Application of Pulsed Detonation Engine for Electric Power Generation

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A compact sized PDE with an i.d. of 0.75 in. and length of 1 m was paired with an automotive turbocharger. The turbine-compressor shaft was used to drive a small ac generator by means of speed reduction wheels. The PDE was tested with propane-oxygen mixture at 15 Hz for a period of about 20 s. The turbine spun up to a speed of 127,000 rpm, whilst the generator produced electric power at 27 W and the compressor pumped air at a rate of 0.055 kg/s. The exhaust of the turbine was measured to be 800˚C, which implies that the exhaust has enough enthalpy to drive a few more turbine stages. The radial turbine results in more losses as it diverts the flow by 90˚ and its housing also creates hot spots. Axial turbines are better suited for application with PDEs and also enable better speed reduction gearing mechanisms to be applied, allowing larger and heavier generators to be used with turbines. The turbocharger did not exhibit any signs of damage after several minutes of testing. In subsequent tests with the PDE, detonations were observed for H_2-O_2 mixtures, but H_2-Air mixtures failed to detonate.

Nomenclature

ac	=	alternating current
atm	=	atmosphere
C-J	=	Chapman-Jouguet
DAQ	=	Data Acquisition System
dc	=	direct current
DDT	=	Deflagration to Detonation Transition
EMI	=	Electro-Magnetic Interference
i.d.	=	internal diameter
in.	=	inch
I_{sp}	=	Specific Impulse
k	=	kilo
M	=	Mega
m, m	=	meter or milli, as in mV
o.d.	=	outer diameter
PC	=	Personal Computer
PT	=	Pressure Transducer
rpm	=	revolutions per minute
s	=	second
s	=	second

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S/s, kS/s, MS/s	=	Samples/second, kilo and Mega
TOF	=	Time of Flight
TTL	=	Transistor-Transistor-Logic (0-5V)
V, Vac, Vdc	=	Volts, dc Volts, ac Volts
Φ	=	Equivalence Ratio
Ψ	=	Static Temperature Ratio
Ω	=	Ohm, unit of resistance

I. Introduction

Pulsed Detonation Engines, and other systems that employ detonations, are slated to be the best choice for future propulsion systems, since it has been universally accepted that detonation is a much more efficient form of combustion than deflagration. Presently there are numerous studies being done world wide on detonation engines with the hope of advancing their scope for the next generation of air breathing engines. Unlike turbo-jet engines, which require a compressor stage to increase the static pressure and temperature of the fluid before heat addition, in a PDE, a detonation wave does the work on the fluid, providing higher and quicker energy release, better theoretical efficiencies and specific impulses. Therefore, PDEs have simpler geometries and less moving parts than regular turbine engines. In an earlier work, Kailasanath[1] extolled the merits of detonation and compared the thermodynamic cycle efficiencies of the constant pressure Brayton cycle (27%), the constant volume Humphrey cycle (47%) and the ideal detonation cycle (49%).

[2]Wu et al. performed a comparative study of the same three air-breathing engine cycles, and revealed the thermodynamic cycle efficiencies as a function of static temperature ratio ($\Psi = 1$ to 5) for stoichiometric H_2 and air. It was shown that at $\Psi = 1$, the Brayton cycle has efficiency of 0%, whereas the Humphrey cycle is slightly lower than 25% and the ideal PDE is barely higher than 25%. This suggests that even without the compressor stage the PDE is able to produce a notable output. As Ψ is increased to 5, the Brayton cycle tops out at close to 50%, while the Humphrey and the ideal PDE cycles climb to over 55%, with the PDE edging out the Humphrey cycle by about 1 to 2 percentage points. They also showed a similar trend in specific impulses for the three cycles, again with the Brayton cycle showing 0 s at $\Psi = 1$, whilst the PDE and Humphrey cycles are close to 3900 s. At $\Psi = 5$, the PDE cycle edges out the Humphrey cycle at over 6000 s, while the Brayton cycle maxes out far below that number.

A number of studies have already been done on the integration of PDEs with turbines. [3,4]Hoke et al. performed several studies by combining a single PDE tube, running hydrogen and air, and an automotive turbocharger with the aim of self aspirating the PDE. They ran the PDE in the self aspirated mode for about 25 minutes successfully although there was a 20% reduction in thrust. The losses are ascribed to the fact that the single stage radial turbine of the turbocharger is not suited to this sort of application. Nevertheless, the turbine survived over 35,000 detonations with no significant damage, which is a positive sign. [5]Rasheed et al. successfully tested a system of eight PDE tubes incorporated with a single stage axial turbine, with the following ratings: mass flow rate of 8 lbm/s, rotational speed of 25,000 rpm and power output of 1000 hp; as part of a joint venture between NASA and GE called the PDE Turbine Interaction Program (PDETIP). The system has been put through over 1.5 hours of tests using ethylene and air mixtures with the PDE running at up to 30 Hz per tube. The turbine was able to deliver 18,500 rpm and 350 hp at the above rated mass flow rate, surviving over 1 million detonation pulses.

[6]Bellini et al. performed an exergy analysis on a PDE system with single stage compressor and two stage

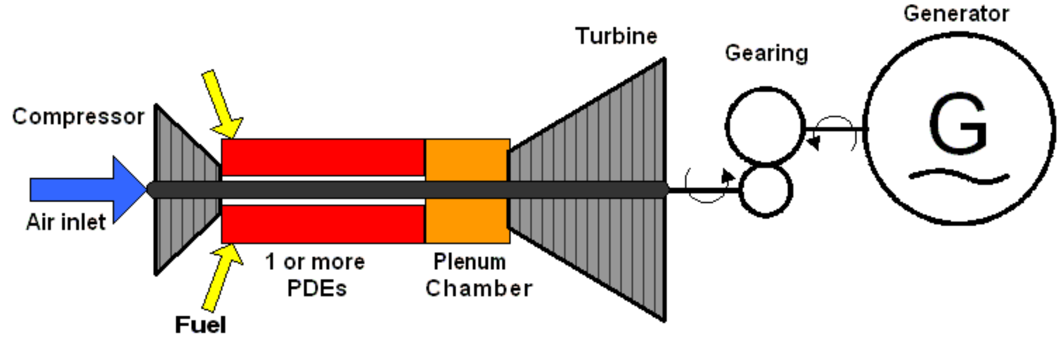

Figure 1. If the combustion chamber in the turbo-jet engine is replaced with a PDE, a smaller compressor is sufficient to deliver higher power output and better efficiency.

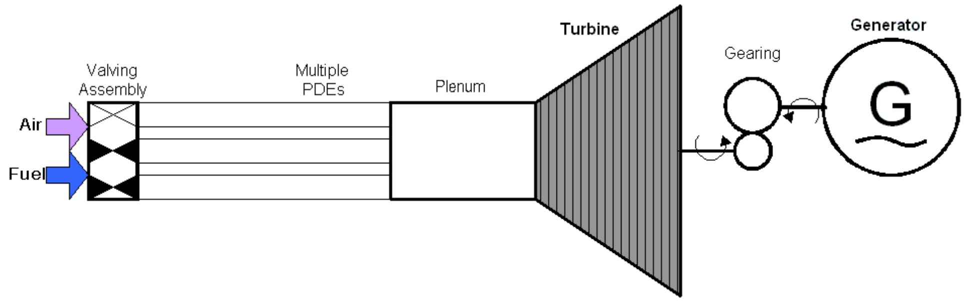

Figure 2. A schematic of multiple PDE tubes firing in sequence with turbines and generators. This combination can smoothen out the pulsing nature of the flow and also allows for larger turbines.

turbines, driving a power generator, in a set up similar to that shown in Fig. 1, using methane and propane fuels with air and it was found that second law efficiencies for the system are significantly higher for detonation over deflagration. For methane with air, deflagration combustion can deliver a maximum efficiency of 27.5% as opposed to 55% for detonation. The efficiencies for propane with air are found to be 38.3% for deflagration and as high as 79.1% for propane.

Apart from studies by the academic and commercial sector into PDEs and turbines, over the recent years, there have been many amateurs who have retrofitted hand crafted fuel delivery systems and combustion chambers to automotive turbochargers to create fully working turbo-jets by ducting the compressor air into the combustor and then directing the burnt gases to the turbine inlet. These engines, once started with a blower, will run as long as fuel is provided. References to these turbo-jets can easily be found on the internet.

PDEs have been tested and analyzed using a wide variety of fuels, both gaseous and liquid. This is another advantage that PDEs can offer which is that PDEs can be adapted to run on any current or upcoming fuels, at the same time delivering better performance than engines that work on the deflagration mode of combustion. According to the US Department of Energy, presently more than half of the electric power generated in the US is by power plants running coal, followed by a large fraction from those running natural gas, which is also reportedly the fastest growing fuel. Natural gas, which is comprised mainly of methane and propane, is a clean burning fuel with less harmful emissions than gasoline or diesel. Coal dust suspension in air forms an aerosol that is extremely explosive, as seen from coal mine explosions, which implies that it is possible to apply coal dust as a viable fuel in PDEs. Steps are underway to produce clean burning gas from coal. In keeping with the move away from petroleum based fuels, other fuels are being developed including bio-gas and hydrogen, which is the cleanest fuel of all. No matter what the fuel choice is, PDEs have a great role to play as the engine for running power generators of the future.

When used with PDEs, the turbine blades will be subjected to shock waves, very high pressures and temperatures. Therefore, the turbine rotors, stators and other parts will have to be made of more robust materials with active cooling. The severity of the PDE exhaust can be mitigated by adding an ejector so that cold flow is mixed in with the hot flow. Turbines are generally run at very high rotational speeds in the upper tens of thousands

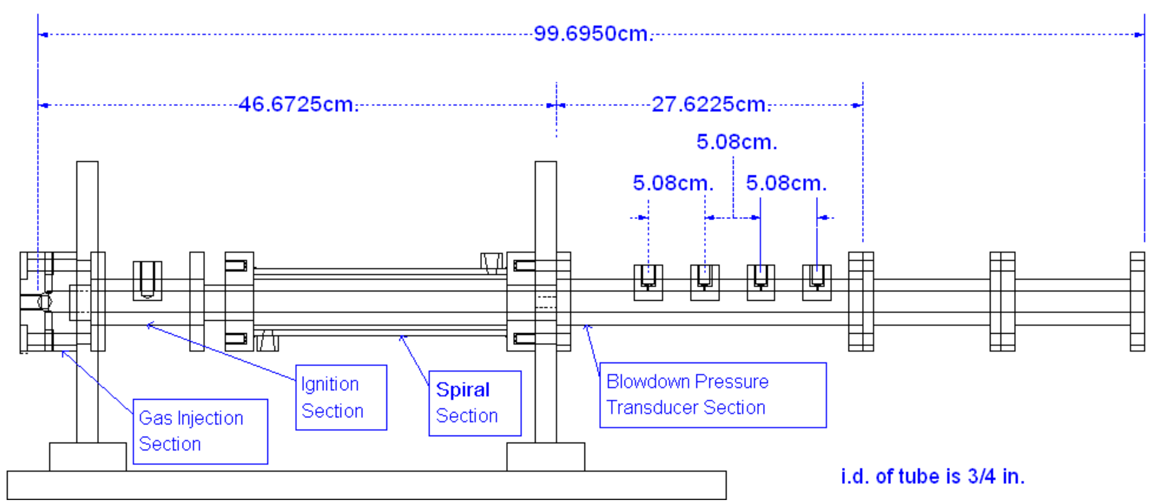

Figure 3. Schematic of the PDE.

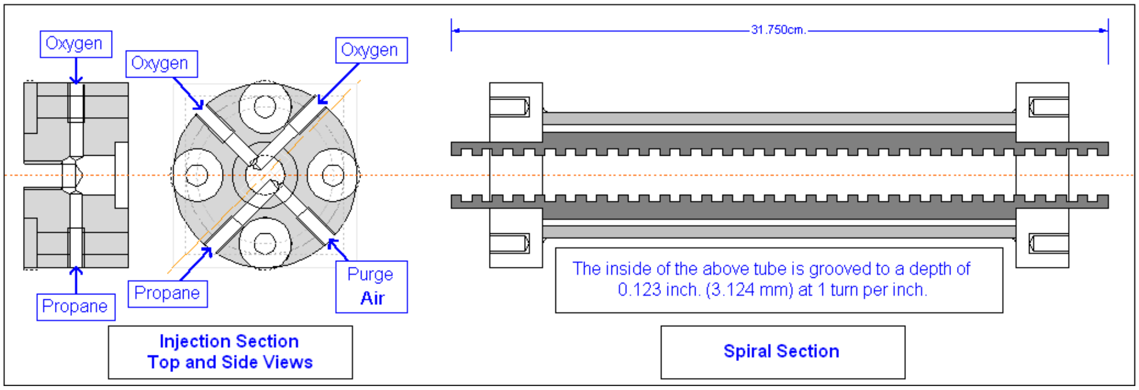

Figure 4. Profiles of the gas injection section and the spiral section of the PDE.

or even hundreds of thousands of rpm with very low torques, while generators are typically run in the low thousands of rpm. Therefore, speed reducing gear assemblies will have to be employed to match the rotational speeds and torques of the two devices. Another issue that may be relevant is the pulsing nature of the flow from the PDE, which may affect the performance of the turbine and induce noise in the electric power supply. This can be overcome by running the PDE at higher frequencies or using several PDE tubes with each one firing in sequence, as shown in Fig. 2. Another method is to add a heavy fly wheel to the generator shaft, whose moment of inertia will smoothen out the pulses. In addition to the obvious advantage, PDEs can be made smaller and lighter, owing to its lack of heavy moving parts, and hence can be easily maintained. Therefore, PDEs can be used for residential or small commercial scale power generators.

The thrust of this study is to demonstrate that a PDE can be coupled with a turbine and a generator to produce electricity. With that aim, a working model has been assembled and tested. It was not intended to actually get an efficient conversion of the chemical energy to electrical energy. Accordingly a commercially available automotive turbocharger and a small ac generator were used in this set up. The details are provided in the ensuing sections.

II. Experimental Program

A. PDE Apparatus

The PDE is almost 100 cm in length internally and has a circular bore size of 0.75 in. as shown in Fig. 3. All the parts of the PDE are made of carbon steel. The gas injection section has orifices drilled into the chamber such that the flow enters tangentially to the cross section and perpendicular to the axis of the tube. There are two orifices for oxygen, one for fuel and one for purge air. Following the ignition section, which accepts one automotive spark plug, is the spiral section. This section has the internal wall cut out into 0.25 in. grooves at 1 round per in. and to a depth of 0.123 in. This method of implementing spirals was adopted for longevity which helical spirals lack. Earlier PDE studies conducted[7,8] used steel springs of various wire thicknesses to study the effect of Shchelkin spiral parameters on DDT and the spirals quickly disintegrated after about 10 seconds of run time within the propane-oxygen detonation environment. The grooved spiral section is encased in a water jacket with the water entering at the bottom and leaving at the top as shown in the figure. Following the spiral section is the blow down section which holds four pressure sensors, spaced 2 in. apart. The pressure ports are 16 mm deep to accommodate water cooling adapters for the PTs and also have a 1/16 in. bore to the interior surface from the bottom of the socket. The sections of the PDE that are not internally water cooled are cooled on the exterior by wrapping them with cotton cloth and then constantly wetting them with flowing water during the tests.

B. Turbocharger

The turbocharger used for this study is a BorgWarner Turbo Systems K03 model (part number 53039880029) that is used in Volkswagen Passat 1.8T and Audi A4/A6 1.8T model cars, which have 5 valve 4 cylinder gasoline engines. This particular model turbocharger is also found in turbo-diesel passenger vehicles. The manufacturer's specifications for this turbocharger, which has a single stage radial flow turbine and a single stage radial flow compressor coupled to the same axial shaft, states that the compressor can deliver a maximum air flow rate of 0.17 kg/s and is recommended for automotive engines of up to 150 kW power rating. The inlet and outlet inner dimensions are as follows: turbine's inlet is 40 mm in diameter; and the outlet is 65 mm in diameter, the compressor's inlet is 36 mm, while the outlet is 38 mm in diameter. The turbine is capable of withstanding

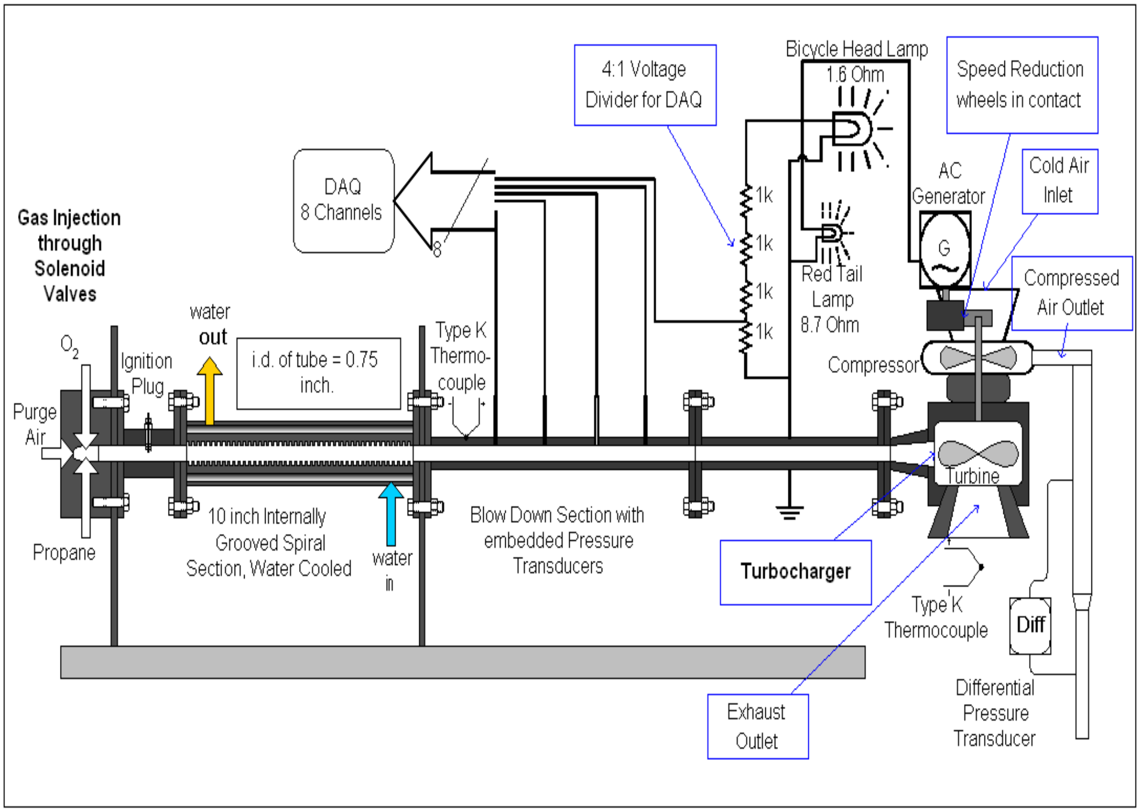

Figure 5. A schematic of the PDE, turbocharger and the generator system.

temperatures as high as 1050˚C and running at up to 200,000 rpm. In this radial flow turbine, the hot engine air enters in a radial direction from the side of the turbocharger and exits in an axial direction. The turbocharger was mounted at the exit of the PDE such that the exhaust flow is directed downwards after passing through the turbine, as shown in Fig. 5. This 90˚ turn means that the turbine and the housing will suffer the effects of high total pressures and high total temperatures from the flow exiting the PDE, thus requiring efficient cooling and reducing the run times of the tests to a few tens of seconds. Similar to the turbine, in the compressor, the cool air enters the compressor axially from the top of the turbocharger and leaves in a radial direction to the compressor blades. At rotational speeds beyond 200,000 rpm, the flow at the compressor blade inlet can reach sonic velocities at which point the air flow is choked. To avoid this predicament, the device has a built in control system that opens a waste gate whereby the flow to the turbine is bypassed to the exhaust, thereby reducing the air flow to the turbine. For this study, the waste gate was firmly bolted shut, as it was determined that the flow rates of an intermittent PDE are lower than that of an auto-engine. As mentioned above, it is extremely important to supply the turbocharger with oil flow to constantly cool and lubricate the bearings during the high speed operation, and water or coolant flow, to keep the housing and the components cool. Oil was delivered by means of an oil pump from an old Dodge truck, which was turned by an electric motor at a constant speed such that the oil pressure was maintained at about 40 psig. Cooling water was supplied at the utility tap pressure. The turbocharger is attached at the turbine inlet to the PDE by means of a specially built nozzle expands from the 0.75 in. diameter of the PDE to the 40 mm i.d. of the turbine inlet. And additional water cooled section 9 in. in length with a 0.75 in. i.d. was also added to the end of the PDE tube. The air flow rate of the compressor was obtained by passing the flow through a hand built Venturi tube and by measuring the differential pressure.

C. Generator System

Turbochargers are low torque high speed machines running as high as 200,000 rpm. Electric generators are never run at higher than a few thousand (<10k) rpm. Moreover, to pair a generator to a turbocharger, it was necessary to find a generator that has very low torque, one that will not load the turbocharger considerably. The matter is complicated by the fact that the shaft of this turbocharger cannot be modified in anyway so that it can be lengthened or gears retrofitted on to it, without affecting its finely tuned balance, which is very critical at high rotational speeds, as it can cause damage to the vital components such as the shaft, the bearings, the blades and the seals.

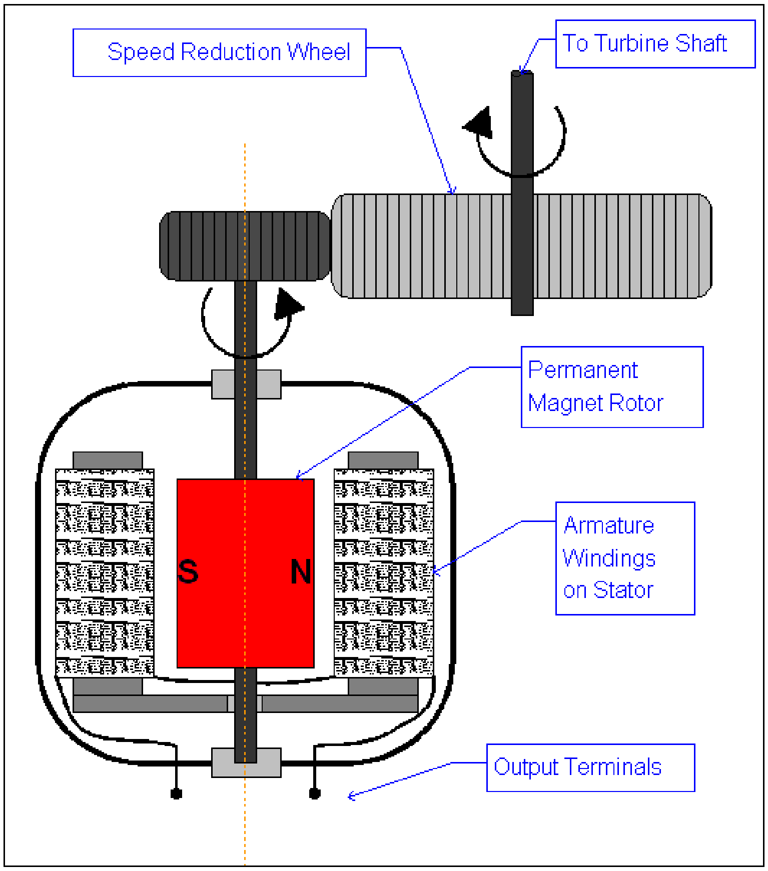

Figure 6. Schematic of the bicycle dynamo ac generator and speed reduction wheel.

The generator chosen for this study is a bicycle bottle dynamo rated at 6V 3W. It is a brushless ac generator which consists of a 2 pole permanent magnet rotor and a wire wound stator armature having a dc resistance of 4.2 Ω. The magnitude of the voltage output is proportional to the strength of the magnet, the number of turns in the windings and the speed of rotation of the rotor. There will be a measurable voltage drop across the armature windings due to its internal resistance, but the voltage output across the output terminals of dynamos usually hover around 6 V when used on normal bicycle applications. Bicycle dynamos are operated at a few hundred to a few thousand rpm as they are powered by the moving wheels of the bicycle. Therefore, speed reduction is necessary to couple the bicycle dynamo to the turbocharger. The speed reduction was achieved by using wheels of different diameters: by fitting a 1.85 in. diameter rubber wheel to the dynamo rotor and welding a 0.56 in. diameter steel disk to end of the turbine shaft at the compressor's cold air inlet. The dynamo was then mounted using clamps and brackets such that its rubber wheel was in contact with the steel disk of the turbocharger and the motion would be transferred by means of friction, as shown in Fig. 6. This method proved to be adequate for the short run times expected, as well as for the purpose of this study. The effect of slip between the shafts of the two machines was neglected. The turbocharger was expected to have a slight reduction in speed due to the small loading caused by the dynamo.

The dynamo's output was connected to a bicycle headlamp (1.6 Ω, 22.5 W) and a red tail lamp (8.7 Ω, 4W) in parallel and to the DAQ through a 4:1 voltage divider, as shown in Fig. 6. Since the voltage can be measured and the resistances of the loads are known, the current and consequently the power output can be found out by Ohm's law. The total parallel resistance $R_{//}$ is 1.351 Ω. The lamps are considered to be purely resistive loads allowing for a simple analysis of the dynamo's output. In the following equations, I_{RMS} is the RMS current, V_{RMS} is the RMS voltage and P is the power output.

$$I_{RMS} = \frac{V_{RMS}}{R_{//}} = \frac{V_{RMS}}{1.351\Omega} \tag{1}$$

$$P = \frac{V_{RMS}^2}{R_{//}} = \frac{V_{RMS}^2}{1.351\Omega} \tag{2}$$

An advantage of using an ac generator is that the rotational speed can be determined from the output voltage frequency, without having to measure the speed of the generator or turbocharger. In the following equation, N_D is the rotational speed of the dynamo rotor in rpm, f is the frequency of the ac voltage in Hz and p is the number of pairs of poles.

$$N_D = \frac{120f}{p} = \frac{120f}{2} = 60f \tag{3}$$

Thus, the rotational speed of the turbocharger N_T can be easily calculated by dropping in the dimensions of the speed reduction wheels into the following relation.

$$N_T = N_D \cdot \frac{1.85\,in.}{0.56\,in.} = N_D \cdot 3.3 \tag{4}$$

D. Ignition System

The ignition system comprises of a Mallory Hyfire 1A ignition driver and Mallory ProMaster 29440 coil, with rated spark energy of 135 mJ. The ignition driver is powered by a 12 V automotive lead acid battery. The ignition driver is triggered by means of a transistor control circuit that accepts TTL signals from the DAQ. Thus, the ignition timing can be precisely controlled remotely by the user from the DAQ PC. The spark plugs used are Bosch Platinum tipped automotive spark plugs (6234 model). These spark plugs have a built in resistance of 3.18 kΩ, ensuring that the spark current is reduced and the resulting electro-magnetic interference (EMI) does not notably corrupt the weak transducer signals. Automotive spark plugs suffer considerable damage when used inside PDEs. The most common signs of damage include attrition of the ground electrode, breakage of the ceramic insulation around the core and melting of the screw thread. The spark plugs sockets are designed such that only about 6 mm of the ceramic coated tip and ground electrode extends out into the combustion chamber. This ensures that no large blockage to the flow exists within the chamber and helps to protect the spark plug from being destroyed. Nevertheless, the ground electrode erodes away after a cumulative service life of about 5 to 10 minutes.

E. Diagnostics and Control

The diagnostics of the test apparatus is performed with the help of a National Instruments DAQ consisting of a 1042Q chassis that contains a pair of 8 channel 2.5 MS/s S-series PXI-6133 cards. The DAQ is connected to a remote PC via fiber optic cable which ensures smooth, EMI free signal transmission. The various sensors can be monitored in real time and the solenoid valve fuel injectors of the PDE can be operated remotely from the PC through the DAQ. For the initial study, only 8 channels were utilized, including four PCB piezo-electric dynamic pressure transducers (111A24 model, 1000 psi maximum, 450 kHz resonant frequency), one differential pressure transducer for measuring flow rate of the compressor air output (Honeywell Micro Switch model number 164PC01D37), a pair of type K thermocouples to measure temperature of the PDE tube surface and of the flow exiting the PDE or turbocharger and finally, one channel to measure the voltage output of the generator.

The PTs are encased in water cooling adapters (064A01 recessed sensor and 064B02 flush sensor models). During the tests, water was constantly passed through the cooling adapters at tap pressure. The PT signals are sent through a 12 channel 483A model signal conditioner, which converts the charge output of the transducers to voltage waveforms. The sampling rate for propane-oxygen tests were set at 500 kS/s, but the rate was increased to 2 MS/s for the hydrogen-oxygen and hydrogen-air tests. Gaseous flow rates for the hydrogen tests were performed using Flow-Dyne Engineering critical flow nozzles, which can yield flow rates based on the nozzle exit flow pressure alone, provided the supply pressures and temperatures are known. The nozzle exit pressures were measured using Omega pressure transducers (PX302-200GV, 200 psig full scale and PX302-300GV, 300 psig full scale models).

The control and monitoring is performed on graphical interfaces created with National Instruments' LabVIEW on the PC. The program enables the user to change PDE frequency, valve and ignition frequency and timing and signal sampling rates as required.

F. Test Program

To run the PDE, the purge air valve is opened for a preset period. When the purging stage is finished, the fuel and oxidizer valves are opened simultaneously. The ignition signal is given at the end of the filling stage or can be advanced or delayed as required using the LabVIEW interface. The ignition and blow down stage is again followed by the purging stage and this cycle is repeated at the desired frequency. Propane and oxygen were used for the tests in which the turbocharger and generator were mated with the PDE. Although the PDE was tested for frequencies ranging from 10 Hz to 25 Hz, the most favorable frequency chosen for the turbocharger tests was 15 Hz. The results are presented below. Subsequently, tests were carried out on the PDE sans the turbocharger and generator using H_2-O_2 and H_2-Air. This was done to test the efficacy of this compact PDE to achieve detonation with these gases.

Table 1. Results of the PDE-Turbocharger-Generator system test with propane-oxygen at *Φ* = 1.2 and mass flow rate of 0.0057 kg/s.

Time (h:m)	Time (s)	Peak Voltage	V_{RMS}	Freq. of Output (Hz)	Power (W)	Generator Speed (rpm)	Turbo Speed (rpm)	Compressor Flow Rate (kg/s)
19:59	10.6562	5.7	4.03	225.124	12.02	13507	44575	0.0464
19:59	11.6562	8.41	5.95	621.922	26.18	37315	123141	0.0526
19:59	15.3906	8.42	5.95	641.491	26.24	38489	127015	0.0539
19:59	16.3902	8.34	5.90	600.519	25.74	36031	118903	0.0543
19:59	21.9219	8.11	5.73	501.458	24.34	30087	99289	0.0553
19:59	22.9219	8.01	5.66	484.447	23.75	29067	95921	0.0516

III. Results

The PDE with turbocharger and generator was run at 15 Hz with propane and oxygen supplied from industrial cylinders and purge air from a compressor. The results of one test are presented below. The equivalence ratio *Φ* was set at 1.2, with a total mass flow rate of the propane-oxygen mixture being 0.0057 kg/s. The output of the generator is shown in Fig. 7 as captured by the DAQ. The acquisition process was configured such that the data was acquired for 1 s at 500 kS/s and then stopped for 2 to 3 seconds during which time the data was written into the hard drive of the PC. This accounts for the large gaps in between the dark regions. Figures 8,9 and 10 show enlarged 0.1 s wide views of the three 1 s blocks of output voltage data. The data acquisition was started about 3 to 4 seconds after the PDE had been started. Before the PDE was running, the turbine was at rest, as the purge air did not have enough pressure to turn the turbine with the small loading induced by the generator and the speed reduction wheels. Fig. 8 shows that during the initial stage after the PDE has been started, the turbine accelerates smoothly, driving the generator with it, as output peak voltage and frequency increases gradually. This is followed by a period of almost steady voltage and frequency. About 15 seconds after the PDE was started, the generator's wheel lost contact with the turbine wheel and stopped running. Thus the output voltage falls to 0 at this point. Table 1 shows the generator output, and the rotational speeds of the generator and the turbine at the beginning and end of each 1 s acquired data block. It is seen that a power output of over 26 W is attained during the test.

In addition, the compressor was supplying air, with a high of over 0.055 kg/s, demonstrating that a turbine and compressor could be used to self aspirate a PDE. Since the PDE was being run in a fuel rich state, combustion was taking place within and outside the turbocharger. An orange-yellow flame could be observed at the exhaust of the turbine. Temperature of the flow at the turbine exit was measured to be as high as 800˚C. Therefore, if a turbine with several more stages were used, additional work could be derived from the engine. It also means that the PDE could be run at higher speeds, as some of the fuel was evidently being pushed outside its volume.

The turbine speed, as determined from the generator's output frequency, went well over 127,000 rpm, which is considerably within the operational limits of the turbocharger. This again indicates that the PDE could be operated at a much higher frequency or that multiple PDE tubes could be used to achieve higher turbine speeds and consequently higher output voltages and compressed air flow rates.

The pressure readings were used to calculate the TOF velocities which were found to be greater than the C-J velocity (2440 m/s), showing that the grooved spiral successfully induced DDT within the short combustion chamber. [9]The PDE also satisfies the requirement that the i.d. of the PDE (0.75 in. = 19.05 mm) be larger than the cell size of the mixture, which for propane-oxygen is 7 mm. It is apparent from Fig. 12 that the pressures measured by the PTs are not as high as the C-J values obtained from calculations (such as the CEA or STANJAN codes). This shortcoming is attributed to damping of the pressures caused by the recessing of the PTs and the phenomenon is further explained in the discussion on the hydrogen test results.

Following the above mentioned tests, the PDE without the turbocharger, was tested in the single shot as well as multi-cycle mode using hydrogen-oxygen and hydrogen-air mixtures at a range of equivalence ratios, to test for its ability to produce DDT. In addition, the PT sockets on the blow down section were modified, with the 1/16 in. bores enlarged to ¼ in. and PT3 and PT4 were placed in PCB 064B02 water cooling adapters, which allow the sensing surface of the PTs to be flush with the bottom tip of the adapters. The only drawback to this move is the reduction is testing time for the PTs as now they are subjected to higher pressures and has less protection from heat. Therefore, the multi-cycle tests were limited to about 5 to 10 seconds only. Figure 13 shows the pressure traces for a single shot hydrogen-oxygen test at equivalence ratio of 0.9995. The first two PTs recorded lower pressures, since they were recessed. PT3 and PT4 however recorded dramatically higher pressures, showing pressure plateaus behind the tall spikes close to the C-J value of 19 bar. The non-recessed PTs also do not show the expansion waves behind the detonation front relaxing into the negative region, as seen in PTs 1 and 2. TOF velocities again indicate detonation. Multi-cycle tests at 15 Hz also yielded detonation for the same mixture conditions. However, hydrogen-air tests at $\Phi = 1.9$ did not result in detonation. This is ascribed to the dimensions and shape of the spirals not being effective in inducing DDT and the length of the detonation chamber is shorter than that required for DDT.

The turbine did not suffer any damage after several minutes of testing. In spite of the water cooling and oil supply, long duration tests with this turbocharger would result in sure failure of the device, as it was never meant to be used for detonations. Therefore, axial turbines are preferable for union with PDEs. Axial turbines with stator stages at the entrance of the turbine can prevent detonation waves from harming the rotor blades. Another reason to use axial turbines is that they are better suited to add speed reduction (torque multiplying) gearing systems to the shaft, which enable high speed turbines to couple with lower speed electric generators. This will facilitate bigger and heavier generators to be coupled to turbines, enabling them to produce larger amounts of electric power. While it is clear that 27 W of electric power and 0.055 kg/s of compressed air are miniscule in comparison to the chemical energy of the fuel being supplied, it does mean that the system has to be refined to a great degree to get close to the levels of theoretically predicted efficiencies. Nevertheless, it is encouraging from this study that PDEs can be used in power generation and also that miniature PDEs can yield detonation or close to detonation conditions, and if they are coupled appropriately with turbine-compressor systems and electric generators, it is assured that they will outperform deflagration engines.

IV. Conclusion

A PDE with a 0.75 in. and close to 1 m in length has been coupled with an automotive turbocharger driving an ac generator. The PDE was run at 15 Hz with propane and oxygen mixtures at an equivalence ratio of 1.2. From the generator output frequency, the speed of the turbine was found to be higher than 127,000 rpm, which is below the maximum rating of 200,000 rpm. This is well within the operational range of a turbocharger on an automobile. The generator produced over 26 W of electric power, while the compressor pumped out air at a rate of 0.055 kg/s, showing that PDEs can be made to self aspirate if combined with a turbine and compressor. The temperature of the flow exiting the turbine was measured to be over 800˚C, suggesting that the flow had enough enthalpy to drive several more turbine stages. Thus, a proof of concept model has been successfully created demonstrating the use of a PDE to derive electrical power from a turbine-compressor-generator system. While the turbine and compressor survived many tests with no damage, it is evident that radial turbines are not suited to PDE application, since they result in large losses and hot spots from turning the flow around 90˚. Multi-stage axial flow turbines could produce better results. If the turbine shaft can be modified to attach speed reduction gears, they can be made to drive larger generators, thereby increasing the power output. Finally, the compact PDE used for this study also achieved detonations with H_2-O_2 mixtures, but H_2-Air mixtures failed to detonate, owing to the spiral dimensions and the length of the detonation chamber not being long enough to achieve DDT.

Acknowledgments

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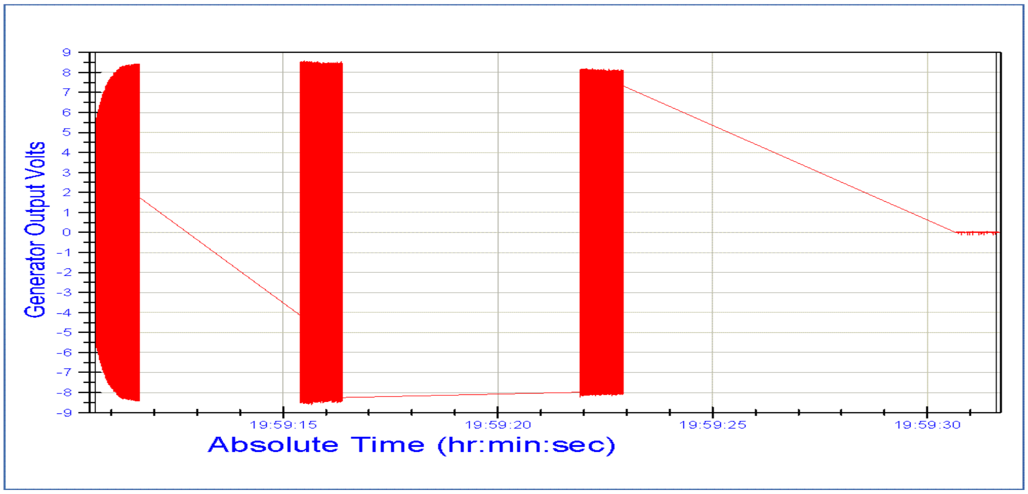

Figure 7. Generator output voltage waveform captured by the DAQ. The 1 s wide record blocks are separated by empty regions where the acquisition process was suspended to conserve memory. The x-axis shows real time. After about 15 seconds of run, the generator stops turning and output drops to 0 V, when the speed reduction wheels lose contact.

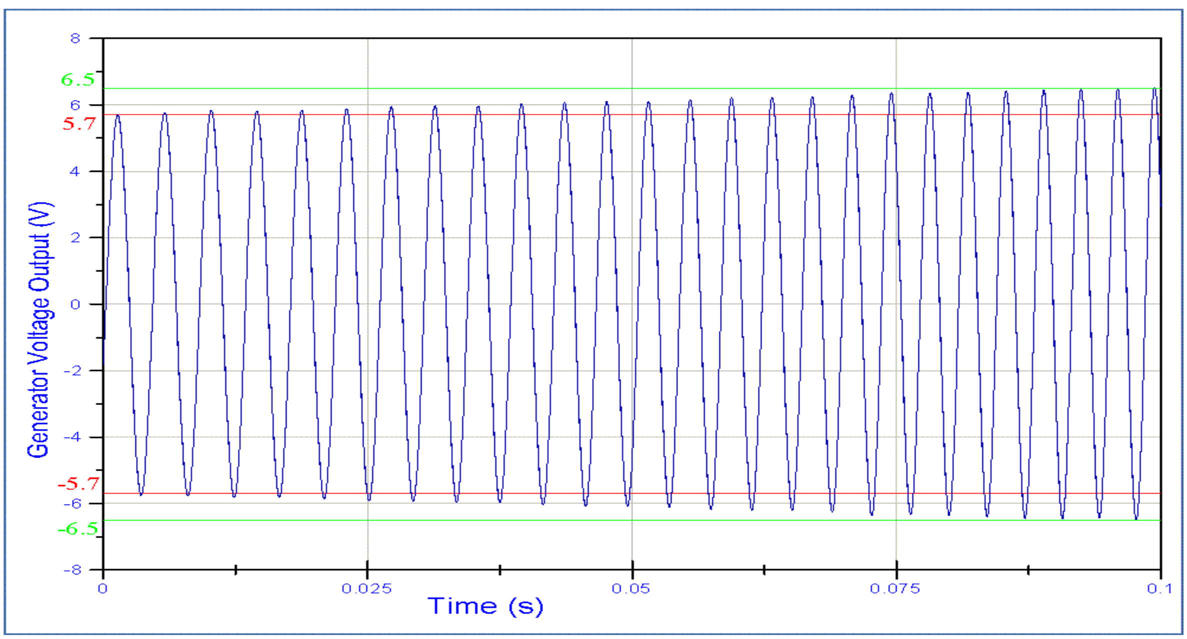

Figure 8. The figure shows the expanded view of the beginning of the first 1 s block of voltage output, as the turbine is spooling up in speed and correspondingly the generator builds up peak voltage and frequency.

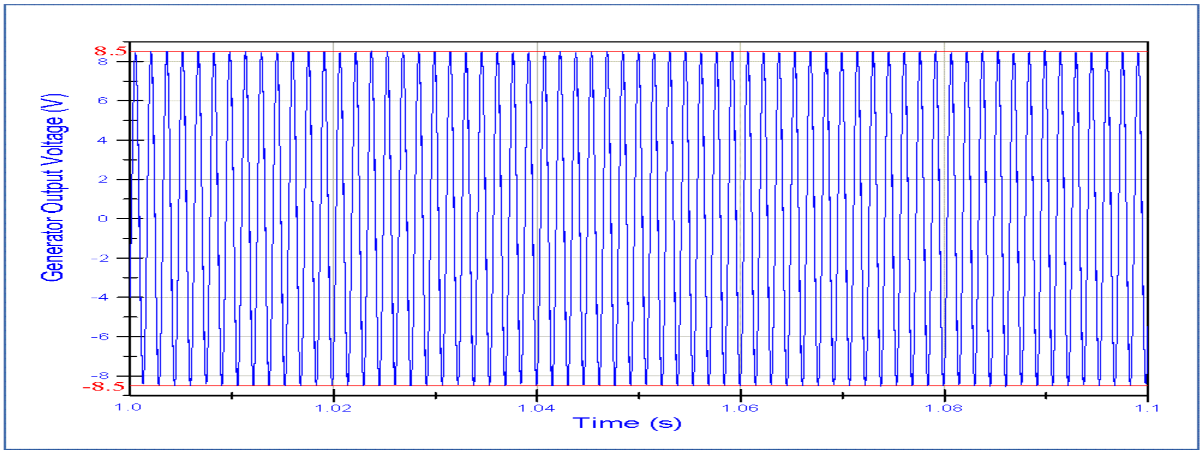

Figure 9. The figure shows the expanded view of the beginning of the second 1 s block of voltage output. The generator is now running at a constant speed with a steady peak voltage and frequency.

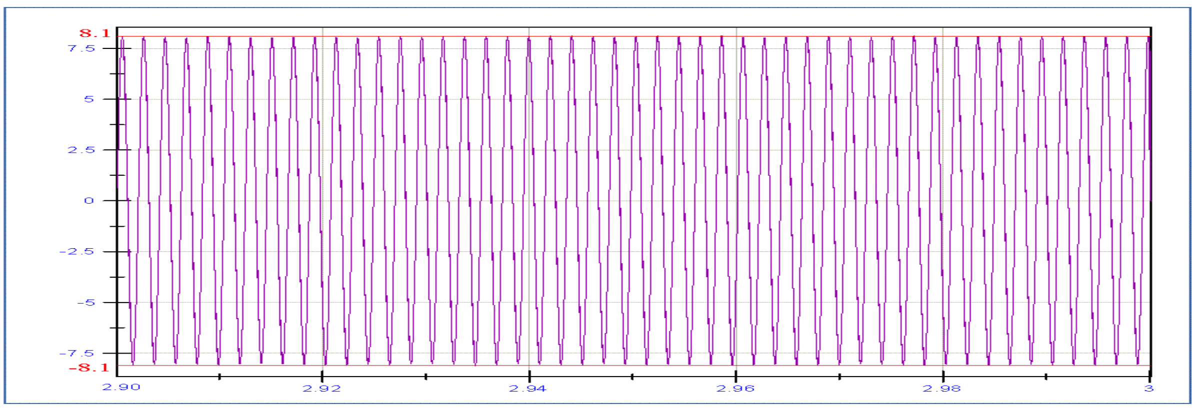

Figure 10. The figure shows the expanded view of the third block of voltage output. The generator has slowed down slightly due to slip between the speed reduction wheels, consequently showing a reduction in peak voltage and frequency.

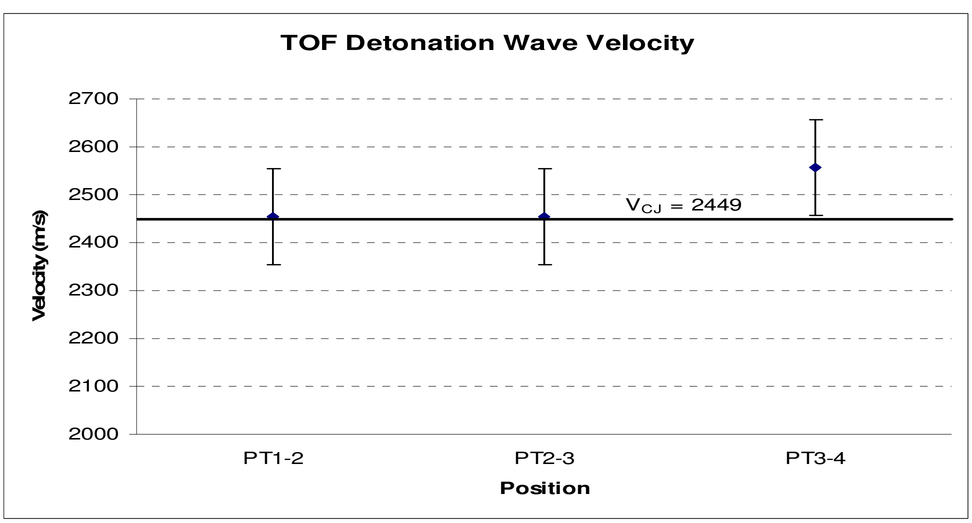

Figure 11. TOF velocities for propane-oxygen mixture at Φ = 1.203.

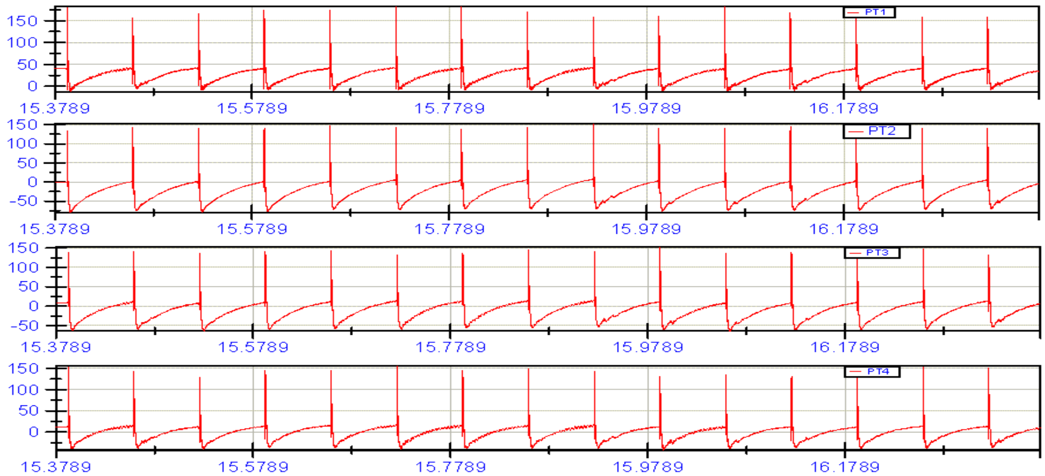

Figure 12. Pressure traces for the propane-oxygen test at Φ = 1.2. The x-axis shows real time in seconds and the y-axis shows pressure in psig.

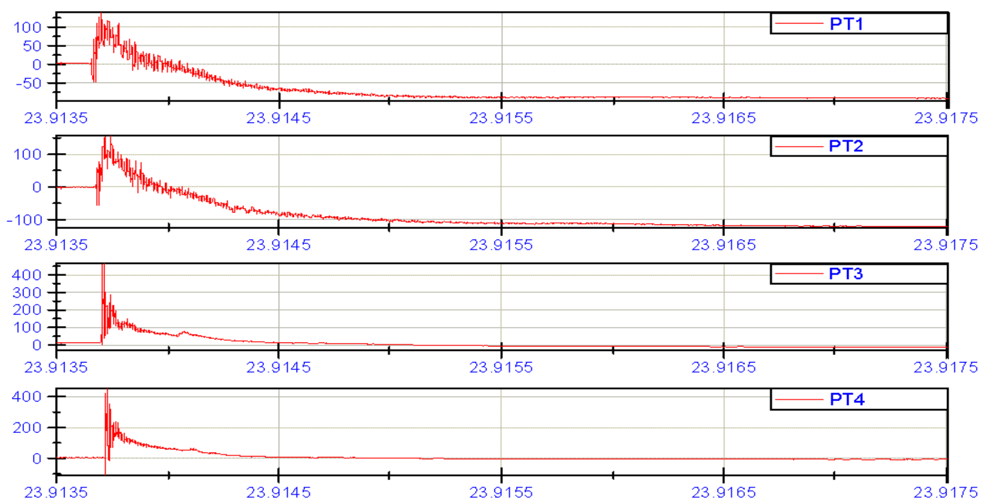

Figure 13. Pressure traces for the H_2-O_2 test at Φ = 0.9995. The x-axis shows real time in seconds and the y-axis shows pressure in psig. PT1 and PT2 are recessed whilst PT3 and PT4 are flush mounted. The plots of PT3 and PT4 show sharper peaks and more defined curves.

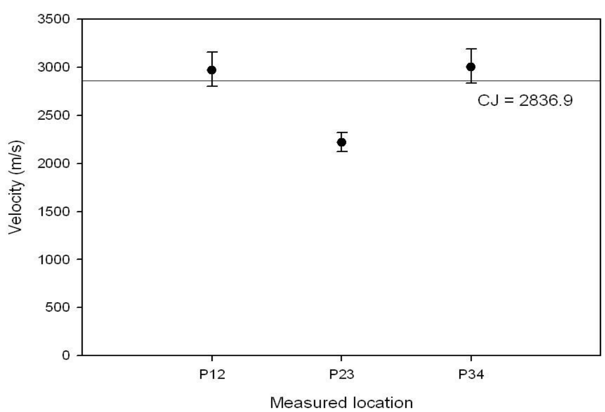

Figure 14. TOF velocities for H_2-O_2 mixture at Φ = 0.9995.

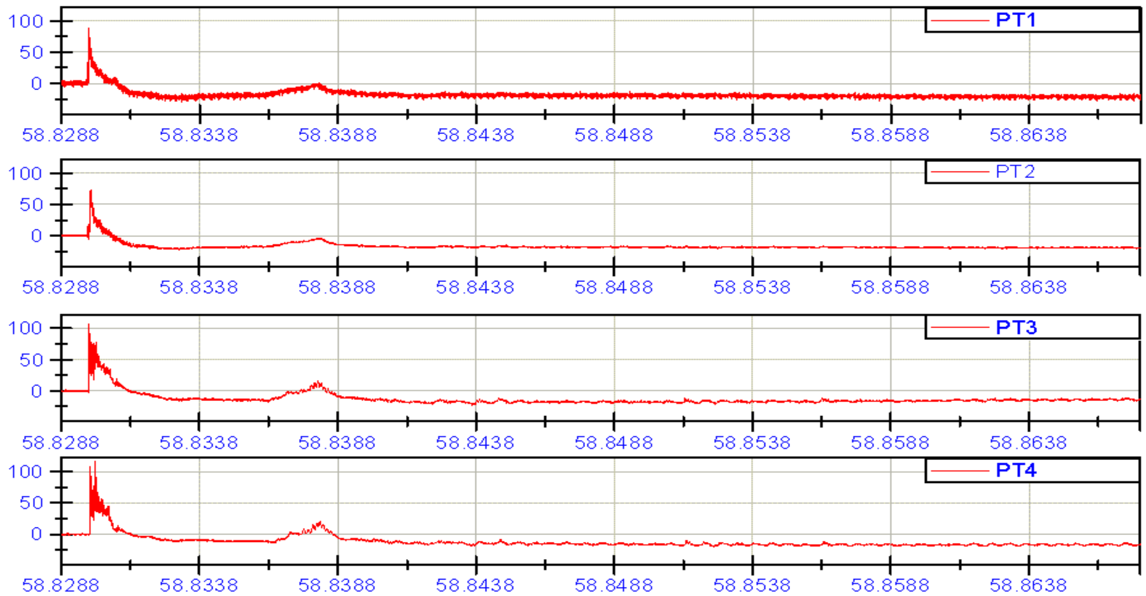

Figure 15. Pressure traces for H2-Air at *Φ* = 1.8886. PT1 and PT2 are recessed whilst PT3 and PT4 are flush mounted, giving sharper peaks and well defined curves.

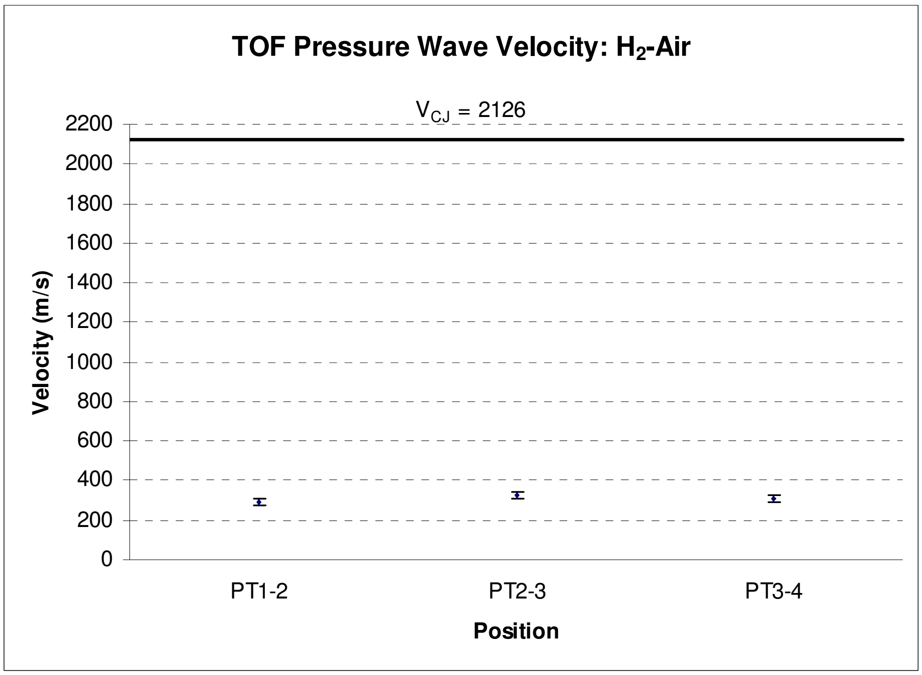

Figure 16. TOF velocities for H_2-Air test at *Φ*= 1.8886. The pressures are significantly below the V_{CJ} values.