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PRACTICAL ISSUES IN GROUND TESTING OF PULSED DETONATION ENGINES

Philip K. Panicker, Frank K. Lu, Donald R. Wilson
Aerodynamics Research Center, Mechanical and Aerospace Engineering Department
University of Texas at Arlington
Arlington, Texas 76019
U.S.A.
philipkpanicker@uta.edu, franklu@uta.edu, wilson@uta.edu

ABSTRACT

Pulsed detonation engines can potentially revolutionize aerospace propulsion and they are the subject of intense study. However, most of the studies involve single shot and very short duration test runs. Some of the practical issues in developing PDEs are discussed from the viewpoint of developing ground-based demonstrators. This represents only the beginning of a roadmap toward the successful development of flightweight engines. Viable solutions are offered that may help overcome the difficulties posed by the high temperature and pressures on the test rig and instrumentation. Commercial solenoid valves and electronic fuel injectors are presented as means to achieving higher operational frequencies. Issues concerning data acquisition, such as proper implementing procedures for pressure transducers and choosing the appropriate sampling rates are discussed. Methods for mitigating electromagnetic interference are discussed.

INTRODUCTION

Pulsed detonation engines (PDEs) offer many advantages over conventional propulsion systems and are regarded as potential replacements for airbreathing and rocket propulsion systems, for platforms ranging from subsonic unmanned vehicles, long range transports, high-speed vehicles, space launchers to space vehicles [1]. Theoretical studies have indicated a higher thermodynamic efficiency than achievable in conventional, deflagration-based systems [2–5]. Moreover, there are savings in weight and reduction in complexity and cost. For example, the high compression achieved in the detonation process may allow the compressor in a conventional engine to be dispensed with or replaced by a low-pressure fan. Compact designs may be feasible, thereby achieving high thrust-to-weight ratios. In addition, various combinations and hybrids have been proposed, including ejector-augmented and combined cycle engines [6–8], thereby extending the PDEs versatility. There are also other potential non-aerospace applications of pulse detonations, including electric power generation [9,10], slag removal [11] and others [12].

While a roadmap has been proposed for developing PDEs [13], there are no known operational PDEs presently. Instead, it appears that the lion's share of experimental studies have been performed using single-shot test beds or with short run times at frequencies below 50 Hz in the range of 10 to 20 s. However, longer test times are required to move PDEs toward practice, either for propulsion or for power; see, for example [14] which reported test times exceeding 5 minutes. The longer test times are expected to introduce a host of issues. In this paper, a number of these critical issues pertaining solely to ground testing will be reviewed. Many of these issues will remain as flightweight systems are developed. Before reviewing these issues, a brief introduction of basic PDE processes will be provided.

A PDE is shown schematically in Fig. 1 [15]. The figure shows that the reactant, comprising of oxygen and propane, is introduced on the left. The gases are metered and are at an equivalence ratio of unity. Downstream is an igniter, followed by a deflagration-to-detonation (DDT) section, wherein a DDT device is inserted to help transition the combustion process to a fully-developed detonation wave.

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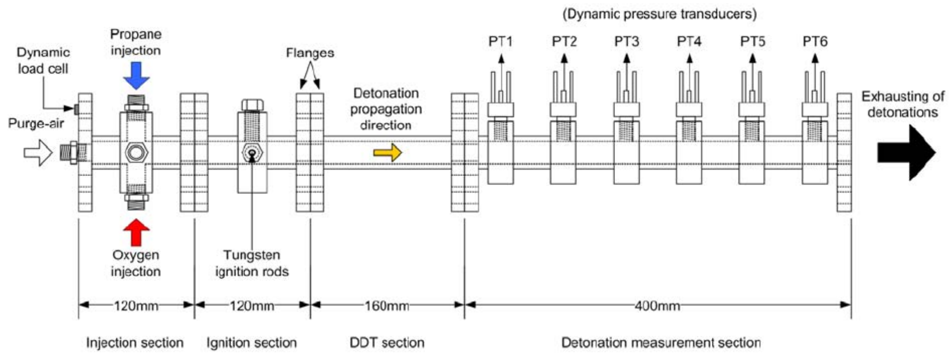

Figure 1. Schematic of a PDE operating with propane and oxygen [15].

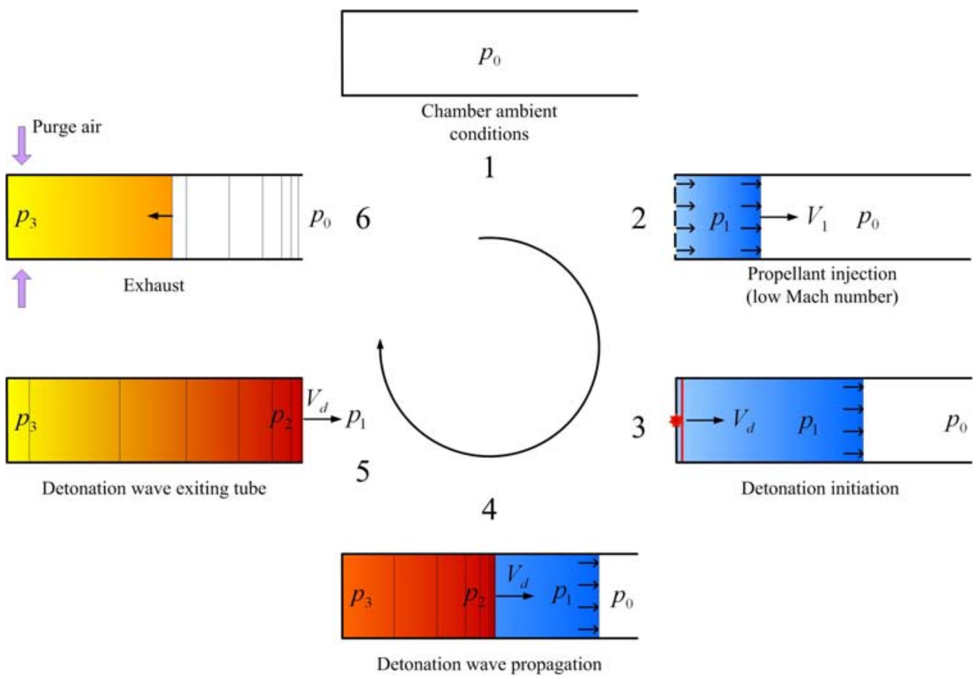

Figure 2. Stages of a PDE cycle.

From various studies, the Shchelkin spiral has proven to be most effective in inducing DDT in relatively short run up distances, although not much have been reported on its use in a PDE [15–18]. Previous studies [17] found that spirals with 55% blockage ratio are the most effective.

Further downstream is a tube for measuring the transient pressures that are developed. Also shown in the figure to the left is a port for introducing purge air. Finally, the rig is instrumented with a load cell.

The stages of a PDE cycle are shown schematically in Fig. 2. The detonation chamber is initially at quiescent, ambient conditions (1). It is then filled with a fuel/oxidizer mixture (2), which in Fig. 1 is shown as end-wall injection. At some time (3), the mixture is ignited, ideally such that the detonation wave meets the mixture front at the exit of the detonation chamber (4,5). The detonation chamber is then scavenged by a blowdown or exhaust stage (6) after which the cycle repeats itself.

The unsteady processes can be displayed in a displacement-time diagram. Figure 3 shows such a diagram for a simple ideal process which we call the unit cycle. The figure depicts relatively the time required for the various events. Therefore, ideally, the time for the unit cycle comprises of

$$T_{cyc} = T_{ign} + T_{fill} + T_{prop} + T_{exh} + T_{purge} \tag{1}$$

The cycle frequency is thus given by

$$f = 1/T_{cyc} \tag{2}$$

The ignition time is not shown in Fig. 3 but ignition starts just ahead of (3). Moreover, while the fill time is shown explicitly in Eqn. (1), it is absorbed into the propagation time in Fig. 3. Obviously, any departure from the ideal unit process

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shown in Fig. 3, such as extra time required for filling or any other non-ideal effects such as viscous attenuation or mismatches in timing of various components, will lengthen the cycle time.

Figure 3 shows that the PDE unit process is dominated by unsteady gasdynamics phenomena, namely, the filling/propagation, exhaust and purging processes. However, the bulk of the fundamental studies have concentrated on ignition and detonation propagation, perhaps rightly so as these are crucial to the success of a PDE. As has been known for some time, direct initiation is practically impossible due to the exorbitant energy requirements [19]. Thus, less energetic ignition has been the approach but this requires a sufficient length for deflagration-to-detonation transition to occur, usually shortened by a detonation enhancement device such as a Shchelkin spiral.

The aforementioned gasdynamics phenomena can be particularly vexing in bringing PDEs into practice. For example, the purging stage is particularly important as this cools the chamber as well as cleans it for a fresh charge [20]. Without this stage, the PDE may suffer serious damage as the heat release from the detonation process is much larger than ordinary deflagration processes; for example, see the review by Bazhenova and Golub [12], This specific issue of heating will be discussed later.

This paper is organized into a number of topics that are pertinent in developing PDEs and their ground-based demonstrators.

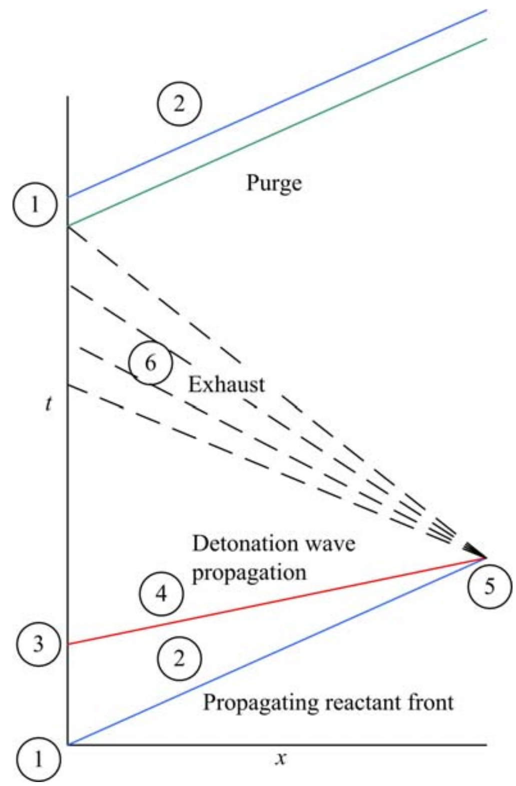

Figure 3. PDE unit process.

MECHANICAL VALVES VS. SOLENOID VALVES

Early PDE designs made use of mechanical valves, such as rotary valves [16,21–35]. Rotary valves possess a few limitations. They are leaky and elaborate sealing techniques have been proposed [25]. Moreover, the difficulties in sealing also limit their operating pressure. Rotary valves are difficult to time precisely. Synchronization with the ignition is usually achieved by a sensor, such as a magnetic pickup or a photodetector, to detect a reference position of the valve or cam. However, transmission belts slip and the valves lose synchronicity as a result. Since the valves are ganged together to a common driveshaft, adjustments for minor departures in timing cannot be done. Thus the loss of synchronicity leads to improper filling and misfiring.

Most of PDE designs fill from the closed end. This, together with the low operating pressures of the rotary valves, means that the engine may not be filled rapidly for high frequency operation. (A simple analysis shows that thrust scales with the frequency [36], a subject that will be addressed later.) This inability to fill rapidly causes many practical problems. For example, it is difficult to control the mixture stoichiometry. The poor filling characteristics at high frequencies or due to a long chamber mean that there is uncertainty that a precise amount of reactant has been delivered uniformly throughout the detonation chamber. Other issues to contend with include electromagnetic interference (EMI) and vibrations from the motor driving the valves, both of which can affect the signals from transducers used for monitoring the performance of the engine. Finally, there also appears to be a practical limit in the speed of mechanical valves for engine applications. The fastest mechanical valves today are found in Formula 1 engines. For example, the Cosworth CA2006 V8 engine achieved a Formula 1 landmark of 20,000 rpm in the 2006 Bahrain Grand Prix. This means that the twin intake valves (and twin outlet valves) operate at 10,000 rpm (or 167 Hz each).

The trend in the automobile industry is to move toward electronic fuel injection systems, where the injection is accomplished by solenoid or piezo-driven valves. Such fuel injectors are used for gasoline, diesel and alternative fuel engines and their designs for gaseous and liquid fuel delivery are the subject of substantial recent research [37–45]. For diesel injectors, pressure boosters raise the injection pressure to as high as 2500 bar [46]. Such a high pressure is required to spray the fuel directly into the engine, right after the compression stroke. Modern gasoline injectors also inject directly into the engine at high pressures. Moreover, valves for alternative automotive fuels, such as propane [47], methane, LPG [48], biodiesel and ethanol-based blends [49] and, increasingly, hydrogen [50–52], are presently available off the shelf. These gas injectors are extremely crucial in advanced engine concepts [53,54].

The favorable features of electronic valves such as their fast action (opening times of 5ms or less) and precision control by TTL signals from a computer make these valves attractive for

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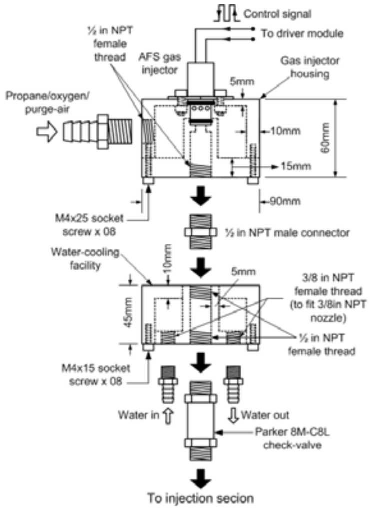
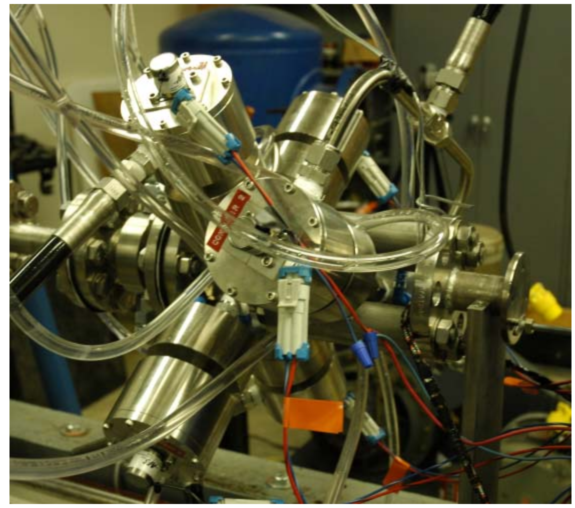


a. Schematic of the custom-designed gas injector housing incorporating safety features such as check valves and water-cooling subsystems.



b. **Photograph showing gas injector housing and water cooling subsystem mounted on the PDE platform.**

Figure 4. Gaseous fuel injectors for a PDE.

PDE use. Commercially available solenoid valves (Alternative Fuel Systems, Calgary, Canada) for gaseous fuels have been used for a propane/oxygen PDE [15]. The valving arrangement is shown in Fig. 4. The schematic in Fig. 4a shows the fuel injector assembled with a water jacket for cooling purposes. A photograph of the injector manifold is shown in Fig. 4b. These valves have thus far been operated at up to 20 Hz for about 30 s. Further testing to determine the durability of these valves under the harsh PDE conditions are planned.

REDUCING THE DURATION OF GASDYNAMIC PROCESSES

There appears to be a consensus that a frequency of 75–100 Hz/tube is a desirable goal. However, to the authors' knowledge, there has not been any mention of this benchmark in the open literature except in [55] which was to address a specific problem of flow unsteadiness in the air induction system of a 500,000 lb cruise vehicle at Mach 3. Despite the lack of any direct evidence of the need for high-frequency operation, the scaling between thrust and frequency makes high frequency operation a desirable feature of PDEs. But this goal of high-frequency operation is elusive. Amongst various factors that limit the frequency, the literature tends to address limitations due to valving and due to the need to maintain a certain length in order to develop deflagration-to-detonation transition.

As mentioned above, gasdynamics processes occupy vastly longer times than the ignition or the combustion processes. It appears that the use of electronic valves can radically alter existing designs to reduce these gasdynamic times through sidewall injection and purging via a large number of ports and valves. (As a side note, increasing the injection pressure to increase mass flow rate is not always feasible and introduces other difficulties, such as an adequate compression system and power supply.) An early attempt at sidewall injection with mechanical valves was not successful [56]. The rotary system used had a large inertia which restricted operational frequency. Moreover, the seals did not function adequately at high pressure and under repeated cyclic loading.

Figure 5 shows an arrangement for sidewall injection of a premixed reactant and purge air. The multiple valves and phased opening times ensure good fills and high frequencies. It can be noted that the purge air can be used to minimize or eliminate the exhaust stage.

Electronic injection appears to be able to mitigate the difficulties due to mechanical valves. Electronic control allows these valves to be phased to open at precise moments to fill the tube with minimum waste of reactant or air. The ability to tune the valves individually is important. Although solenoid valves are fast, they have finite reaction times for opening and closing, ranging from a fraction of a ms to a few ms. Another reason for being able to fine tune the valves arises from the residual magnetism that lingers in the steel body of the valve even after power has been cut off, causing a delay in the closing of the valves. Therefore, beyond a certain frequency, solenoid valves tend to chatter. This can be overcome by using multiple sets of valves, whose operation can be phased as shown schematically in the timing diagram of Fig. 6. Figure 6 shows the duty cycles and time delays for two sets of valves. Within one clock pulse, each set of valves open and close only once but, by using two sets of valves, the operational frequency of the PDE is doubled. The ignition signal is given right after the fill valves close, at the beginning of T_{d0}. The detonation and exhaust stages occur during T_{d0}.

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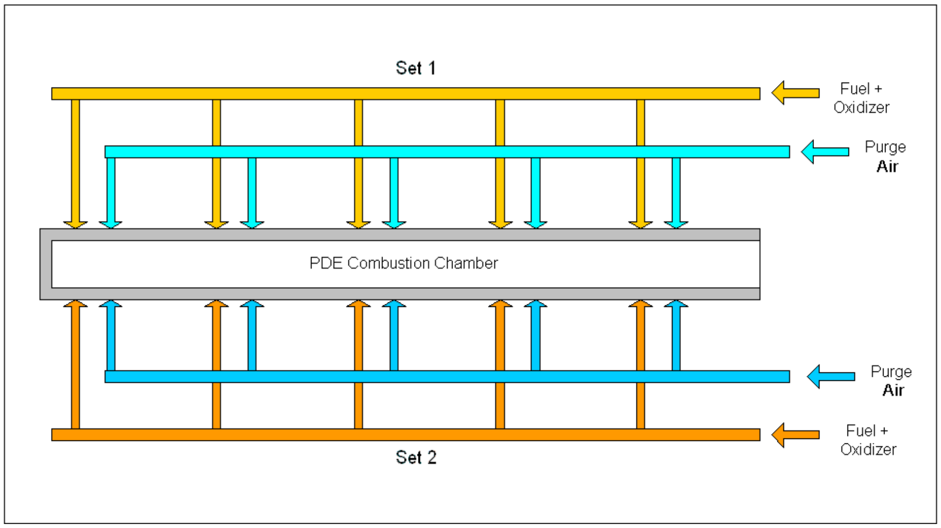

Figure 5. Schematic showing arrays of sidewall injection ports for premix fuel/oxidizer and purge air.

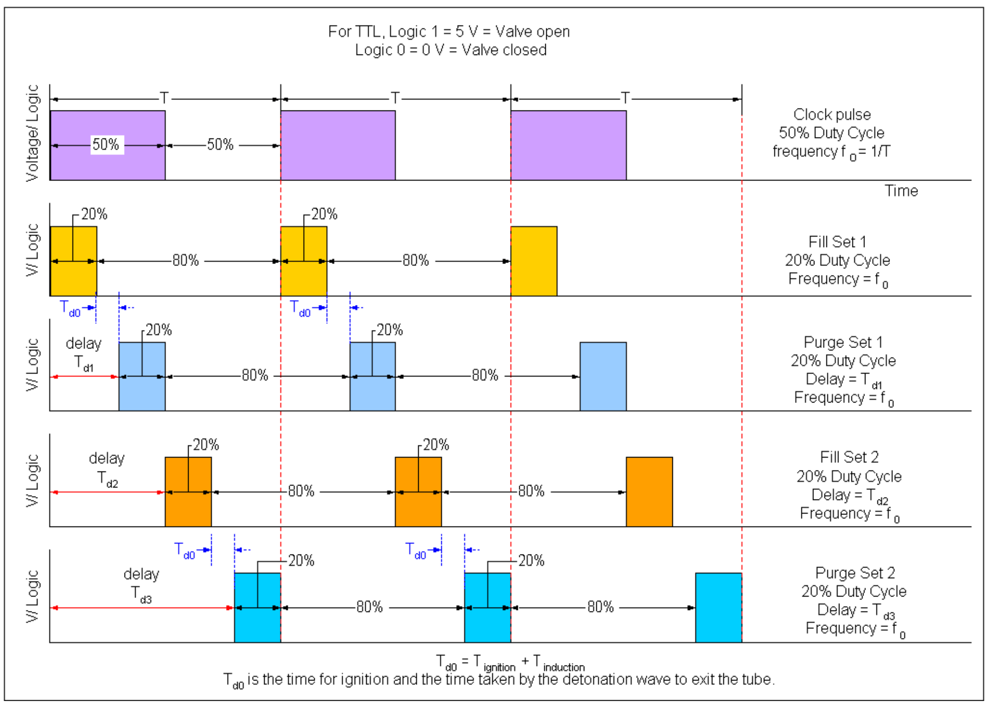

Figure 6. A schematic of the TTL control signals for injection valve timing for two sets of valves.

Since the volume of fuel required for combustion is less than the volume of air, smaller or fewer valves can be used for the fuel service compared to the number of air/oxygen service valves. Also, the air valves can be used twice within a time period, once for supplying air to mix with the fuel and, secondly, during the purge stage of the cycle. Thus, the number of valves can be reduced through proper design.

COOLING

The rapid energy release in a detonation also results in high temperatures and heating rates. The high temperature in the post-detonation gas has been well documented in computations [57–60]. However, there are fewer experimental reports of encounters of high temperature or heat flux; see, for example the review by Bazhenova and Golub [12].

An example of the damage that is caused by rapid heating is shown in Fig. 7 which is the test rig of [15] undergoing propane/oxygen testing at 15 Hz. The figure shows that the DDT section is glowing red hot. Failure whereby the Shchelkin spiral is destroyed and ejected occurred within 15–20 s. Figure 8 shows the damage suffered by the Shchelkin spiral. The spiral material is stainless steel. The stainless steel reverted to iron and became magnetic after the high heating. Moreover, there were also instances where the gaskets caught

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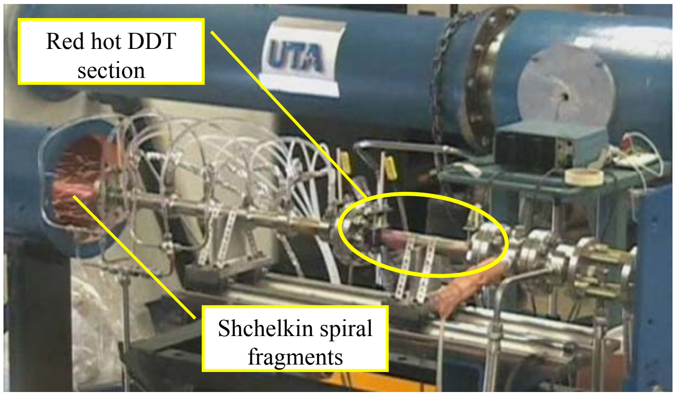

Figure 7. A PDE without cooling showing red hot DDT section after a few seconds of testing.

fire due to the high heating. It is thought that the DDT section is the hottest due to the turbulent mixing. Even if the Shchelkin spiral is undamaged, the heat can cause pre-ignition of the reactants, thereby preventing detonations from occurring.

It is clearly important to have a cooling system for the PDE, to protect the combustion chamber, valves, diagnostic instruments and other components from damage and to ensure sustained testing. A forced-water heat exchanger system, shown in Fig. 9, was developed that proved effective. Further refinements are being developed to improve the cooling system.

PRESSURE MEASUREMENTS

Dynamic pressure measurements are by far the most common form of diagnostics employed in PDE research and development despite a number of limitations. The most crucial limitation is due to the frequency response of the transducer and its size. An important measurement is the wave speed from which one can ascertain whether a fully-developed Chapman–Jouguet detonation has been achieved. The wave speed is determined by a simple time-of-flight (TOF) technique, whereby the speed is obtained from the time it takes the wave to pass two transducers at a known spacing. However, some error is incurred as the wave passes the surface of the transducer. Consider, for example, a wave traveling at 3000 m/s past a flush-mounted transducer with a diameter of 5.54 mm. The time required to pass the transducer face is therefore 1.85 μs. Just to resolve this time and to satisfy the Nyquist criterion requires a sampling rate of $2/1.85\times10^{6} \approx 1$ MHz. Such a sampling rate, however, will still fail to properly capture the von Neumann spike. The inability of a low sampling rate in resolving the pressure peaks is evident in Fig. 10 where the sampling rate was 240 kHz for a PDE operating at 15 Hz with a stoichiometric propane/oxygen mixture.

It is also necessary to cool the pressure transducers for long duration testing since the thermal drift is significant. Heating causes the stainless steel casing of the 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, as is evident in Fig. 11 [61]. The figure also shows the erratic spikes due to a low sampling rate, in this case, of only 20 kHz. The easiest way to cool the transducers is through water jackets whose supply lines are visible in Fig. 9.

a. **A broken piece of the spiral recovered from the PDE tube.**

b. **The remainder of the spiral that has melted and fused together.**

c. **Parts of the spiral have been compressed and parts of it has melted away leaving residue.**

Figure 8. Photographs of Shchelkin spirals destroyed in the PDE test shown in Fig. 7.

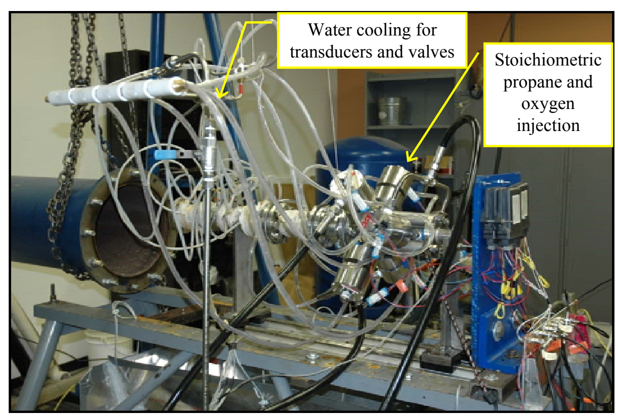

Figure 9. A water-cooled PDE.

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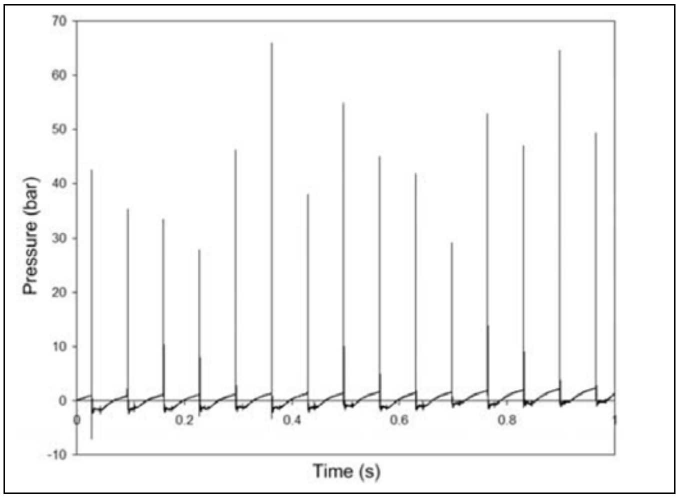

Figure 10. The fluctuation in peak pressure due to low sampling rate.

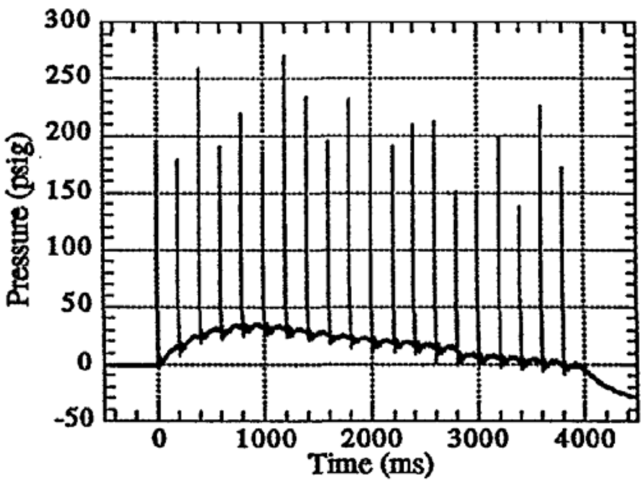

Figure 11. Example showing thermal drift of piezo-electric transducer output [61].

ELECTROMAGNETIC INTERFERENCE (EMI)

Most transducers used in PDE diagnostics have outputs on the order of a few mV. Dynamic pressure transducers (such as the PCB 111A type used in many of the PDE studies) generate signals in the 0–5 V range but their sensitivities are on the order of 1–5 mV/psi. Such small amplitude signals may be subjected to significant electromagnetic interference in the presence of high power devices. For a laboratory situation where components are close by, EMI is near field and due to capacitive or inductive coupling [62,63].

Near field coupling can be mitigated by covering the emitting or receiving conductor with a low resistance shielding. On the transmitting conductor, the shield should be connected to the ground of the source, such as a power supply. On the receiving conductor, the shield should be connected to the ground of the circuit. For low frequency inductive coupling (<100 kHz), ferromagnetic material may be utilized as shielding. Magnetic material, such as iron, steel, mu-metal, etc., can be used to provide a path for the magnetic fields around inductive devices.

Power transformers are a source of inductive noise. Therefore, sensitive equipment such as DAQ components and computers must be located away from them. Otherwise, a ventilated magnetic shield should be provided around these components. Transformers should not be mounted using screws through holes to metal fixtures that are part of the building's ground as this will cause a ground loop.

Ungrounded AC and DC power supplies are also sources of EMI. Switched Mode Power Supplies (SMPS) are used in bench top DC power supplies. These devices generate square waves at frequencies as high as 100 kHz which are then rectified and regulated to a smooth DC value. Unfortunately, the high-frequency oscillations along with their harmonics can get transmitted over the supply lines. Some power supplies deliver the hum from the power supply frequency or its harmonics to the instruments, as well as to the ground, as they are tied to the ground through the wall socket terminal. It is therefore important to procure SMPS based systems with good quality built-in filters to avoid the high frequency noise on the ground line or the capacitively coupled noise on signal lines. Adding isolation transformers on the supply lines of power supplies and AC powered instruments also help them from being infected with noise transmitted through the power lines. Line filters should be used on all AC-powered devices to prevent conducted noise coming in or going out into the power lines. Good quality, commercially available power distributors are recommended as these have built-in surge protection, filtering and shielded isolation transformers, for sensitive instruments.

Electric motors also create electrical noise and sparks, the latter in the case of universal motors found in many household appliances. These motors must be shielded and kept away from sensitive instruments. Consider the use of pneumatic motors, instead. Relays, contactors, solenoid valves and other electromagnetic switching devices generate three kinds of noise: electromagnetic noise that can be radiated as well as inductively coupled due to switching of large currents; magnetic flux leakages around the relay coils; and spark discharge due to the creation of a large change in voltage or current at the moment of switching. Therefore, relays should always be placed in protective shielded enclosures. If possible, use solid state switching devices, such as SCRs (silicon controlled rectifiers), transistors, thyristors and electronic relays, whilst ensuring that the switching circuits are housed in shielded boxes.

As a general principle, sparks should be avoided or suppressed. However, the ignition system is an unavoidable spark source. Automobile ignition cables have adequate impedance to prevent radiation from the cables to interfere with the audio system, the engine control unit, etc. In PDEs where the tube is open to the atmosphere, the radiation from the spark can travel outward instead of being absorbed and attenuated by

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a grounded metal body. An effective way to alleviate the spark-induced EMI is to cut down the energy to as low as possible for ignition. The inductive ignition system used can produce 150 mJ per spark. By trial and error, a resistance of 12–16 kΩ was found to cut down the spark-induced EMI to acceptable levels. The authors' experience thus far is that inductive ignition is superior to capacitive discharge. The latter produces higher energy per spark and can deliver a series of sparks in rapid succession. But it is a stronger source of EMI. Nonetheless, capacitive ignition may be a candidate for an operational PDE where diagnostics are not performed. Additional care must be taken when designing the ignition system in PDEs to prevent the spark from discharging through sensitive instruments or transducers.

CONCLUSIONS

A survey of issues pertinent to ground testing of PDEs is provided. Most of the PDE studies up to date involve single shot experiments or short run times of 10–20 s. Much longer run times are required to achieve the goal of an operational engine. Some of the concerns that limit the run time of PDEs are examined and possible solutions are offered. The disadvantages of mechanical rotary valves used for gas injection into PDEs are compared with the advantages of using solenoid valves and electronic fuel injectors. A major obstacle is the heating of the tubes, components and diagnostic instruments. The detrimental effects of electromagnetic interference and methods to overcome them are also discussed. One big source of EMI that cannot be avoided is the ignition system. Possible solutions for noise are offered.

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