Operational Issues Affecting the Practical Implementation of Pulsed Detonation Engines

By

Philip K. Panicker
Graduate Research Associate

Advisors:

Dr. Frank K. Lu
Dr. Don Wilson

Professors, Mechanical and Aerospace Engineering Department
Aerodynamic Research Center
UT Arlington
Agenda

- Introduction to PDEs, cycle, advantages, etc.
  1. Solenoid Valves vs. Mechanical Valves
  2. Shchelkin Spirals
  3. Water Cooling of PDE
  4. Ignition System
  5. Pressure Measurements
  6. Electro-Magnetic Interference
  7. Data Processing and Storage
  8. Safety Suggestions
- Conclusions
Introduction

- PDEs viable for supersonic & hypersonic military and civilian applications. (Vehicle propulsion or power generation.)
- No need for high compression rates. Therefore, compressor stage not required. Less complexity, weight, costs, fuel requirement.
- Compression and initiation of combustion is done by shock wave (detonation).
- Intermittent combustion.
- PDEs theoretically capable of 100s of cycles per second. Practically in the 10s of cycles per second demonstrated.
- Detonation process more efficient than deflagration. Releases more energy from fuel. Better fuel efficiency and longer range.
- PDE can be used in a wide Mach number regime: 0-5.
- PDE can be used in combination with existing or other propulsion systems.
- PDE as afterburner in turbojets.
- PDE as combustor in Ram or Scram jets (M>5 possible in this combination). (Ejector Augmented PDE-mass entrainment).
- In SCRAM jets, multiple PDEs, each one firing in sequence, to attain high frequencies.
Introduction (contd.)

- A profusion of experimental and computational research on PDEs. Most of PDE experimental studies are single cycle (shot) or short duration multi-cycle studies (10-20 s).
- Longer durations are required to study and test technologies for application in flight model engines or ground based engines for power generation.
- Experimental and analytical studies on PDEs, detonation studies at ARC since late 1990s.
- Objective of this paper is to highlight a few of the prominent difficulties encountered during experimental study of PDEs and provide solutions to overcome them.
- Suggest steps to increase the run time of PDEs in the move towards developing a long duration PDE test platform and to widen the scope of experimental studies.
PDE Cycle

The PDE cycle consists of the following stages.

\[ T_{cycle} = T_{purge} + T_{fill} + T_{ignition} + T_{induction} + T_{blowdown} \]

The frequency of the engine is given by \( f = 1/T_{cycle} \).

- The **purging stage** and the fuel-oxidizer **filling stages** are the longest.
- The **purging stage** is very important as this stage cools the tube as well as cleans it for a fresh charge.
- Without this stage, the PDE would suffer a rapid meltdown.
- \( T_{induction} \) is the time for the shock wave to reach the end of the tube.
- \( T_{blowdown} \) is the thrust producing stage and is very short compared to the filling and purging stages.
1. Solenoid Valves vs. Mechanical Valves

Mechanical Valves

Formula 1 allows 8 cyl. 2.4L or V-10 3L engines. (www.formula1.com)

• Cosworth’s 3.0L V-10 engine goes as high as 20,000 rpm.
• Therefore, valves open and close 10,000 times/minute
• 167 times/s
• Very complex. High failure rate.

Cosworth Racing engine dynomometer (dyno) for testing their high performance F1 engines. Cosworth Racing, Northampton, England (www.cosworth.com)
1. Solenoid Valves vs. Mechanical Valves

Mechanical Rotary Valves

• Motor driven. (Motor is source of EMI and vibrations.)
• Belts slip and valves lose synchronicity.
• Need a sensor (magnetic pick up or optical transducer) to sense valve position.
• Very difficult to time ignition.
• Rotary valves leak and higher pressures are not possible.
• Therefore, stoichiometric mix or proper equivalence ratio not possible.
• Higher frequency not possible.
1. Solenoid Valves vs. Mechanical Valves (contd.)

**Electronic Fuel Injectors**

**Diesel Injectors** are capable of 2000 bars (29,000 psi)

Diesel spray injected directly into engine immediately after the compression stroke.

**DENSO CORPORATION**

Japan

http://www.globaldensoproducts.com/

Gasoline Direct Injectors

Pressure rating of 14 MPa (2000 psi)

Particle size of about 50 μm.

DENSO CORPORATION Japan
Solenoid Valves and Electronic Fuel Injectors (3)

Solenoid Valves
- 12 Vdc, 8A peak, 2A hold.
- Fast acting (2ms reaction time). Up to 35Hz tested successfully. 50Hz max.
- Easy and precise control possible using TTL signals from a remote computer.
- Max pressure 550 kPa (90psig)

AFS-Gs60-05-5c series Fuel Valves
Alternate Fuel Systems Inc. Calgary, Canada
Digital (TTL) Control of Valves and Ignition: Control Duty Cycle and Frequency

TTL: Transistor Transistor Logic (0-5V)
How to increase PDE cycle frequency: Multiple port injection with solenoid valves

- Smaller fuel valves than air/Ox valves.

**Table:**

<table>
<thead>
<tr>
<th>Substance</th>
<th>LEL (%)</th>
<th>HEL (%)</th>
<th>IT (°C)</th>
</tr>
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<tbody>
<tr>
<td>Acetylene</td>
<td>2.5</td>
<td>100</td>
<td>305</td>
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<tr>
<td>Avgas 100</td>
<td>1.2</td>
<td>7</td>
<td>433</td>
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<td>Benzene</td>
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<td>498</td>
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<tr>
<td>Butane</td>
<td>1.9</td>
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<td>450</td>
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<tr>
<td>Gasoline</td>
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<td>Heptane</td>
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<tr>
<td>Hexane</td>
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<td>7.5</td>
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</tr>
<tr>
<td>Hydrogen</td>
<td>4</td>
<td>74</td>
<td>572</td>
</tr>
<tr>
<td>JP-10</td>
<td>1.3</td>
<td>8</td>
<td>246</td>
</tr>
<tr>
<td>JP-4</td>
<td>0.6</td>
<td>4.6</td>
<td>241</td>
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<tr>
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<td>0.6</td>
<td>4.9</td>
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<td>Methane</td>
<td>5</td>
<td>15</td>
<td>537</td>
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<tr>
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<tr>
<td>Pentane</td>
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<td>8</td>
<td>260</td>
</tr>
<tr>
<td>Propane</td>
<td>2.1</td>
<td>9.5</td>
<td>450</td>
</tr>
</tbody>
</table>

**Notes:**

- HEL/LEL: Higher/Lower Explosive Limit
- IT: Ignition Temperature
2. Shchelkin Spirals

One method of inducing Detonations in the PDE’s combustion chamber is to ignite the fuel-oxidizer mixture and then to rapidly accelerate the combustion flame front till it becomes a Detonation wave. This is known as Deflagration to Detonation Transition (DDT).

One of the most successful DDT enhancement devices is the Shchelkin spiral, which is a helical spring, inserted into the tube downstream of the ignition point.

The device is named after Russian Physicist Prof. K. I. Shchelkin, who proposed the spiral to bring about DDT in his 1965 book “Gas Dynamics of Combustion”.

\[
\text{Blockage Ratio} = \frac{\text{(Area of Cross Section covered by Spring)}}{\text{(Total Internal Area of Cross Section of Tube)}}
\]

- Blockage Ratio
  (OD, ID, Wire thickness)
- Length
- Pitch
- 50 to 55% BR for effective DDT
2. Shchelkin Spiral (2)

- Blockage causes Drag.
- Spirals disintegrate during testing and do not last too long.
- Causes heating of spiral tube section, impractical for long duration testing.

Condition of spirals after just 10 to 15 seconds of testing.
2. Shchelkin Spiral (3)
Methods to Increase Spiral Life

Modular Spirals that can be replaced after 'x' flight hours.

50 ft/s water flow speed.
3. Water Cooling of PDE

**Effects of not cooling PDE**
- Tube deterioration
- Pre-Ignition and misfiring

**T > 10 s**

**T > 1 min.**
Water Cooling Jacket (1)

PDE test performed at ARC: Application of PDE for Electric Power Generation.
PDE is internally water cooled.
Current study at ARC: 2 stage PDE_Liquid Fueled PDE with pre-detonator
PDE has integrated water cooling system. Duration of tests expected to be 30 mins. To 1 hour.
4. Ignition System

High Energy Arc Ignition to Initiate Detonation

- Requires bulky electrical circuit components.
- Transformers, capacitor banks are heavy and impractical for flight weight model.
- Power generation to initiate arcs will deplete engine’s available power output.
- Most of the power is wasted electrically when arc current flows to ground.
- Ignition plugs sustain heavy damage and have reduced life.
- The Arc is a big source of Electro-Magnetic noise that will drown out signals from transducers.

Before

After a few seconds of Arc discharges
4. Ignition System (contd.)

Ignition Plugs

- Built in house
- Lanthanated Tungsten rods (4mm/ 3/16in dia)
- Variable spark gap
- 3k Ohm resistor reduces spark current and thereby reduces radiated noise.
- (Commercial automotive spark plugs have built in resistance 3k to 8k Ohms, to reduce EM noise. Without that, the car radios and other electronics will not work.)

Ignition plugs suffer heavy damage during PDE tests. A more robust plug is needed capable of withstanding the high temperature and pressures inherent in PDEs.
4. Ignition System (contd.)

Modified Automotive Ignition System

150 mJ max energy per spark Inductive Ignition System

A transistor control circuit built in house enabled the interfacing of the ignition system to TTL controls from the DAQ.
4. Ignition System (contd.)

Spark energy required for ignition of Hydrocarbon fuels with air is 0.20 to 1 mJ (1 atm, static conditions)

5. Pressure Measurements

A characteristic time $T_c$ can be defined for a pressure transducer as the time taken by a shock or detonation wave to traverse the width of its measuring surface.

Consider an over driven case, where the detonation wave velocity is $C_{DET} = 3000 \text{ m/s}$.

Diameter ($d$) of the sensor face of the PCB dynamic transducer type 111A24 is 5.5372 mm (0.218”).

Characteristic time $T_c$ for the pressure transducer is given by

$$T_c = \frac{d}{C_{DET}} = 1.846 \mu s$$

The minimum sampling rate $f_s$ required to fulfill Nyquist's criterion (also known as the Shannon's sampling theorem) is given by the relation

$$f_s = \frac{2}{T_c}$$

From the above relation, the minimum sampling frequency for the PCB 111A24 pressure transducer used in a propane-oxygen test case is found to be 1.084 MS/s.
5. Pressure Measurements: Aliasing

Nyquist's Criterion (Shannon's Sampling Theorem) \( f_{\text{sampling}} \geq 2 f_{\text{signal}} \)

\[ V = V_m \sin (2 \pi f t + \phi) \]

Case 1: sample < signal

Case 2: sample = signal

Case 3: sample = 2 signal

Case 4: sample = 2 signal
The time delay $T_d$ can be expressed as follows

$$T_d = \frac{h}{a_2}$$

$h$ is the depth of the recess and $a_2$ is the sonic speed behind the shock or detonation wave.

The new characteristic time of the recessed transducer is given by the following relation, where $d'$ is the diameter of the recess bore.

$$T_c' = \frac{d'}{C_{DET}}$$

For a recess hole of 1/16 in. diameter, the $T_c'$ for a $C_{DET}$ of 2600 m/s, is found to be 0.61 ms. This is less than the rated 1 ms rise time of the 111A24 transducer.

Since, the center of the transducer’s sensing surface is the most sensitive, a sampling rate of close to $1/T_c'$ is satisfactory. For the above value of the sampling rate is found to be 1.64 MS/s.
5. Pressure Measurements (contd.)

An actual pressure spike seen from a PDE test run at 15 Hz with propane and oxygen mixture and a sampling rate of 240 kS/s.
5. Pressure Measurements: Thermal Loading

Thermal loading causes the stainless steel casing of piezo-electric transducer to expand and thus reduces the preloaded stress on the sensing crystals. This causes a negative charge buildup, which when passed through the signal conditioner, appears as a monotonic rise in the base line of the pressure readings.

The manufacturer suggests several ways to combat this problem, such as, mounting the transducers in **recessed ports, coating the sensor with ceramic coatings** and most effectively, **water cooled mounting adapters**.

For long duration PDE testing, the water flow through the water jackets be pressurized (within manufacturer’s safety ratings) and be passed through a heat exchanger to ensure sufficient cooling.

For detection of detonation waves, **ionization probes and fast acting photo-diodes are viable options**.

Photo-diodes require complicated mounting methods in the high temperature and pressure environment of PDEs.

Ion probes are relatively simple in construction but are harder to cool and may not be useful for long duration testing.
6. Electro Magnetic Interference

EM Noise can be coupled into circuits in 3 ways.

1. **Inductive** Coupling (Due to high current flow, varying magnetic field): e.g. motors, power cables, etc.
2. **Capacitive** Coupling (Due to voltage difference, Electric field): e.g. power cables, high voltage sources, etc.
3. **Radiation** Coupling (Far field coupling)

Inductive and Capacitive couplings are near field coupling.

**Common Mode (CM) vs. Differential Mode (DM):** Noise is conducted in cables as either common mode or differential mode.

A signal cable has two conductors, one to carry the signal from the source and one to return the current back to the source.

In **differential mode** noise, the currents on both conductors due to noise are equal in magnitude and opposite in direction.

In **common mode**, the currents are in the same direction.

DM noise is easier to remove as most DAQs have terminals with DM configuration, in which the difference of the two conductors are measured at the terminals.

CM noise can be minimized by using ferrite core beads on both conductors.
6. Electro-Magnetic Interference

A major source of EMI is the ignition system.

Sparks can appear like a sharp fast rising spike, and can be interpreted as an impulse (delta) function. Delta functions have flat frequency spectrum.

The darker plot is of the readings of a pressure transducer in static conditions when a low energy ignition system is running, with a 16 kOhm resistor in series with the spark plug electrode. Notice the distinct positive and negative spikes that correspond to the ignition sparks. The lighter plot is of static pressure reading with no ignition. Sampling rate = 100 kS/s

Sensitivity of the transducer is 5 mV/psi.

With the addition of the series resistance, the noise is within acceptable range.

Transducer reads up to 1000 psig.

Noise captured in the pressure transducer signal.
6. Electro-Magnetic Interference: Spark Suppression on Relays and Switches

- Another source of sparks related EMI are relays, contactors, solenoid valves and other switching devices.
- Use spark and surge suppressors.
- Replace with solid state switching devices (thyristors, Silicon Controlled Rectifiers, Power Transistors, etc.) and shield the switching circuits.
6. EMI (contd.)

Steps to Reduce EMI

- Shield Cables, components, circuits.
- Use Coaxial cables with BNC connectors. Shielded twisted pairs. (For short distance analog signal transmission only.)
- Avoid Ground Loops. Ground loops occur when the return line is grounded at both ends to ground references that may be at different potentials.
- Keep the signal conductor close to its return conductor and avoid separating the two wires. Such wide loops behave as antennae creating DM loops that can transmit or receive noise, leading to cross talk with other conductors. This is why Wiring Harnesses are used.
- Tie down coaxial cables carrying sensitive analog signals so that they do not flex or vibrate during test runs, to avoid electric noise due to triboelectric effect. Triboelectric effect is observed as static electricity when glass is rubbed with silk. Copper, nickel, vinyl, polyester, Teflon, etc. develop a net negative charge, while glass, mica, nylon, aluminum, paper, etc. contract a net positive charge when rubbed against other materials. Some of the above mentioned materials are commonly used in cables, insulation and mounting equipment.
- If after all possible preventive measures have been taken and the signals are still affected by noise, then one must employ filters. Hardware filters & Software filters.
7. Data Processing and Storage

- Use **Binary** file format for storing large amounts of data.

- LabVIEW (National Instruments) TDM (Technical Data Management) files store descriptive properties of the data in XML, allowing for data mining, a valuable tool when sorting through very large volumes of data. The bulk of the data in TDM files is still stored as binary.

- The bottlenecks in most computers when it comes to writing data rapidly are the **RAM** and the **hard drive**. For **32 bit** computers, **4GB** of **RAM** is the maximum possible limit.

- To handle large volumes of data, implement **RAID**. RAID stands for **Redundant Array of Inexpensive/Independent Disks**.
In RAID 0, each packet of data is broken up into \( n \) pieces and each piece is stored in one of the \( n \) disks in the array in serial order. (This is known as striping.) Thus RAID 0 is used for high speed writing and reading. Each disk must be of the exact same size and the total capacity is the sum of all disks together.

RAID 1 creates a mirror copy of one disk onto one or more disks. Thus RAID 1 creates redundancy for the protection of data from perishing in the case of disk failure.

RAID 0+1 is the combination of the two for speed and safety.

Another useful method for storing data fast is to set up a RAM disk on the computer.
Safety Suggestions

- All fuel and oxygen lines should have flame arrestors or detonation arrestors installed on them.
- Install check valves on supply lines just before the solenoid valves to prevent back flow during the high pressure stages in the chamber.
- Install a glow plug in the exhaust system to burn away any un-burnt fuel gases.
- On exhaust systems, avoid electric motors, as they produce sparks during operation. Use Pneumatic Venturi blowers. Use pneumatic motors wherever possible.
- Position the igniter away from sensitive transducers on the test rig to prevent it sparking to the transducer. Route the ignition cables away from sensors and their cables. Electricity takes the path of least resistance and if there are breaks in the cable insulation, the spark will occur where it is most convenient for it.
- The ignition sparks are strong enough to stop an adult’s heart and can be fatal. Always use electrical insulating gloves when handling high voltage equipment. Gloves rated from 500 V to 40 kV are commercially available.
- Use Right hand to handle electrical systems.
- In the event of a fire near the ignition system, do not spray the fire extinguisher jet directly on to the ignition system, unless one knows for sure that it is turned off and discharged. This is because high voltages can be conducted through the mist onto one’s body and deliver shocks.
Conclusion

- Major concerns that limit the run time of PDEs have been examined. Several suggestions have been provided for increasing PDE cycle frequency, including the use of electronic or solenoid valves, cooling of tubes.
- Suggestions to improve the efficacy and life of Shchelkin spirals provided.
- High energy ignition systems are impractical for flight model PDEs.
- Attention to details needed for measuring pressure using dynamic pressure transducers. Choose high sampling rates (1 to 5 MS/s per channel).
- EMI has to be considered at the design stage.
- Some steps to help store large amounts of data: RAID and using binary files.
- Safety concerns discussed.