 diesel injectors, spraying into a stream of hot air. Initial testing only used one or two injectors. Pre-heating the fuel assists in atomization. The hot fuel/air mixture is injected into the detonation tube via seven proprietary nozzles located along one side of the PDE combustor. The exhaust from the engine is vented out of the test cell by a fan located on a dump tank. Excess fuel is condensed and captured into a reservoir.

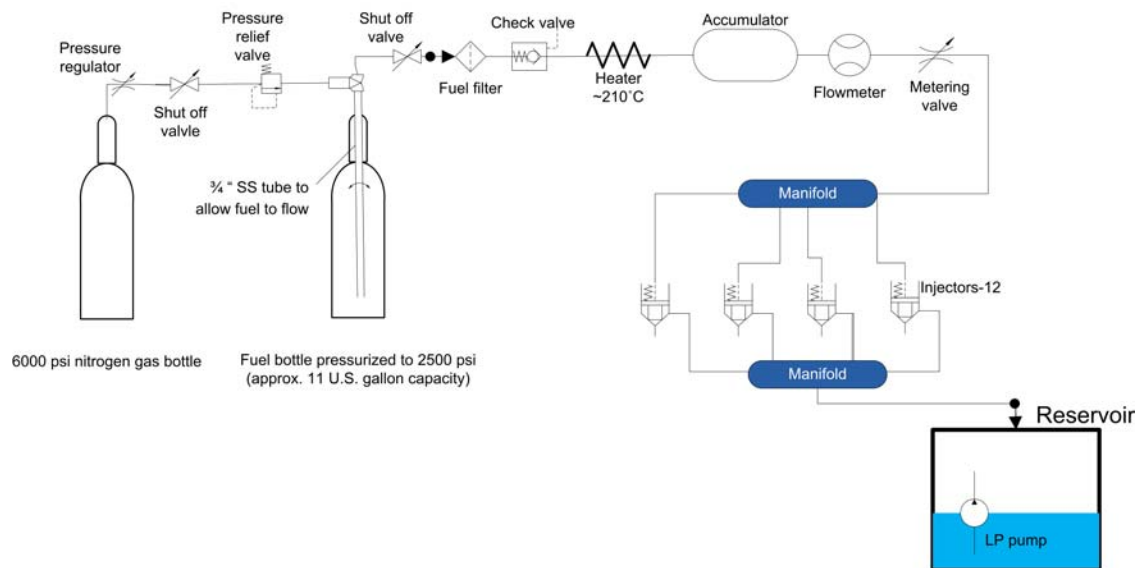


Figure 7. Fuel delivery system.

### F. Ignition System

The ignition system consists of two separate subsystems, the primary ignition system and the corona discharge system. The primary ignition system, consists of a high voltage spark generator, and eight igniters, connected by low-resistance, helical wire-wound automotive ignition cables. The in-house design spark generator is a capacitive-discharge type, with one high voltage ignition coil per plug. The partially assembled primary ignition system is shown in Fig. 8. The spark generator simultaneously fires all eight spark plugs upon receiving the rising edge of a TTL signal from the LabVIEW control program. The ignition coil primary side voltage is 120 V, resulting in a secondary voltage of approximately 12 kV, with the capability to increase the primary voltage up to 480 V. When operating at



Figure 8. The partially assembled primary ignition system.

120 V on the primary side, the ignition system delivers approximately 1.6 J total energy per ignition event. The partially assembled primary ignition system is shown in Fig. 8. The igniters are commercially available Bosch Platinum +4 automotive spark plugs, a semi-surface gap discharge design with four ground electrodes positioned radially around a platinum center electrode. The eight igniters are installed radially at even intervals around the combustion chamber.

The corona discharge system comprises the second subsystem of the ignition system. The corona discharge system ionizes the air in the vicinity of the igniters so as to reduce the voltage required to initiate a spark, leading to a faster electrical discharge and subsequently more powerful ignition event (same amount of energy delivered in a shorter time span). This is intended to offset the need for a high energy ignition system at higher chamber pressures that would be encountered at higher operational frequencies. With the exception of the corona discharge system, the ignition system performed satisfactorily. The corona discharge system was found to short to ground after only a few test runs and was subsequently decommissioned, after attempts to troubleshoot the system proved unsuccessful.

### G. Data Acquisition and Control System

The data acquisition and system control (DAQ) hardware is from National Instruments. It includes up to 24 channels at 2 MS/s simultaneous sampling for high-frequency dynamic pressure transducers, ion detectors and optically-based measurements. Up to 48 low-speed channels at 10 kS/s for low-speed acquisition of static pressure, flow rates, temperatures, heat transfer rates, etc. More than eight simultaneously operating counters are available for controlling valves, ignition, etc. for PDE operation. Two stepper motor controllers are also included. The data are streamed at high speed to a RAID hard disk array for storage, allowing for high-speed diagnostics and data acquisition. Software to drive the DAQ is LabVIEW. Digital inputs are directly acquired while analog inputs conditioned as necessary and converted to digital signals for processing by the LabVIEW controller program. Data are written and saved when requested by the operator.

Because of the hostile environment caused by the PDE arising from shocks, high noise levels and potential fire and explosion hazards, operators are required to vacate the test cell during tests. Thus, the data acquisition and control system is configured for remote operation. The electronic cart in the test cell was connected through a protective concrete wall to a computer in the control room which accessed all data acquisition and control functions remotely.

A data acquisition and control system, controlled using a custom LabVIEW program, was located on a cart in the test cell. The electronics were protected by a deflector shield which was covered in foam rubber to attenuate shock loads. It was discovered however that the shocks prevented data from being written by the read-write heads in the hard drives. Another problem was the high electromagnetic interference level from the stepper motors that caused noise contamination in the data. Interference issues were later resolved by routing power lines away from the data lines.

The LabVIEW program took a rotary valve position encoder input and use that rotary valve position to control the PDE detonation cycles. The program initiated the rotary valves by turning the stepper motors according to user inputs. The program also activated air valves to introduce compressed air into the plenum chambers according to user inputs. The duration of a run is also a user input. Once the PDE started operating, the operator in the control room can manually control the activation of the ignition system as well as the introduction of reactants, purge and inerting processes. The control board also had displays and alarms to warn the operator of emergency situations and which allowed the operator to terminate operation safely. At the end of the test or in the event of an unsafe operating condition, computerized and manual switches were used to shut down the engine and to purge and relieve pressure in the lines.

To prevent a potential backfire into the fuel/air mixer or purge air plenum, the LabVIEW controller program initiated ignition when the rotary valves were in the closed position. The ability to introduce oxygen, methane, hydrogen, and kerosene, are all separate, operator-controlled items. Once the test was stopped, the program ensured that the rotary valves reverted to a closed position and prevent potential backfire into the plenum chambers. The air control valves are also returned into a closed state if a failure

condition occurs. The air valves however, are primarily manually controlled by one of the operators to allow for variables to be altered during a run. This also provides a safety mechanism should any failure condition occur.

## IV. Conclusions

The development of a modular, large-scale pulse detonation engine demonstrator is described. This demonstrator was designed to operate with oxygen or air and a variety of fuels. The demonstrator integrated various innovative concepts into one package. The modular design allows the facility to be used as a testbed for various detonation-based systems for propulsion and power production.

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