Enhancing Propulsion Efficiency: Investigating Pressure Gain Combustion Dynamics in Pulse Detonation Engines

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***Abstract**: In order to obtain important knowledge for raising the performance and efficiency of propulsion systems, in this paper we investigate the dynamics process of pressure gain combustion in the Pulse Detonation Engine. Through comprehensive experimentation, we analyse the intricate mechanisms governing the pressure gain combustion in PDEs. Our findings present innovative methods for increasing combustion efficiency, boosting thrust generation, and addressing operational difficulties in PDE designs. Additionally, we discuss creative strategies for utilizing pressure gain effects to enhance engine performance metrics.*

***Key Words**: Pressure gain combustion (PGC), Pulse Detonation Engines (PDEs), Thrust generation, Engine performance, Combustion efficiency*

1. INTRODUCTION

Pulse Detonation Engines (PDEs) hold promise for propulsion systems, offering enhanced efficiency and performance over conventional combustion engines through pressure gain combustion at supersonic speeds. Despite advancements, research challenges persist, prompting this study to explore the dynamics of pressure gain combustion in PDEs through experimental analysis. By addressing the gaps in understanding, our research aims to improve combustion efficiency, thrust generation, and PDE designs, with implications for aerospace, automotive, and power generation industries.

This study contributes to the advancement of propulsion technology by enhancing our understanding of pressure gain combustion in PDEs, which is crucial for meeting future transportation and energy needs.

Over the past 25 years, NASA has explored pressure gain combustion (PGC) to harness its thermodynamic advantages in aerospace propulsion. Research spans various PGC concepts and subsidiary components like inlets and turbines. This study aims to refine the understanding and advance the PGC propulsion integration in aerospace [1]. Another study was conducted that compares a Joule-cycle based turbofan system to the same technology level of situation. The potential of PGC has been identified [2].

PDEs have an ideal thermodynamic cycle efficiency of 0.4 to 0.8 for typical hydrocarbon fuels, surpassing Brayton cycles, especially at low flight Mach numbers.

Real PDE performance is better than real Brayton cycles for Mach numbers below 3 but declines rapidly beyond this value [3].

PGC can enhance the thermal efficiency of stationary gas turbines. By using pressure gain combustion, more work is extracted from the same fuel amount, improving efficiency in power generation [4].

To compare thermodynamic efficiency, we consider basically three different thermodynamic cycles, with the only difference between them being the way heat is added at constant pressure, constant volume, or in a detonation. For three cycles, the thermodynamic efficiency is 27% at constant pressure, 47% at constant volume, and 49% at detonation [5].

2. PULSE DETONATION ENGINE

The evolution of propulsion systems has significantly advanced aerospace technology, enhancing the transportation speed and efficiency. Pulse Detonation Engines (PDEs) emerge as promising contenders in this realm, offering potential breakthroughs in efficiency and performance through cyclical, rapid combustion.

Operating on the principles of detonation rather than deflagration PDEs enable higher thrust-to-weight ratios, reduced fuel consumption, and lower emissions, addressing key challenges in modern propulsion.

PDEs utilize repetitive detonation waves to generate propulsion thrust, with combustion occurring at speeds thousands of times faster than deflagration processes, defining their unique operating cycles [6].

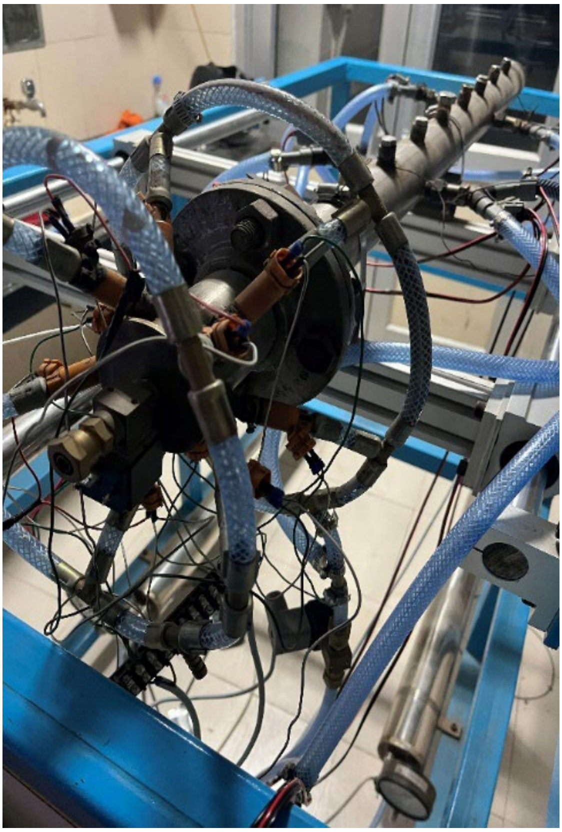


Figure 1: PDE Test Rig at PEC

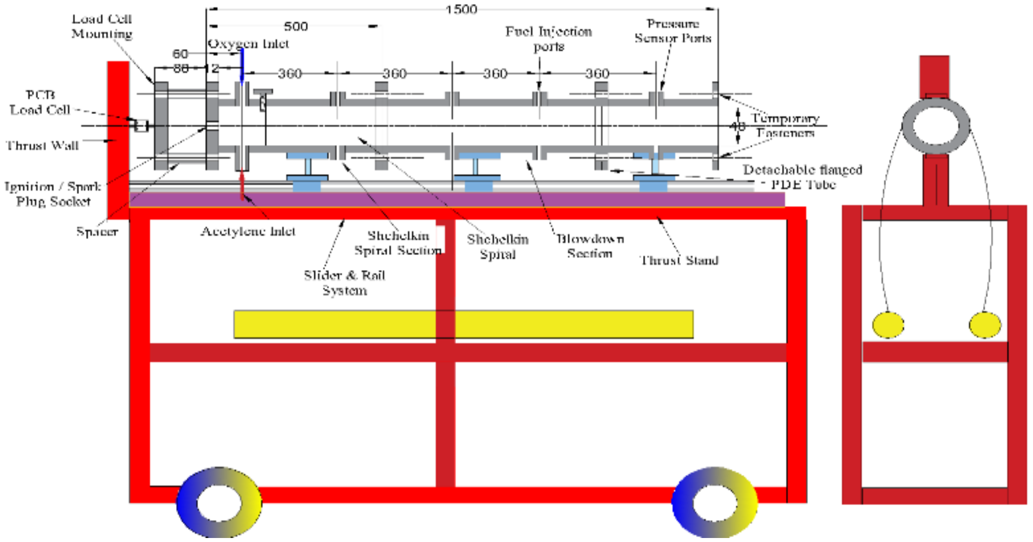


Figure 2: Schematic diagram of PDE setup at PEC

3. SYSTEM DESIGN & DEVELOPMENT

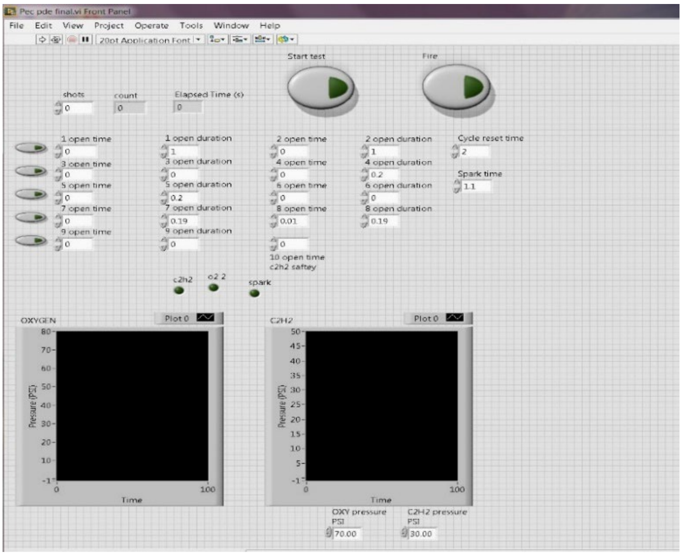
A thorough analysis was conducted, comparing theoretical models with experimental data to examine pressure gain in a Pulse Detonation Engine (PDE) tube. Piezoelectric sensors were calibrated for data acquisition along the detonation tube, enabling measurement of pressure rise. LabView software facilitated operational control of the engine and data collection from sensors. There was a more precise measure of the mean PDE firing pressure as determined by the high frequency pressure measurement sensors [7].

Components of the in-house system included a segmented PDE tube made up of SS-304 grade, with sections for fuel-oxidizer mixing, Shchelkin spiral, and blowdown.

Stop bolts were employed to fix the Shchelkin spiral at a specific location as per the literature study while a thrust stand was used to determine the transmitted thrust via a Piezoelectric load cell and the movement of the detonation tube was governed by slider and rail system. A thrust wall served as a mount for the load cell used in thrust measurement.

Figure 3: Load cell arrangement on thrust wall

Figure 4: Piezoelectric Load Cell



shots 0
count 0
Elapsed Time (s) 0
1 open time 0
3 open time 0
5 open time 0
7 open time 0
9 open time 0
1 open duration 1
3 open duration 0
5 open duration 0.2
7 open duration 0.19
9 open duration 0
2 open time 0
4 open time 0
6 open time 0
8 open time 0.01
10 open time c2h2 saftey 0
2 open duration 1
4 open duration 0.2
6 open duration 0
8 open duration 0.19
Cycle reset time 2
Spark time 1.1
OXY pressure PSI 70.00
C2H2 pressure PSI 30.00

Figure 5: Lab VIEW Interface

Figure 6: PCB Piezo electronics sensor

Ports were strategically positioned along the tube's length to integrate pressure sensors along with individual ports assigned for gaseous fuel and oxygen injection near the tube's terminus. Acetylene and Oxygen were Injected at an acute angle which promotes efficacious mixing, with adjustable ratios tailored to specific requirements. Ignition was triggered by a spark plug affixed at the tube terminus.

4. EXPERIMENTATION & ANALYSIS

Experimental trials utilized a flow control apparatus capable of modulating oxygen and gaseous fuel injection durations, along with spark delay adjustment. Varied Shchelkin lengths were tested while maintaining consistent parameters. Notably, a Shchelkin spiral of 300 mm length, featuring a 28 mm pitch, was selected for experimentation. The tube's length for experimentation was set at 1000 mm.

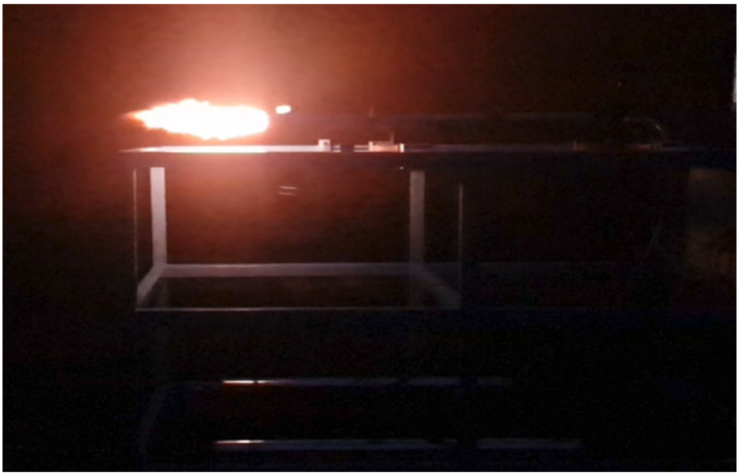


Figure 7: PDE Experimental firing

Based on a comprehensive literature review, the test setup and subsequent experiments provided a solid understanding of Pulse Detonation Engines (PDEs). The experiment was carried out by injecting Acetylene-Oxygen as the main fuel oxidizer into the combustion chamber at a pressure of 15-40 psi, respectively [8]. For proper atomization and uniform mixing at constant volume, automobile injectors were used for single point injection. Lab VIEW software was used to control parameters such as fuel injection duration, spark time, and number of shots fired. Pressure gain combustion converts the operational basis of the gas turbine from a Brayton cycle to something approaching an Atkinson cycle which, for an equal addition of heat and mechanical compression, is thermodynamically superior [9].

This system uses digital signals generated by piezoelectric sensors to convert digital signals into numerical values along with graphical plots so that the pressure variation and thrust generated along the tube length can be measured.

Figure 8: Lab VIEW software Launchpad

5. RESULTS & DISCUSSIONS

Three pressure sensors are placed equidistant along the length of the detonation tube. The first sensor is placed after 200 mm from the combustion chamber, providing pressure curves along the tube length of 1000 mm.

The dimensional parameters were kept constant and the fuel-oxidizer pressure was maintained at 15-40 psi, respectively. The injector valves were opened for different durations with timing ranging from 0.4 to 1 second, and the spark timing ranging from 0.06 to 0.1 second after closing of injector valves.

Based on these conditions, a large dataset was captured and the axial pressure characteristics along the tube were recorded using the pressure sensors. Table 1 explains the data recorded for the experimentation and presents an insight into advantage of PGC.

Open duration refers to the time for which the injectors are electronically engaged to inject fuel and oxygen into the combustion chamber. The spark time refers to the time at which the spark plug is engaged. In other words, it is the duration after which the spark plug is stimulated once the injection phase is over.

Example: In case 1, the injectors were engaged for a duration of 0.4 seconds and the spark was provided to the mixture in combustion chamber after 0.1 seconds, i.e. at 0.5 seconds.

Similarly, the timing of opening and closing of injection valves and spark plug operations were decided and implemented to gather the dataset.

Table 1 : Collected Dataset for Fixed Parameters

Case	Spark Time (s)	Open Duration (s)	Pressure (MPa)		
			P1	**P2**	**P3**
1	**0.5**	**0.4**	0.7 MPa	0.21MPa	0.23 MPa
2	**0.58**	**0.5**	0.71 MPa	0.23 MPa	0.33 MPa
3	**0.66**	**0.6**	0.96 MPa	0.43 MPa	0.47 MPa
4	**0.78**	**0.7**	0.93 MPa	0.74 MPa	0.40 MPa
5	**0.86**	**0.8**	1.05 MPa	0.54 MPa	0.68 MPa
6	**0.98**	**0.9**	1 MPa	0.83 MPa	0.55 MPa
7	**1.06**	**1**	1.04 MPa	0.79 MPa	0.88 MPa
8	**1.3**	**1.2**	1.04 MPa	0.8 MPa	1.09 MPa
9	**1.56**	**1.5**	0.9 MPa	0.81 MPa	0.98 MPa

Combustion process must meet several key criteria and employ several key measurement techniques to qualify as pressure gain combustion (PGC).

The parameters below can be used to determine if a combustion process is a PGC combustion.

- ➢ Pressure Measurement
  - o Inlet and Outlet Pressure: By checking the static pressure at the combustor's inlet and outlet. A higher outlet pressure than an inlet pressure is required for PGC.
  - o Transient Pressure Data: Transient pressure profile can be captured during combustion using high-frequency pressure transducers. As a result, we are able to understand pressure dynamics throughout the cycle.
- ➢ Combustion Dynamics
  - o Deflagration-to-Detonation Transition (DDT): PGC in PDE's tends to involve detonation waves, which are identified by a significant rise in pressure. PGC can be determined by distinguishing between detonation waves or successful DDT occurrences.
  - o Shock wave Analysis: Pressure gain can be strongly indicated by shock waves and how they move through the combustion chamber.
- ➢ Experimental Validation
  - o Test Rig Data: Conduct controlled investigation by using PGC-specific test rig and verifying the pressure gain by comparing experimental data with theoretical estimation.

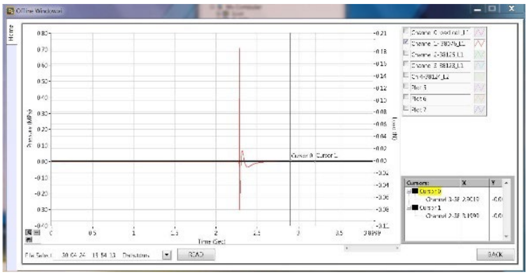


Figure 9: P1 reading case- 1

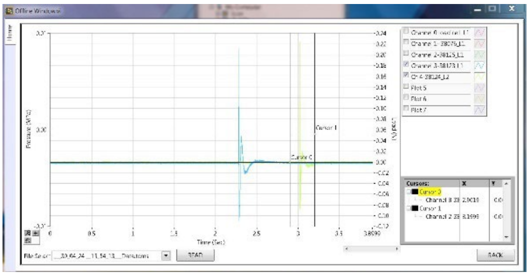


Figure 10: P2 & P3 reading case- 1

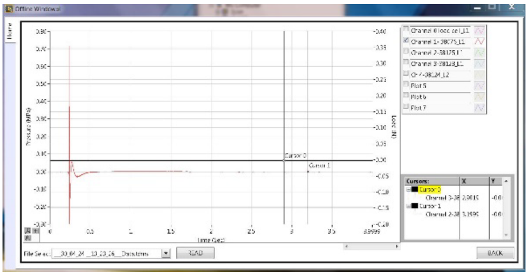


Figure 11: P1 reading case- 2

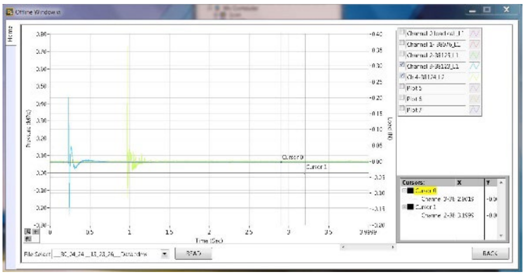


Figure 12: P2 & P3 reading case- 2

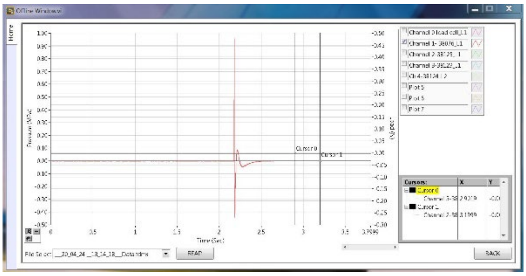


Figure 13: P1 reading case- 3

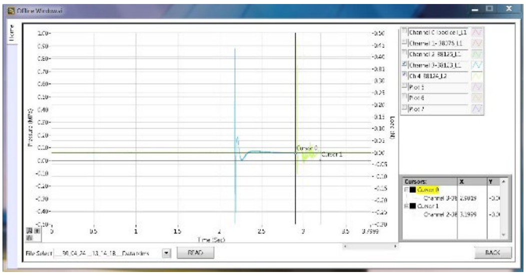


Figure 14: P2 & P3 reading case- 3

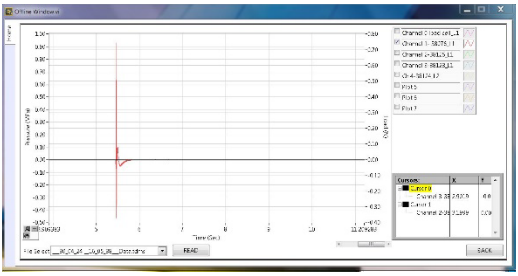


Figure 15: P1 reading case- 4

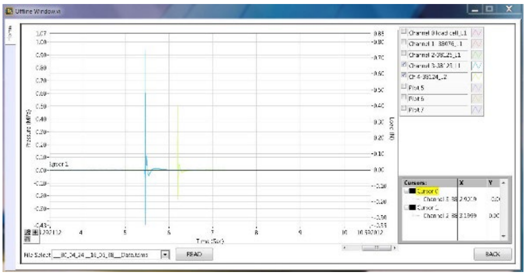


Figure 16: P2 & P3 reading case- 4

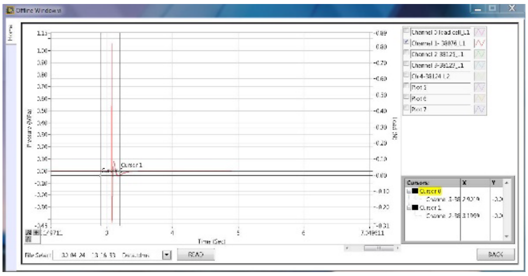


Figure17: P1 reading case- 5

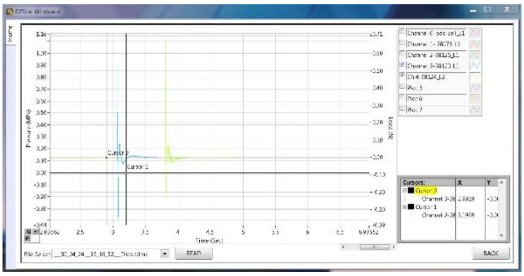


Figure 18: P2 & P3 reading case- 5

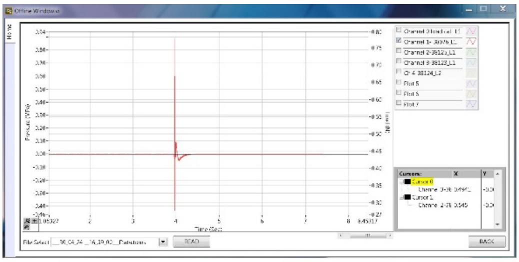


Figure 19: P1 reading case- 6

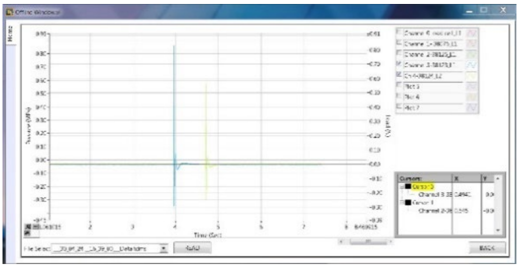


Figure 20: P2 & P3 reading case- 6

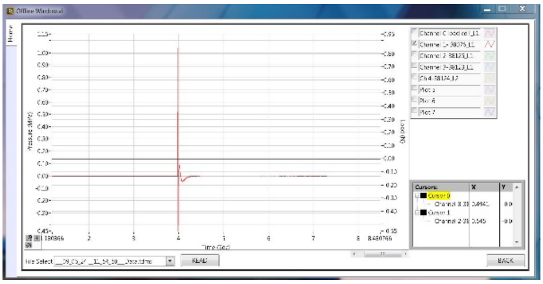


Fig. 21: P1 reading_case-7

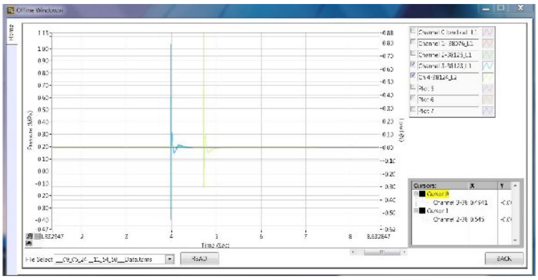


Fig. 22: P2 & P3 reading case- 7

The on-board data show that the outlet pressure in the combustion chamber consistently exceeds the inlet pressure, with P1 ranging from 0.7 to 1 MPa and the inlet pressure around 0.2 MPa (40 psi).

Additionally, P2 and P3 readings confirm the pressure trend of the detonation wave along the tube length being consistently above ambient pressure.

Physical observations were made in addition to the data collected by the DAQ system, confirming the DDT transition phenomenon, shock wave creation, and propagation along the tube in accordance with theoretical analysis.

In simpler words, the study has extensively investigated the pressure gain combustion process in Pulse Detonation Engines (PDEs) and its influence on propulsion efficiency and performance.

The experimental analysis has shown the ways in which pressure gain combustion works, thus giving new ideas on how PDE designs can be improved. From our study, we have seen that if the dynamic pressure in the chamber is carefully controlled, the engine performance can be greatly improved.

It is expected that these techniques will be used for other applications besides increasing efficiency in propulsion of vehicles, such as space flight.

Although an increase in pressure may offer some improvements in thermodynamic efficiency, we would like to reiterate that many aspects contribute to the development of a functional aircraft engine besides the increase in pressure levels. Furthermore, additional considerations should be made, such as providing enough thrust needed for the operation of any system under different flight conditions (both take-off/landing as well as cruising), ensuring compatibility with other internal/external components as well as reasonable amount of fuel consumption [10].

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