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Experiences in Testing of a Large-Scale, Liquid-Fueled, Air-Breathing, Pulse Detonation Engine

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A large-scale pulse detonation engine utilizing air and kerosene was constructed to demonstrate its practical implementation. Testing this ground demonstrator revealed successes and areas requiring improvement in the design, fabrication, installation and actual testing of a large PDE. Many of the challenges of translating smaller, single shot experiments have been overcome in this implementation of a 4 inch diameter detonation engine. This paper will discuss the experiences in testing the engine as a whole, and also on some of these subsystems involved. Full testing has not been completed, but successful operation provides a positive outlook for further innovation and modification.

Nomenclature

°C	=	temperature - Celsius
C-J	=	Chapman-Jouguet property
d	=	diameter of tube
D	=	detonation velocities
DAQ	=	Data Acquisition System
DDT	=	deflagration to detonation transition
d*t*	=	time step
f	=	frequency
Hz	=	Hertz generic functions
i.d.	=	inner diameter
in.	=	inch
J	=	Joule
kN	=	kilo Newton
LHC	=	liquid hydrocarbon fuel
m	=	meter
p	=	pressure, Pa
PDE	=	Pulse Detonation Engine
φ	=	stoichiometric ratio
rpm	=	revolutions per minute
s	=	second
V	=	velocity, m/s
λ	=	detonation cell size

I. Introduction

PULSE detonation engines (PDEs), while simple in concept, have long proven difficult to operate effectively for reliable transition into practical applications. While the possible applications of the PDE are numerous, being able to incorporate a reliable air-breathing PDE for use in high-speed single or augmented engine application is of obvious importance. A large-scale ground demonstrator has been built to develop an understanding of operational issues. Testing of this PDE has shown that many of the obstacles have been overcome to the point where minor

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modifications can yield a reliable engine. This paper will not delve into the minute details of each subsystem. However, a general overview of the findings from the testing of this PDE will be discussed.

There were several primary hurdles that had to be overcome by the design. The primary objective of this PDE was to create an engine capable of producing approximately 500 pounds of thrust and operate at up to 50 Hz, while utilizing air and a liquid hydrocarbon fuel. Given that the thrust is proportional to the frequency of detonation, area of the detonation tube, the initial pressure, and the number of tubes, it was desirable to create a 4 inch diameter detonation tube capable of operating at the higher frequencies. The 4 inch size was chosen as it exceeds the normal diameter for the detonation of liquid hydrocarbons based upon the sizing rule of tube diameter $D > \lambda / \pi$, where λ is the detonation cell size[1], and matches the theoretical thrust requirement. Once that could be achieved successfully, increasing the number of detonation tubes would simply be a matter of replication. One of the primary difficulties with the larger tubes at higher frequencies is the sheer volume of air and fuel required. Another primary difficulty is the ability to detonate liquid hydrocarbon (LHC) fuels without the assistance of a predetonator. All other concerns are with the design of subsystems which support these requirements. Thus, the PDE design incorporated the introduction of heated and vaporized kerosene through large volume sidewall injection. Kerosene was used as it mimics jet propulsion and rocket propulsion type fuels in its base chemical makeup. The chemical makeup of the kerosene was Dodecane ($C_{12}H_{26}$) with chains of $CH_3(CH_2)_{10}CH_3$. This replicated Jet A fuel and had a known thermal value of 18400 BTU. Since the fuel LHC's are typically similar, being able to reliably detonate the kerosene should translate into similar ability to detonate the other liquid hydrocarbon fuels. While the demonstrator has the ability to interchange multiple detonation inducing abilities, the initial tests involve the use of orifice plates with more than 50% blockage. A constant plasma field was also to be used to create an ion-doped environment to assist in the cracking of the kerosene hydrocarbons. The plasma energy field[2] was also to serve a secondary purpose of reducing the overall high electrical energy needed for ignition so as to increase the longevity of the spark generators. To assist with the overall simplistic nature of a PDE, the air and fuel was introduced into the PDE by means of a variable speed rotary valve system. Sidewall injection of fuel is intended to maximize thrust output.

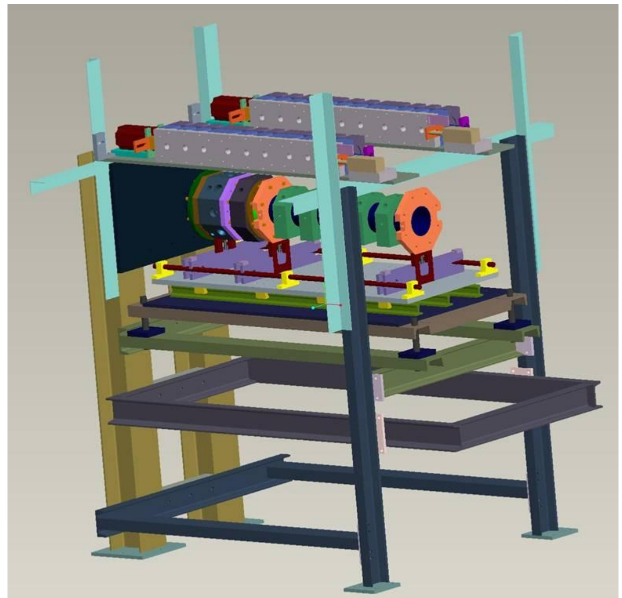

Figure 1. PDE model on stand with rotary valves on top.

II. Testing

Testing of this ground demonstrator began on April 16, 2010. Over 150 runs were made initially, utilizing operational frequencies of 1 to 4 Hz. The test runs ranged in time from 30 seconds to 13 minutes. While all indications point in the direction of achieved detonation velocities, preliminary data analysis revealed test runs with sub-C-J velocities. One run for instance provided a wave velocity of 992 m/s and only about 200 pounds of peak thrust while operating at an erratic 4 Hz. Another run observed 240 pounds of thrust. The 240 lbf of thrust was however, achieved utilizing only one of 12 fuel injectors while operating at 3 Hz instead of the designed 20 Hz. Given the large number of initial test runs, and the sheer volume of data through which to sift, promising better results may yet evolve.

A. Fuel and Air System

Because of the inherent difficulties of detonating the kerosene, every effort was made to create optimal conditions for initiating the deflagration to detonation transition, DDT, consistently. The fuel and air was to be heated so that the fuel is delivered at close to 200° C., near the flash vaporization temperature for the kerosene. The fuel was able to be reliably heated to 210°C. The kerosene was also to be introduced as a vapor, instead of droplets, for better fuel-air homogeneity, through the use of standard diesel injectors. The diesel injectors required a cracking pressure of about 2500 psi. The injectors were tested with oil having a similar viscosity as kerosene. They were also tested with water and kerosene to find the cracking pressure of 2500 psi. It was discovered that testing diesel injectors with water yields undesireable results. They were not able to be tested with vaporized fuel. When the PDE was being tested with the vaporized fuel, the injectors experienced a hydro locking condition. This condition prevented any fuel from exiting the injectors. The injectors were examined and modified. After modification, they worked as required. The fuel was pressurized to the use of a 6000 psi gaseous nitrogen bottle. The fuel is then routed through a liquid bath, which heats the fuel to the proper temperature. The fuel is manually controlled by a switch that since the fuel through a valve which pulses the fuel and varies the volume introduced. The redesigned fuel delivery system utilizing the pressurized fuel bottle minimized the system complexity and overall size. The pressurized bottle system allows the PDE to be portable easily modified for flight weight design. Since this is a ground demonstrator, the air is provided by the use of a large air compressor that is able to deliver large volumes of air at about 2 atmospheres pressure into the engine. The air design can easily be translated into in-flight air breathing environments. The air goes through a heat exchanger that is heated by a gas powered heater. The air then travels into a plenum chamber, where the heated kerosene is vaporized and introduced through one of 12 fuel injectors. This is to allow fuel mixing to occur before the rotary valves permit the fuel air mixture to enter the engine at the appropriate times. The initial fuel delivery system involved the use of a modified pressure washer. This was abandoned after, the pressure washer itself continued to exhibit failures and unacceptable operating conditions when kerosene was utilized instead of water for which it was designed.

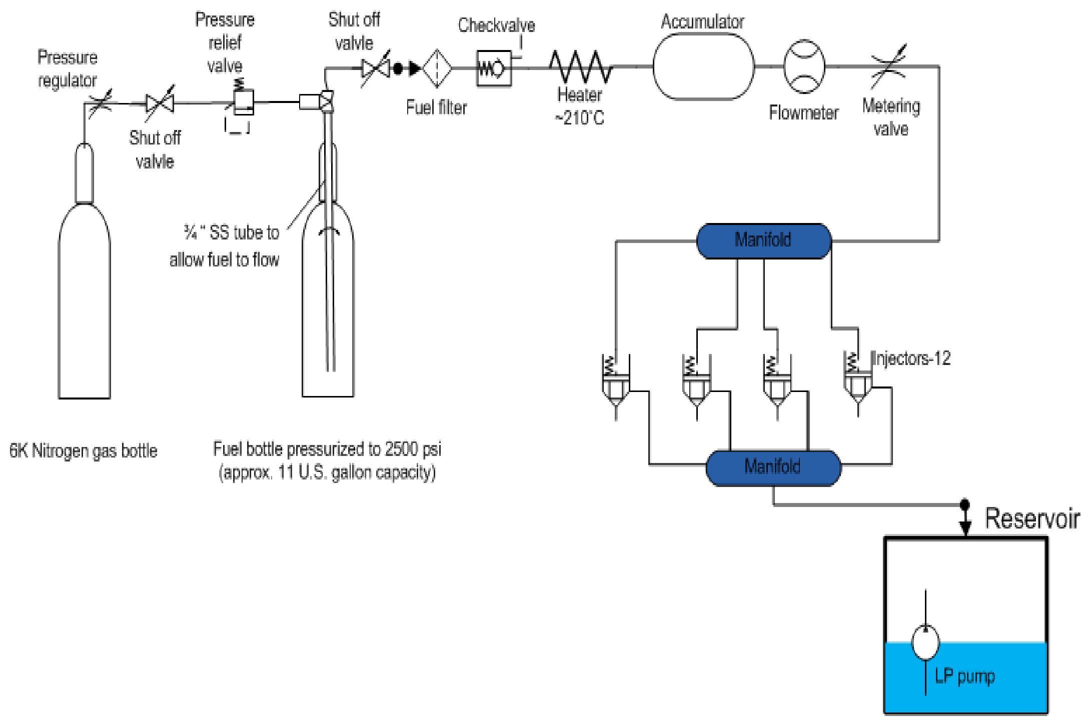

Figure 2. Modified fuel delivery system.

The initial fuel delivery design provided for kerosene to be introduced into a 20 US gallon tank. The fuel is inerted by percolating nitrogen. Further, nitrogen is used to pressurize the fuel tank to 15--45 psig. The fuel then flows past a filter before being further pressurized by a pressure washer to 2000 psig. The fuel then enters an accumulator and subsequently is heated by traveling through a metal coil submersed in a glycerin/water bath to about 210°C which is sufficient to vaporize the fuel at 1--2 atm. The pressure washer and glycerin/water bath are used for simplicity and cost. The heated fuel then enters an array of 12 diesel injectors, spraying into a stream of hot air. Initial PDE test runs only utilized one active fuel injector to assist in the determination of the actual amount of fuel that is atomized and enters into the PDE detonation chamber. More injectors are to be added appropriately when the PDE test run frequency increases and the need for higher volumes increase proportionally. Pre-heating the fuel assists in atomization. The intent is to assist the liquid hydrocarbon, kerosene, and becoming as likely todetonate as possible by pre-heating and injecting liquid fuel into a hot air stream. These conditions are hoped to flash vaporize the fuel instead of introducing the fuel in water droplets form. The inability of the air heating system to continuously deliver large volumes of heated air did cause water droplets to occur. Condensation was even formed inside of the fuel air mixing chamber as the hot fuel came in contact with the cooler air during the mixing process. This condensation created a condition whereby only about 15 to 20 % of vaporized fuel was able to be introduced into the PDE detonation chamber. The remaining 80% of the condensed fuel was recycled into a fuel capture system. The design of the PDE ground demonstrator was to introduce approximately 1 L of fuel per minute. This was to be adjusted as necessary when the number of fuel injectors utilized was increased. Other than making minor adjustments to optimize the fuel delivery volume, the fuel system as a whole, worked as designed. The air heating system on the other hand, was only able to produce a heated air temperature of about 25° C. by the time it mixed with the fuel. Being able to heat large volumes of air will require a different air heating subsystem.

Air from a compressor in the laboratory at 11 atm is used to supply the engine. The air entering the upper branch is heated and hot liquid fuel is injected into the hot air. 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 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 the chamber and provide some cooling.

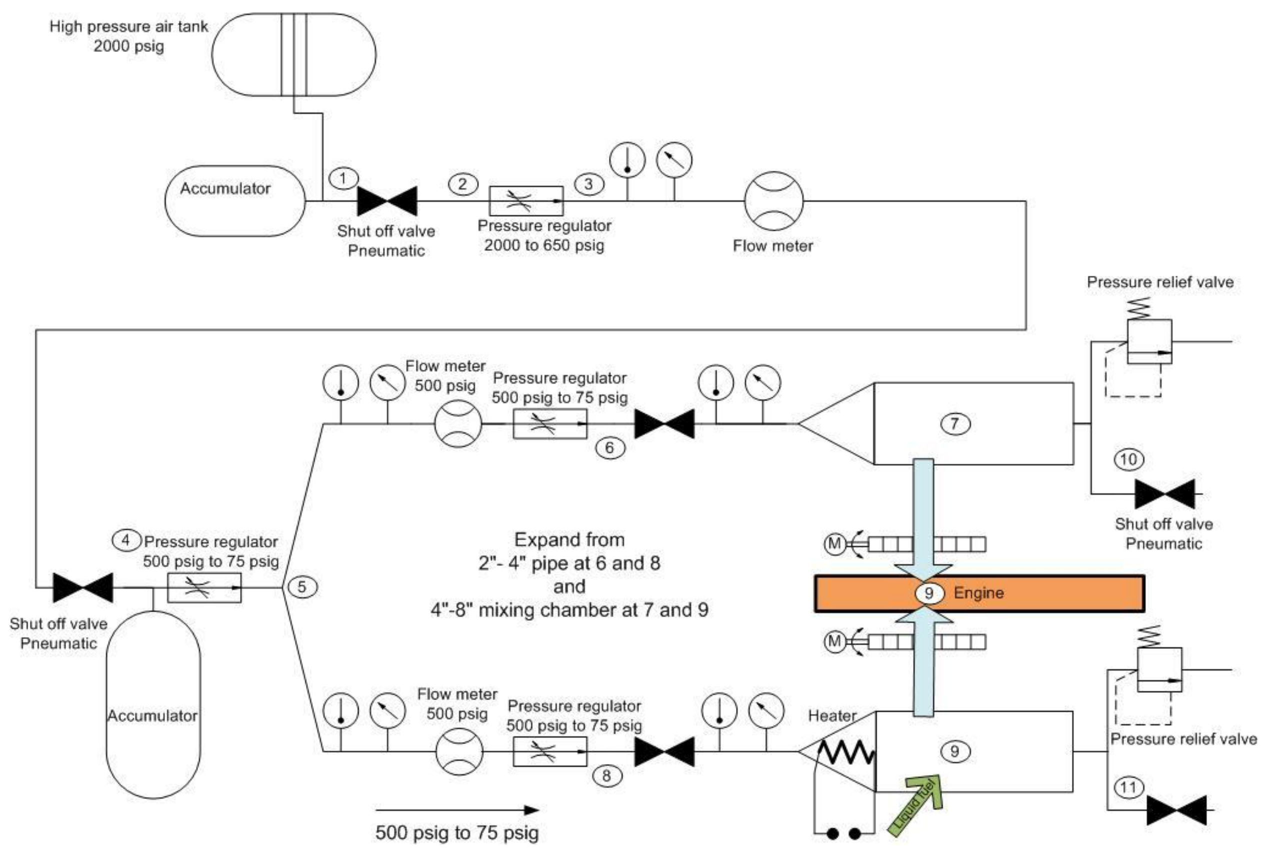

Figure 3. Diagram of air supply.

Figure **3.** is a diagram showing the air and gas delivery system. Air is delivered from an existing 2000 psig compressor via a 1 in. ID pipe and first regulated to 650 psig before being finally regulated down to 75 psig. A 2 in. ID pipe is used for the lower pressure lines. Two accumulators are used to dampen fluctuations and accommodate varying air demands. The two accumulators were filled with metal that heated when the bottles were pressurized. The hot metal assisted with heating the air. Within the air delivery system are the usual pressure gauges and flow meters. Preliminary calculations indicate that air at 75 psig can be used to feed the engine to for it to operate at up to 50 Hz.

The air is split into two lines, one for the purge and the other for mixing with fuel. 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 was designed to be heated to 100-200°C. Actual constant air temperatures in the fuel air mixing chamber plenum were only in the mid 70°F range. Heating the air assists 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 75 psig enters a plenum chamber 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.

B. Ignition

Initiation of DDT was initially designed to occur with only kerosene and air. After was discovered that the air heating system was unable to provide the higher temperature sustained for long time periods with large volumes of air, it was decided to utilize a pre-igniter to make up for the lower temperature fuel–air mixture. Attempts were made to detonate the fuel or mixture at the lower temperatures, however, the lower temperatures caused a condition whereby a significant amount of the vaporized fuel began to condense into droplets. Once a stoichiometric ratio of hydrogen and oxygen and kerosene was established, the DDT began occurring consistently. Cold flow and run-up tests showed that the kerosene was being introduced in controllable volumes. The hydrogen and oxygen were able to be detonated easily. Once combined, obvious deflagration was visible until the stoichiometric ratios were achieved. Experiments were also conducted whereby methane and oxygen were utilized as a pre-detonator and initial appearances show the methane and oxygen mixture to be more energetic. This is important as the methane would make for safer onboard storage ability. Also, creating the methane on board could even further reduce operational flight weights. Given that safety was a primary concern, the use of snubbers and flash arrestors was required because of the explosive hydrogen and oxygen introduction into a volatile environment. The use of the safety devices, however, created difficulty in obtaining the stoichiometric ratios. Since they made calculating volumetric flow rates difficult, the actual pressures needed to obtain the correct volume of each gas had to be experimentally obtained after an approximate calculated value was obtained.

The ignition system of the PDE is designed to utilize a Corona electrode system to ionize the air, in conjunction with the utilization of eight circumferentially mounted spark plugs.the Corona electrodes are to be in a constant on position for the vitiation of the air, and not for ignition purposes. The Corona electrodes set up involved the location of eight large electrodes mounted in the head end of the DDT chamber. As discovered during prior PDE testing at UT Arlington, the lifespan of spark plugs in detonation type systems is often minimized because of the high energy output and the extreme detonation conditions. The design of allowing the air to be ionized, creates a condition whereby the fuel air mixture is more likely to detonate with a lower energy output from the spark plugs. The Corona electrode system was set to utilize a high-voltage power supply to provide no more than 10 kV of energy so as to prevent arcing and premature ignition. When working properly, a blue glow and a slight ozone odor are observed. Arcing is heard if the voltage is set too high. The use of eight spark plugs permits the overall energy output of the spark plugs to be individually less while still providing a sufficient amount of energy overall. These spark plugs are energized by a TTL activated spark generator, which sends energy to all eight spark plugs at the same time. A LabVIEW controller program provides the TTL signal through a predetermined timing condition. The timing is determined by the location of the rotary valves. Each rotary valve is in an open condition twice per rotation. This allows for 180° of rotation of the fuel air rotary valve to be used as the basis for timing. For conceptual terms, this allows for 60° of rotation to permit

Figure 4. Corona electrodes mounted in head cap.

introduction of the fuel air mixture, and the closing of the intake rotary valve. The next 60° of rotation would be allotted for DDT and blowdown with the intake and purge valves in the closed position. The last 60° of rotation would be available for introduction of purge air from the purge air rotary valve. The cycle would then repeat. The exact position of the rotary valves are determined through the use of the rotary valve encoder located on the ends of each rotary valve. The National Instruments stepper motors used did not contain an internal position encoder that could be used. Any future designs will have larger stepper motors with built in encoders. The rotary valve encoders translate 0 to 360° into a 0 to 5 V output, which is conditioned and analyzed by the LabVIEW programs. To allow for an additional safety factor, ignition TTL is initiated after the fuel air intake rotary valve has been in a closed position for at least 10° of rotation. This allows for delay and any possible inaccuracy in the zeroing of the initial position of the rotary valve. Also, this helps in the prevention of back flash conditions since the DDT will not be initiated unless the rotary valves are closed. If either of the rotary valves is an open position, the TTL signal is prevented from occurring. The addition of position encoders to the ends of the rotary valves was problematic. The position encoders are very small and the shafts are fragile. Manufacturing difficulties with one of the rotary valves caused a condition where multiple encoders shafts broke. This problem was eventually solved with the introduction of a U-joint. Because this particular design would not be preferable in a real application, the use of stepper motors with built in encoders would be preferable. Other types of controllable motors were not investigated.

The spark plugs are located circumferentially because of the toroidal DDT initiation that is expected in the ignition chamber. Examination of the spark plugs after multiple test runs did seem to indicate that a slight carbon build up difference on the spark plugs was noticed. The primary build up was found to occur on the opposite side where the fuel air mixture enters the DDT chamber. The condition appears to decrease as the location of the spark plugs go from the opposing side of the fuel air introduction, downward along the bottom, and then back upwards around to the opposing spark plug. It was discovered however that the spark plugs fared very well and did not exhibit any degradation other than the slight carbon buildups noticed. These spark plugs used were Bosch Platinum +4, model number 4481, spark plugs. The design of the spark plug electrodes did not require any gapping. For reference, the spark plugs are located by numbers one through eight. Number 1 is located on the top of the PDE. When looking at the closed ahead and of the PDE, the spark plugs are counted clockwise with 2,3 and 4 on the right side, 5 at the bottom, 6,7 ,and 8 on the left side. Number four would be the spark plugs located across from the fuel air introduction tubing. On May 27, 2010, the spark plugs were removed to check their condition after being subjected to numerous test runs. Plug number one, at the top, which dry, clear, and the insulator was still white. There was no discernible damage nor erosion. Plug number two, appeared to have a slight fuel film on its surface. The insulator was a light tan in color and slight carbon deposits on the metal shell of the spark plug was visible. There was no visible damage nor erosion. Plug number three, on the right side, exhibited the same light film of fuel, with the insulator being slightly tan. There was no visible damage nor erosion. Spark plug number four, is the one directly across from the fuel air introduction. Tubing. It exhibited a heavy film of fuel and the insulator was a darker tan, with slight carbon deposits on one half of the insulator while the other half was white. There was no damage, nor erosion. Spark plug number five was soaked in a fuel water mixture. This appeared to be kerosene with beads of water. When the spark plug was removed from the lowest point, approximately 5 to 10 mL of liquid drained out of the opening. It was believed that most of the liquid was from a fuel rich, kerosene environment, while the water may have come from a slight coolant leak. The head unit was tightened to correct this problem. Spark plug number six, exhibited the heavy film of fuel on the insulator. The insulator was dark tan, but did not have heavy carbon buildup. There was no visible damage nor erosion. Spark plug number seven exhibited the light film and a light tan color. There was no visible damage nor erosion. Spark plug number eight exhibited a dry, clean, white insulator. Spark plug, number eight appeared practically brand-new with no visible damage nor erosion. a subsequent examination of the same spark plugs in July yielded the same conditions. The same spark plugs were then reinserted for continued use, since there appear to be no signs of degradation.

Figure 5. Spark plugs showing negligible degradation.

The Corona electrodes operated for a short time before a short condition manifested itself and prevented the high-voltage generator from providing energy to the Corona electrodes. The problem appears to be a short condition caused either by an electrode irregularity that allowsa short to occur. Moret geometry design flaw, which manifested itself after a short duration. The Corona electrode system was deactivated for further testing until the faulty condition can be corrected. The Corona electrode system did operate as designed during its operational time.

The initial design involved the use of free radical ion doping through the introduction of the plasma field. Only a few runs utilizing the unique high energy system were able to be performed. An unknown electrical failure occurred in parts of the high-voltage, low amperage, plasma generation system. Time constraints do not allow for the production of a new plasma system component and the subsystem was inactivated. This as well contributed to the decision to use a pre-detonator. Previous experience with ignition initiators such as spark plugs has yielded a minimal lifespan of the spark plugs and a detonation environment. A solution to this problem was to recess the spark plugs, slightly, and locate the spark plugs radially around the detonation chamber. This allowed less energy to be required of each spark plug to achieve the same total energy required for DDT. Test runs with the present PDE design show that over one jewel of total energy is required to initiate DDT consistently. The use of eight spark plugs provided 1.6 J of ignition energy without the plasma source. After over 150 test runs, the spark plugs were in such good condition that they were not replaced when the engine was rebuilt. One additional advantage to the multiple spark plug initiation is as a redundant measure in case of one or more spark plugs failing.

This demonstrator has multiple abilities to utilize orifice plates, Shchelkin coils, and combinations of DDT enhancing devices. For the initial sets of experiment runs, orifice plates with a greater than 50% blockage ratio were utilized. They set up two orifice plates of equal size was used successfully. Further tests will evaluate the effects of smaller blockage ratios. The fuel air mixture was introduced into the detonation chamber area and perpendicular directions. It is believed this and initiated a swirling and mixing. The orifice plate created wave reflections also combined with this swirling and helped create a minimal DDT required distance. The orifice plates themselves were made with cooling jackets. These cooling jackets, as well as cooling jackets integrated into the detonation tube itself, were able to keep the heat flux at a condition where destruction of the orifice plates and internal parts was not discovered. The cooling jackets also assisted in defeating the auto ignition problem from excessive temperatures.

C. Rotary valves

The fuel air mixture was introduced through variable speed rotary valves. These rotary valves, incorporated position sensors and were controlled through a stepper motor that was further controlled by the LabVIEW controller program. The rotary valves provided the limiting factor for the PDE maximum operating frequency of 4 Hz. While the basic design appeared sound, the actual manufacture and design yielded problems whereby the rotary valves were unable to be turned with the available torque of the stepper motors. Larger stepper motors and or redesigned rotary valves will be required to operate the PDE at the designed 50 Hz frequency. These stepper motors that turn the rotary valves, was the limiting factor in setting a maximum up operating range of 50 Hz.. After 1500 rpm,(50 Hz.), the rotary valves could not be used for this PDE application because the time for a 90° rotation is less than 10 ms. 10 ms was found to be the timeframe for a full detonation and blowdown cycle to complete. This value is achieved utilizing calculations involving the PDE size with decane utilized in a fully vaporized state. With this limitation in mind, the rotary valve openings were designed to allow a sufficient volumetric flow rate of the fuel and air mixture at up to 50 Hz.

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 rotors are made of steel. The rotor is driven by stepper motors. The design has nine ports. Each port has a large identicle orifices to allow large volumes of air and fuel to pass. The rotary valves were built as a modification of prior designs.

The new design used graphite rod seals and rotary seals (as used in water pumps) to prevent leakage. There is a pneumatically operated, master shutoff valve, with additional spring return. 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. Nine ports are available although only eight were eventually used, with the extra capped. Of the eight ports, seven are connected to the side of the combustor and one is connected to the head manifold. While attempting to keep costs down, the new design utilized a rotary of consisting of multiple plates that were held together to create the solid rotary valve housing. It was found that this is undesirable, because of the tight tolerances between the graphite rod in the walls of the rotary valve housing. By having to connect all of the plates,

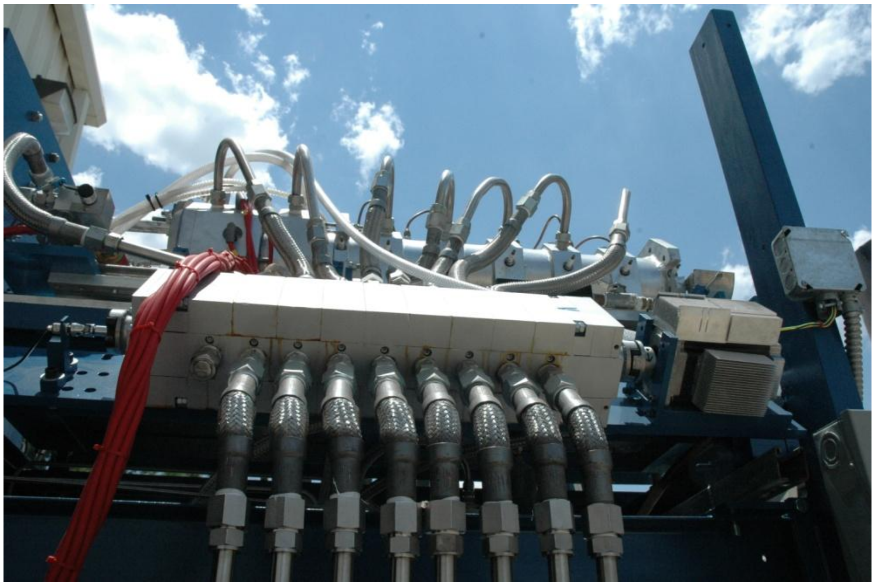

Figure 6. Rotary valve leading to PDE on top.

difficulty was found in creating a bore which was consistent the entire length. Even mounting the rotary valve created just enough torque to cause the shaft to want to bind. Once put together, the valving housing was bored straight through yet, the mounting torque continued to cause binding. This eventually limited the maximum operating frequency to 4 Hz. The redesign of the rotary valve as a single unit would be the next design evolution that should eliminate the problem. The non-failing rotaryvalve was able to spin at desired frequencies while only requiring approximately 25 inch pounds to turn the valve. The amount of force required to spin the valves was found to increase as the air pressure applied to the valves during operation increased. The stepper motors used were found to be underpowered for the final condition of the valves. Future design, should have a larger stepper motor was an integrated position sensor.

D. Data Acquisition System

A LabVIEW controller program was specifically made for this PDE application. The program is able to take input readings from the rotary valve position encoders and create proper ignition timing, as well as purge and intake, to operate the PDE from low to high frequencies. The difference in the frequencies is compensated by the LabVIEW programs by altering the rotational speeds of the rotary valves to match volume requirements. The program also acquired numerous points of data to be analyzed further. The ability to measure thrust, pressure, ions, flow rates, and temperatures was available.

The use of National Instruments interfaces and the LabVIEW controller program is the primary method for running the PDE. This was in combination with manual operator controlled switches. While the entire process could be automated, critical items were purposely made to be controlled by the operators for this ground test demonstrator. This allowed for the operators to have control for modifying test parameters and variables at a moment's notice as well as for systematic testing purposes. A high speed digital acquisition, DAQ, PXIe-1065, is utilized to process condition and high-speed pressure sensor data and thrust measurement data. Thrust measurements were handled by the use of a PCB ICP 201B03 model load cell with a signal range of 0 to 500 pounds force and an output of 0 to 5 V. Pressure transducers utilize model number PCB ICP 111A 24, dynamic pressure transducers, with the signal range of 0 to 1000 psig added output of 0 to 5 V. Static pressure transducers, which utilize the similar voltage outputs, are used to monitor pressure conditions of the air flow lines and chambers, as well as the gaseous flows. Some of these are connected to a BNC box, 2110, which is then attached to the high speed DAQ at NI PXI 6133 card.the others are transferred to the high speed DAQ through a USB cable.

A low speed DAQ, PXI 1042 Q, is utilized to handle the acquisition of thermocouples, flowmeters, and rotary shaft encoders. BNC 2110, SCB 68, and SCC 68 connection boxes are utilized for these items. The data is transferred into DAQ cards PXI 6255 and 6133 cards.the high and low speed DAQ's are connected. An optical cable that connects the low speed DAQ to a control room computer. The control room computer remotes into the high speed DAQ and the control room computer, thus has full operational control. Six ion detectors were also attached to the system. They are created by removing the electrode from NGK Brand spark plugs. As a detonation wave passes these ion detectors, the altered ion concentrations create a difference in the output readings from the ion detectors. The time difference between these changes can be used to calculate the detonation wave velocities. Because of the ion field would tend to coalesce around the ion detectors and prevent the ability to measure differences, the use of purge air to eliminate this build up was required. The purge air was required anyway by design, but also found to be beneficial to create a proper environment for the ion detectors. Total cycle time can be reduced by beinning the purge before the detonation front exits the tube.

The LabVIEW controller program utilizes multiple virtual instruments, VI's, which utilize front panel faces for operator control. An initial VI causes the hydrogen and oxygen valves to be initiated. When initially activated, the hydrogen and oxygen valves are in an open state, and must be initialized to close them and prepare for operational runs. This initialization is one of the first steps performed when turning on the LabVIEW computer systems. The initialization is only required one time, upon turning on the system. The next virtual instrument utilized is one which resets the rotary valve positions to a pre-determined initial state. The initial closed positions of each rotary valve are manually verified and the related and proportional voltage output is recorded. This voltage output is used to determine the position of each rotary valve through the use of the rotary encoders out putting a 0 to 5 volt reading for the 0 to 360° of rotation. The initial position for each rotary valve is one in which the rotary valves are in a closed position. This is a safety feature which prevents unexpected failure or backflash conditions. It is operational practice to reset the rotary valves after each run. National Instruments motion controllers are utilized to operate the National Instruments brand stepper motors that turn the rotary valves. The controller program outputs precisely timed and controlled signals to the stepper motors, which are able to turn the rotary valves and steps of 1.8°. This provides the ability to accelerate the stepper motors, both positively and negatively so that the rotary valves can be sped up or slowed down at higher velocities to allow the correct volume of fuel and air into the engine. Manufacturing difficulties created a condition where the force required to turn the rotary valves can exceed the output power of the stepper motors utilized to turn the rotary valves. This can cause a rotary valve to be out of position at the end of the run and the operational procedure is to reset the rotary valves after each run as a precautionary measure. Separate low-speed and high-speed VIs are utilized for activating the data acquisition function in each DAQ. These are manually turned on and off before and after each run. Care is to be taking that the high speed DAQ is taking data for the least amount of time since it is acquiring data at a minimum rate of 2 million samples per second. The enormous size of the data files can cause difficulty in the transferring of the entire data file. The operator has control of the Main control VI and has the ability to manually input certain test parameters. The frequency of the test run and the acceleration to reach that frequency are available options. The operator sets the duration of the test run, and also controls the volume of air that enters the purge and the fuel air mixing chambers. Large Fisher brand control valves are activated utilizing a 0 to 5 V voltage input. It was found that the rotary valve operating conditions limited the purge air voltage input to 1.9 V, and the fuel air side was limited to 2.3 V max. This volume fair was acceptable for the lower frequencies of the initial operational test runs. Once the run is activated, the operator has the ability to alter the Fisher valve’s volume flow rate, as well as the push button ability to stop the oxygen and hydrogen solenoids from activating.

Thrust measurements were taken from a load cell that was mounted on the head end of the PDE. The entire engine is mounted on a thrust stand, which does not permit moments to occur. A thick steel plate was mounted onto the thrust stand, which was securely bolted to the floor of the test cell room. A thrust probe was designed to mount to the head end of the PDE and the load cell was mounted into the end of that cylindrical peace. A cap was then mounted on the end of the load cell. That cap was designed to mate up with a ball nose end. This ball nose and was then placed in direct contact with the reaction plate and held in place by the application of a constant force which allowed the load cell to equalize.

An unforeseen difficulty in the writing of data, while the computer was near the harsh PDE environment was encountered. It was discovered that the buffers and the DAQ system quickly became overloaded as the vibrations caused the doubt to be unable to write the data to the disk. This caused only the first part of a minimum 32nd test run to be recorded. An attempt to minimize the vibration interference was made by placing a large wooden shield between the PDE and the DAQ. The wooden shield was covered with thick foam rubber that could absorb all minimize vibrations reaching the DAQ. They shield had some affect. However, it only blocks direct vibrations. The PDE was set up inside of an enclosed cement test room, which allowed reflected vibrations to still reach the DAQ. Yet another problem with the sensitive instruments wires being too close to power wires also yielded enormous amounts of unusable data. The room dynamics caused the high-voltage lines to be close enough to interfere with the data lines. The stepper motors were also found to generate a significant enough electrical field to cause interference with nearby sensor wires. Shielding was added to the electrical wires and other wires were rerouted. The rebuild has modified and alter the position of the wires to attempt to eliminate the excessive noise due to the proximity to the power wires. The PDE was purposely rebuilt with all power lines being purposely routed through flexible metal conduit to act as a shield. The conduit was then routed along one side of the PDE while the data lines were routed on the other side. While initially requiring a minimum of two people to physically operate the PDE, it was discovered that the PDE could be operated manually by one person. Human test operators are necessary for experimental test runs. However, the controller program could easily be modified for autonomous operation.

E. Safety and Control

The entire PDE operation is monitored by eight webcams and two microphones. The PDE is mounted inside of a room with thick concrete walls. Because of the experimental nature of the detonation engine during its break in, occupation of the room by personnel during PDE operation was prohibited.the concrete walls only had one small viewing window through which to visually see the PDE during operation. The engine was run entirely from a remote control room nearby. The cameras were mounted strategically so that viewing of the operational systems and associated gauges, could be monitored remotely. One microphone was mounted directly above the engine, while the other microphone was mounted outside, where is the fuel delivery system and the air heating system were located. Two of the cameras were mounted outside so that of view of the fuel heating system and the fuel delivery system was available.

Figure 7. June 10, 2010 - initial testing.

While the PDE design incorporated numerous safety features within its operational systems, manual control by the test operator was available through a set of panel board switches. The panel board switch layout included 12 on and off switches which were wired directly to a relay board inside the PDE test cell room. One switch manually activated the propane air heating system outside with the ability to deactivate the heater. Hydrogen was supplied from outside the building and was controlled manually by two panel board switches. One switch controlled the supply line from the bottle to allow or forbid entry into the building. The other switch activated soleniods which permitted hydrogen to enter the engine itself. The second switch was primarily to be used to variably control the timing of hydrogen introduction used as a pre-detonator during the testing. This control was modified during the early stages of testing to control the introduction of hydrogen and oxygen at the same time. These switches did not however control the timing of the solenoids. The timing of the solenoids was controlled through the LabVIEW controller program. The output of a TTL signal to activate the hydrogen and oxygen solenoids was timed so that entry was only permitted when the rotary valves were in the appropriate position. This prevented the possibility of injecting an explosive mixture at an incorrect time, causing a backflash condition. The hydrogen and oxygen lines themselves had one-way valves, and flashback arrestors incorporated into the system as an additional safety measure. It was found that the safety measures have the undesirable effect of altering the flow rates. These differences were overcome by systematically altering the pressures to relocate the stoichiometric conditions.

The liquid fuel heating and delivering system also had manual switch controls. The liquid fuel electric heater was operated by an additional 24 V AC relay within a fuse panel box. This permitted the test operator to manually deactivate the liquid fuel heater, while also permitting the faster breaker box to activate in case of a failure condition. The liquid fuel pump was controlled through a panel switch that needed to be turned on in order for the fuel pump to be able to start. This also allowed immediate shut off of the liquid fuel pump by the test operator. During its initial use the fuel pump was monitored by one of the outside cameras and the outside microphone. The liquid fuel high-pressure supply solenoid was controlled through pneumatic valve that was activated by the switched solenoid valve on the panel board. This permitted the test operator to control exactly when the liquid fuel was introduced into the engine.

The Corona electrode supply switch controlled the activation of the Corona electrodes. The Corona electrode was designed so that it would ionize the air in the DDT chamber to augment the detonation conditions. The ignition of the system is controlled through a separate panel board switch. This ignition system contact allowed energy to be delivered to the sparkplugs.the LabVIEW program still continue to send a TTL ignition signal to the spark generator device. The spark generator device would not release energy, unless the ignition system contact switch was activated. The LabVIEW control program was designed so that ignition energy would not be activated unless the rotary valves were in the proper closed position for DDT. If the rotary valves became stuck or out of their proper timing sequence, the ignition TTL signal would not be sent. Also, when a programmed stop condition is activated, whether program door manually activated, the LabVIEW controller program automatically stops the rotary valves in the closed position to help prevent any flashback from traveling into the fuel air plenum chamber.

A high volume, 2000 psi air compressor was utilized to provide being large flow volumes of air needed to operate the PDE at 50 Hz. High pressure air coming into the test cell, room was regulated down to 650 psi and permitted to enter at the test cell, by way of a panel board switch. The air was than regulated down to about 250 psi and split off into a purge air side and a fuel air mixture side. Two panel board switches controlled the purge air, and fuel air entry further into the system toward the PDE. In the event that an emergency shutdown condition was required, all of the above listed switches could be deactivated by the operation of a main emergency switch. The remaining switches however were allowed to still be active. These remaining switches controlled the purges and the air dumping abilities. Upon activation of separate switches, the fuel air mixture and the purge air plenum chambers can be dumped quickly. The 2000 psi and the 500 psi accumulators can also be dumped by the test cell operator activating separate switches. These switches quickly relief pressure within the system and eliminate further air entering the system. Nitrogen is used to make the conditions safe after runs, as well as in the case of an emergency condition. Nitrogen was percolated into the fuel system, and that nitrogen is left activated in the case of an emergency shut down to assist in the prevention of deflagration conditions within the fuel supply. The purge air plenum and the fuel air mixing chambers could be quickly purged and made safe through the introduction of a switch controlled nitrogen introduction. The PDE engine itself, had a nitrogen purge that was introduced through the DDT section of the PDE. A single test run tested the nitrogen in safety purging. I condition occurred where liquid fuels, instead of vaporized fuel air mixture was introduced into the operating PDE. The liquid fuel caught fire, and was pushed out of the exit port. The nitrogen purge systems operated effectively. However, an unforeseen condition in which the heavy liquid burning fuel dripped outside of the nitrogen containment area. This required is extinguishing the conditions by test operators. To prevent this condition from happening in the future, a simple redesign was incorporated in the rebuild in which the rotary valves were placed lower than the PDE. Detonation to. This geometric change prevents gravity from letting the heavy liquid fuels dripped into the detonation chamber. While this condition should not occur during normal operation, eliminating safety concerns is a major design consideration.

For safety reasons, the PDE was initially operated with a minimum of three people. The test operator is tasked with ultimate control of the entire operation. The test operator provides instructions to other personnel to perform their tasks. The test operator also controls the PDE operation and authorizes emergency shut down procedures. The personnel are provided a safety briefing prior to the initiation of test runs. Because of the inherent dangers involved with experimental engine testing, each person is assigned emergency shutdown duties depending upon the failure condition present. The test operator controls the panel switches. A second operator controls the LabVIEW programs and is able to shut down the program and manually control the TTL signal introduction as well as the air flow into the engine. The third operator is tasked with monitoring additional gauges. All three operators have multiple CCTV monitors with different views of the engine during operation. This allows remote operation, and close viewing of specific systems. In the event of a fuel fire in the test cell room, the test operator will determine whether that the attempt was made to control the condition by on hand personnel or through the use of emergency personnel. AFF type foam fire extinguishers are available to be used specifically for fuel fires. Chemical fire temperatures are also available in the event a fire condition is near building electricity.

Because the PDE was designed and operated inside of a building, the exhaust required ventilation to the outside. The exhaust was directed into a large container vessel with the back end of the vessel containing a set of three exhaust fans. The exhaust fans provided a negative air pressure conditions to suck out exhaust fumes from inside the room.

The fuel delivery system was later modified so that the liquid fuel was delivered by a 6000 psi. Nitrogen bottle, which delivered 2500 psi fuel into the test cell. This system was found to be more reliable than the water pump, but still has the high pressure to be monitored. The high pressure nitrogen is controlled through a regulator valve that has an additional needle valve to permit the nitrogen to pressurize the fuel bottle. There is a pressure relief valve that can relieve the 2500 psi pressure in the fuel bottle. There is another needle valve in-line from the fuel bottle to the test cell. Once permitted by the switch activated solenoid, the fuel is further controlled by another fine needle valve, which is used to control the amount of fuel delivered to the fuel injectors. The pressure relief valve is located near the solenoid which returns pressurized fuel back to the fuel container system.

The primary safety feature is in the way timing is handled. Timing is controlled through the position of the rotary valves and ignition is not permitted unless the rotary valves are in the proper location. The introduction of gaseous fuels is also not permitted unless the rotor valves are in the proper location.

F. Flight Weight Design

While the PDE design requires a large thrust table and mounting system for demonstration purposes, the major components themselves can be folded and compacted, or elongated to fit into present vehicle designs. The current weight as a demonstrator is still comparable, or even less than, present day engine weights. The PDE design lends itself to even lighter production weights. The ease of modification was demonstrated by the tear down of the PDE demonstrator occupying a large portion of the test cell room. The PDE demonstrator was then geometrically altered in its design locations to fit the entire engine in approximately one quarter of the space is occupied. The rebuild, actually place the PDE on a 16 foot trailer that could become a mobile demonstrator platform. The only modification needed to make the rebuild mobile would be to add air tanks for air supply, and provide a battery pack or small generator for electrical requirements. A 60 V output battery pack of 12 V batteries initially was used to power the stepper motors. The battery packs were discontinued after their proof of liability was demonstrated. Building electricity was then used to eliminate the need of recharging the batteries when multiple testing was occurring. Modification for supersonic flight would make the PDE even lighter. On the other hand, this design can easily be scaled for terrestrial purposes as well. A larger version could be modified for power production for instance.

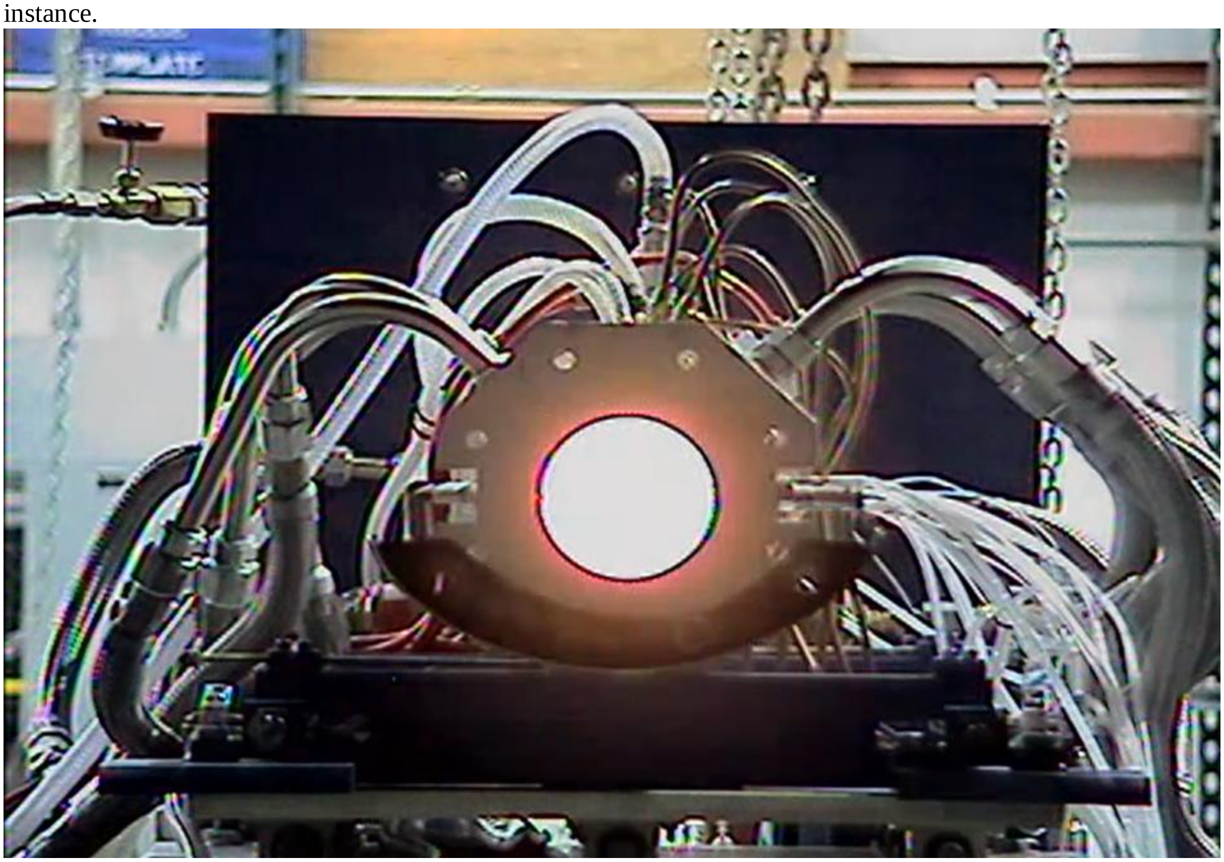

Figure 8. Rebuilt UTA PDE firing.

G. Cooling

Prior testing of continuous detonation engines at the University of Texas at Arlington have shown that it is desirable to maintain maximum ambient temperatures to around 700°C. This is to prevent autoignition of the fuel as it enters into the detonation chamber. Autoignition of fuel at that point could cause an undesirable flashback condition. Because this is a ground test demonstrator, tap water was utilized and provided from a nearby hose bibb. The water is introduced through a set of pressure regulators and distributed to built-in water jackets through connectors at the top and bottom of the PDE. There are water jackets along the length of the detonation tube. There are also water cooling passages inside of the orifice plates. The orifice plates were coated with copper as well. The PDE itself is primarily steel and stainless steel with copper paint applied to the blowdown section. The interior of the detonation tube was also assisted with cooling through the use of purge air. The cooling system worked as designed and no cooling problems were observed. Transition to flightweight design may utilize available fuels as a liquid coolant.

III. Conclusion

A large-scale, air breathing, liquid fuel pulse detonation engine was designed and assembled and tested. Kerosene was used as the liquid fuel as it closely resembles jet fuel. The innovative design lends itself to being easily modified for numerous practical applications. While initially designed for liquid fuel and air only, it demonstrated versatility for modification by being easily adapted to utilize a hydrogen/oxygen and a methane/oxygen pre-detonator to initiate detonation. With only a very small amount of data being analyzed, the engine developed a peak thrust of 1 kN (240 lb.). Current data analysis has revealed a sub-C-J pressure wave with velocities of 1288 to 1530 m/s, which can be sustainable for the length of the 1 m tube when significant volumes of vaporized fuel are introduced through sidewall ports after air heating issues are resolved. While these numbers are from available data, it only represents a few out of over 150 test runs. It may be likely, but not yet verified, that velocities over 1600 m/s were achieved. The sustainability of the detonation wave front is accomplished through the longitudinal, sidewall introduction of the fuel air mixture along the length of the PDE. The amplitude of the wave decreased during that tube length however, the volume of fuel introduced for experimental test runs utilizing only one of the 12 possible fuel injectors. It was found that the utilization of multiple lower energy spark plugs in circumferentially placement has solved the problem of short life spans of the spark plugs. After over 150 test runs, the spark plugs are still usable. This PDE demonstrator has been shown to operate four test runs of 30 seconds to 13 minute durations repeatedly, even after they tear down and rebuild. The pressure sensors were inset slightly in the DDT section and the blowdown section. While this introduces a slight cavitation error, the sensors were not damaged. The ion detectors worked as designed, and could easily be a replacement for the pressure transducers in determining wave front velocities. These ion detectors are durable and inexpensive compared to the pressure sensors. The Corona electrodes worked as designed for the short working life. It is uncertain, if a failure occurred in the high-voltage delivery system or the UTA made 1 inch Corona electrodes. Nitrogen pressurization and inerting of the fuel was utilized on this PDE. Minimal, almost negligible sooting was observed inside, the DDT chamber and along the orifice plates. While detonation of LHC's require acceptable conditions, this PDE demonstrator appears to have overcome most of these difficulties. Crucial issues were discovered and must be addressed before the engine can be considered to run reliably as designed. The numerous test runs did however show that the overall engine design is durable, replicable and reliable in its present operation abilities. When another project required the PDE occupied

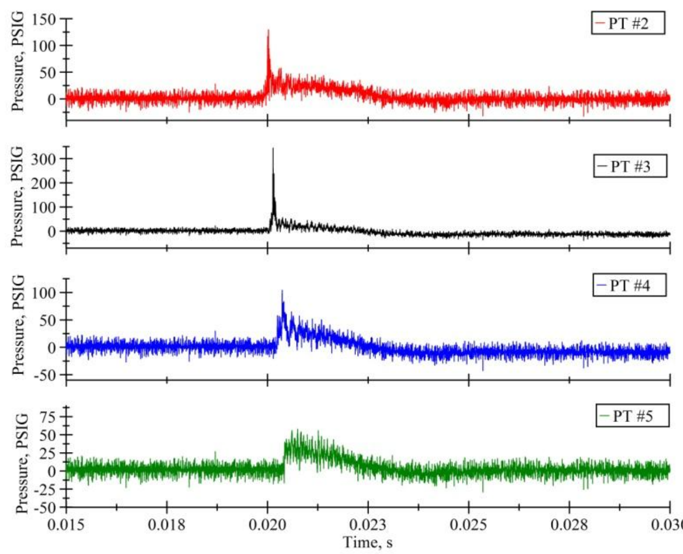

Figure 9. Pressure Spikes - typical.

test cell room, a full tear down and rebuild occurred. The rebuilt PDE was rebuilt on a demonstration trailer and minimal modifications greatly compacted the total footprint. With the exception of the remote DAQ controller equipment and the 2000 psi air compressor, the entire PDE now sits and functions on a 16 ft. trailer. Flight weight designs for subsonic and supersonic applications can be implemented into this PDE design. Further testing in modification is required. But, results obtained demonstrate that real-world applications of the engine are promising.

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