NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY POLITEHNICA BUCHAREST

COMOTI ROMANIAN RESEARCH & DEVELOPMENT INSTITUTE FOR GAS TURBINES

DOCTORAL SCHOOL OF AEROSPACE ENGINEERING

esa

DOCTOR OF PHILOSOPHY THESIS

Design and Analysis of Propulsion Systems with Supersonic Internal Flow

Summary

PhD Candidate: Eng. Andrei Vlad COJOCEA

PhD Supervisor: Prof. Dr. Eng. Daniel-Eugeniu CRUNȚEANU

Bucharest, 2025

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PhD Evaluation Board

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Bucharest, 2025

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   - **Cojocea A.V.**, Porumbel, I., Gall, M. and Cuciuc, T., 2024. Experimental Thrust and Specific Impulse Analysis of Pulsed Detonation Combustor. *Applied Sciences, 14(14)*, p.5999, https://doi.org/10.3390/app14145999, WOS:001276744300001, ISSN: 2076-3417
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   - **Cojocea A.V.**, Cuciuc,T., Porumbel, I., Gall, M., Vrabie,G., Asoltanei,D., 2024. Exploring the Sustainability of Pulsed Detonation in Hydrogen-Air and Hydrogen-Oxygen Mixtures. In *9th Edition of Space Propulsion Conference*, Glasgow, Scotland, `https://www.3af-spacepropulsion.com/images/DOCUMENTS/SP2024_PRELIMINARY_PROGRAMME.pdf`

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Motivation and Objectives

1.1 Fundamental Problem

Modern propulsion systems face significant challenges when striving for higher efficiency, improved fuel economy, and reduced environmental impact. Traditional engines based on subsonic deflagration, such as gas turbine engines (GTEs) operating on the Brayton cycle, are limited by inherent thermodynamic inefficiencies and strict operational constraints [1]. In contrast, propulsion systems based on supersonic internal flow, specifically, Pulsed Detonation Combustors (PDCs), offer the promise of pressure-gain combustion, which can significantly enhance cycle efficiency and performance [2].

Figure 1 illustrates the performance trade-offs across propulsion systems, **highlighting the potential of DEs to achieve higher specific impulse values at varying Mach numbers and different fuels. This puts PDCs in a competitive position to advance next-generation propulsion technologies**.

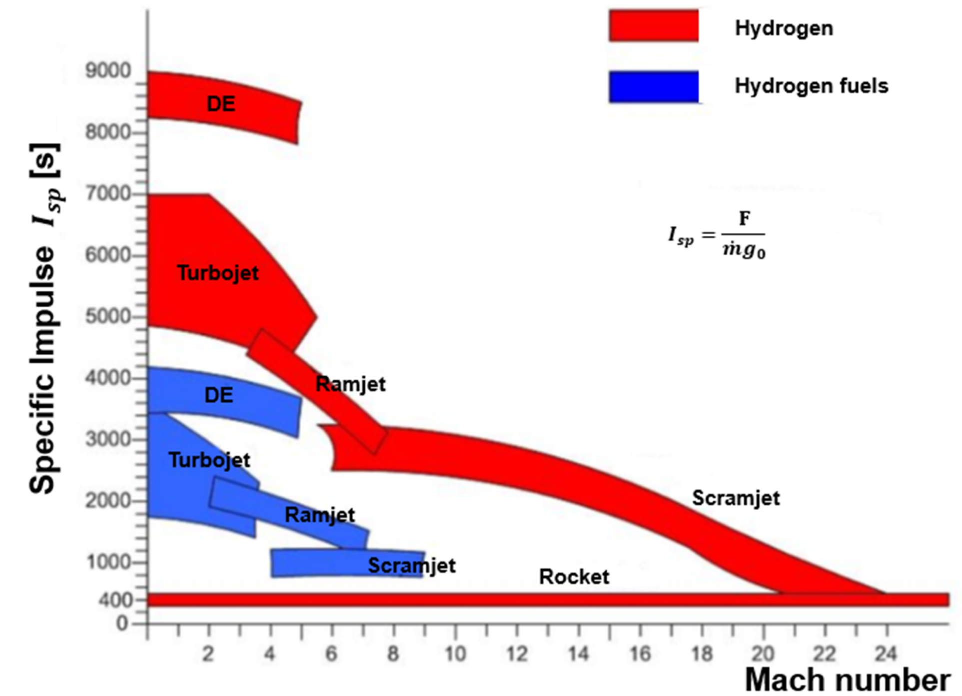


Figure 1: Specific impulse diagram for several propulsion architectures [3].

At its core, this research is motivated by the need for propulsion systems that deliver high thrust-to-weight ratios while operating efficiently under both atmospheric and space conditions. The emerging global emphasis on reducing carbon emissions and achieving climate neutrality further underscores the importance of hydrogen-based detonation technologies [4,2]. Moreover, as the race for interplanetary missions intensifies, there is a growing demand for propulsion systems capable of reducing travel time and minimizing human crew exposure to cosmic radiation [5,6]. The PDC, with its promise of superior thermodynamic performance and adaptability to different fuel-oxidizer mixtures, represents an innovative solution to these challenges.

However, despite their theoretical advantages, practical implementation of PDCs is hindered by complex detonation dynamics, issues with stable detonation initiation, sensitivity to combustor geometry, and challenges in adapting the system to different fuel-oxidizer mixtures

[7]. The fundamental problem addressed in this thesis is how to design, optimize, and validate a PDC system that reliably achieves detonation using hydrogen-based fuels while delivering superior efficiency and performance across atmospheric and vacuum conditions.

The significance of this work lies in its potential to push propulsion technology toward systems that are both efficient and versatile. By bridging gaps in our current understanding of detonation dynamics and applying rigorous experimental methodologies, this thesis contributes to the design of next-generation propulsion systems for terrestrial, atmospheric, and space applications.

1.2 Literature Survey

A thorough review of the literature reveals a rich body of work that has shaped our understanding of detonation-based propulsion systems. Early research primarily focused on the characteristics of subsonic combustion processes; however, the pursuit of higher efficiency has driven the exploration of supersonic combustion, where detonation phenomena are critical. The Chapman–Jouguet (CJ) theory [8,9], along with the Zeldovich–von Neumann–Döring (ZND) model [10], provides a fundamental basis for understanding detonation waves, detailing the induction and reaction zones that sustain rapid combustion.

Complementing the dynamic models, thermodynamic cycle analyses, such as the Humphrey and Fickett-Jacobs (FJ) cycles, offer simplified representations of detonation-based processes. These models typically assume a quasi-constant volume combustion process, which inherently promises higher cycle efficiencies compared to constant-pressure cycles [11,12]. In the PhD Thesis, comparative thermodynamic cycle studies using pressure - volume $p - v$ and enthalpy - entropy $h - s$ diagrams are drawn for H_2/O_2 for an equivalence ratio (ER) of 0.1. These studies, depicted in **Figure 2**, emphasize that detonation-based engines can achieve notable improvements in efficiency and work output (see **Table 1**).

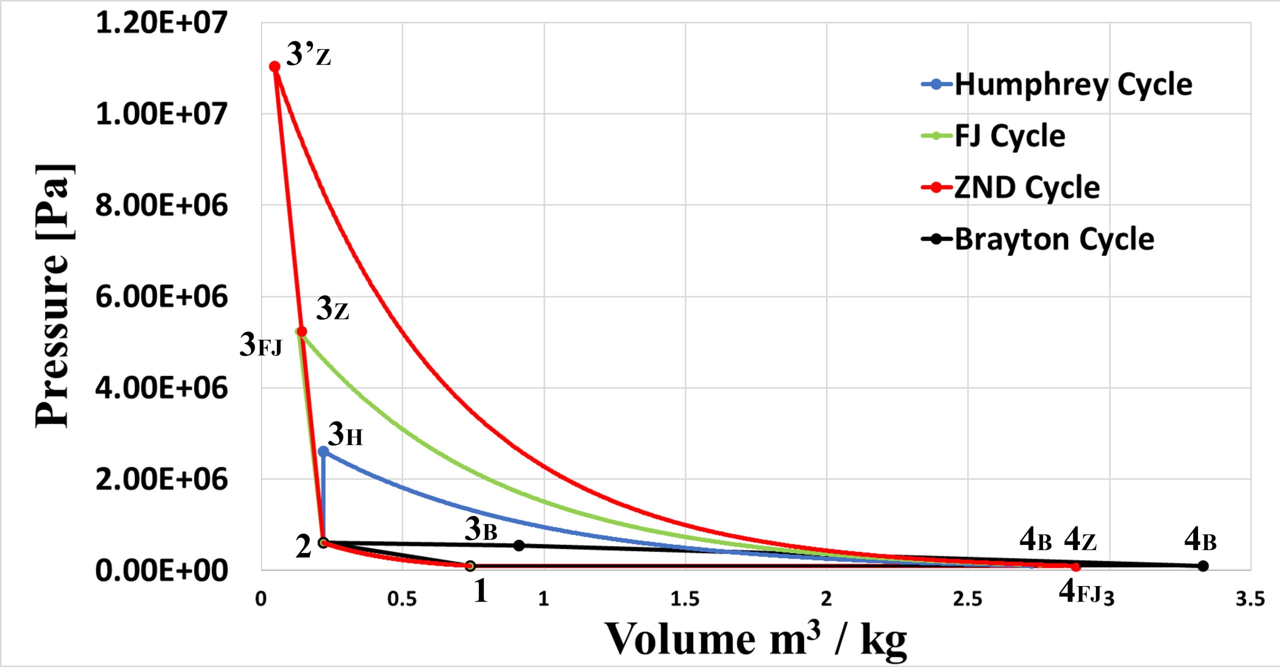
Table 1: Performance Metrics of PDC Across Detonation Cycles

Cycle	Specific Work [J/kg]	Net Specific Heat [J/kg]	Cycle Efficiency [%]
Humphrey	696.229,19	1.019.544,30	68,288
FJ	899.649,88	1.444.379,11	62,286
ZND	1.009.448,79	1.543.630,76	65,394

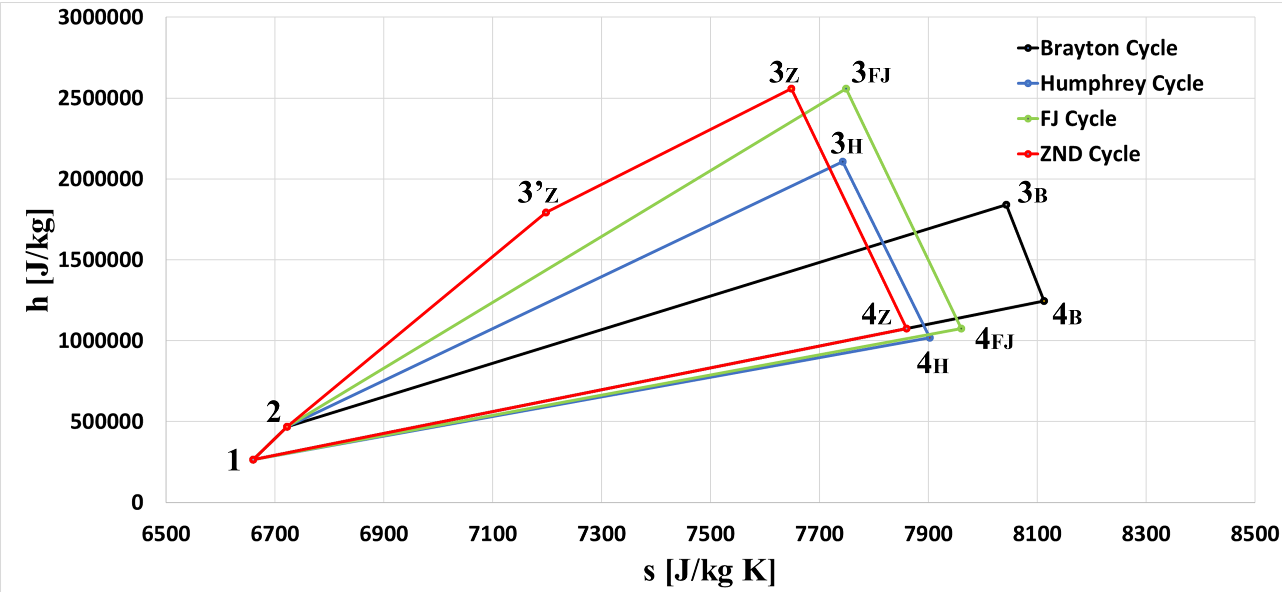
However, the practical realization of PDC technology is not straightforward. Real-world detonation phenomena are inherently complex, involving three-dimensional wave interactions, cellular patterns, and triple-point dynamics that challenge stable detonation initiation and maintenance [13,14,15]. Moreover, while detonation-based combustion has been studied extensively, adapting these systems to work reliably on the same PDC geometry, with hydrogen-based mixtures (both hydrogen–air and hydrogen–oxygen) remains a significant challenge, especially when the system must operate under varying conditions, from atmospheric environments to low-vacuum (space-like) conditions.

1.3 Hypotheses

This thesis is driven by the hypothesis that: **Hydrogen-based PDCs can achieve significantly higher thermal efficiency, greater pressure-gain, and improved thrust-to-weight ratios compared to conventional constant-pressure combustion engines. These enhancements can be realized through careful optimization of combustor**



(a) $p - v$



(b) $h - s$

Figure 2: PDE cycle vs Brayton cycle.

geometry and detonation initiation techniques, combined with a deep understanding of the underlying detonation dynamics under both atmospheric and vacuum conditions.

This thesis is built upon several interrelated hypotheses regarding the performance and applicability of hydrogen-based Pulsed Detonation Combustors (PDCs):

1. **Detonation Performance:**
   The hypothesis is that hydrogen-based PDCs can consistently achieve higher detonation velocities, greater pressure-gain, and improved thermal efficiencies than traditional constant-pressure combustion engines. This is attributed to the intrinsic advantages of pressure-gain combustion, which enable a more effective conversion of chemical energy into kinetic energy. The thermodynamic cycle analysis (**Figure 2**) predicts enhanced

efficiency. Furthermore, under properly optimized conditions, the detonation wave propagation in PDCs will exhibit superior performance metrics relative to conventional systems.

2. **Mixture Adaptability:**
   It is further hypothesized that the same fundamental combustor design can be adapted to operate with both hydrogen–air and hydrogen–oxygen mixtures. The increased reactivity of hydrogen–oxygen mixtures is expected to influence detonation cell size, ignition delay, and cycle stability. Through careful experimental investigations, data analysis and design modifications, it is anticipated that the combustor can accommodate these variations without necessarily compromising performance.

3. **Geometric Optimization:**
   The hypothesis is based on iterative experimental modifications to the combustor geometry, including injector configuration, chamber dimensions, and fuel delivery mechanisms, that can significantly enhance the stability and repeatability of detonation events. By optimizing these geometric parameters, the PDCs can operate at higher frequencies, maintain detonation under a broader range of conditions, and enhance performance metrics, such as pressure gain, thrust and specific impulse.

4. **Vacuum Operations Viability Hypothesis:**
   Finally, the last hypothesis is that the optimized PDC design will be capable of sustaining pressure-gain combustion under vacuum conditions representative of space propulsion environments. Achieving stable detonation under such conditions is critical for the broader applicability of PDCs in aerospace applications, particularly for interplanetary missions where environmental conditions differ markedly from those at sea level.

Collectively, these hypotheses assert that by combining advanced instrumentation and data analysis with rigorous experimental validation, it is possible to design a robust, high-performance PDC system that overcomes the limitations of conventional propulsion systems. This research will test these hypotheses through a systematic investigation of detonation dynamics, geometric optimization, and performance mapping across different fuel mixtures and operating conditions.

1.4 Objectives

To test these hypotheses, the research is organized around several specific objectives (SO):

SO1: Baseline Geometry Feasibility

Demonstrate that the baseline PDC geometry can reliably initiate and sustain detonation cycle using a hydrogen–air mixture at the designated operational frequency of 100 Hz.

SO2: Fuel Mixture Adaptability

Modify and adapt the baseline design to work effectively with hydrogen–oxygen mixture, thereby assessing the impact of increased fuel reactivity on detonation stability and performance.

SO3: Performance Mapping

Conduct comprehensive, full factorial experiment campaigns based on the most important influential parameters, such as fed gasses pressure, spark plug frequency and exhaust pipe length, to map the operational envelope of the PDC. Employ automated data processing scripts, extract means and variance of the performance metrics, while an Analysis of Variance (ANOVA) is used to determine the statistical significance of each parameter.

SO4: Geometry optimization and performance enhancement
Iteratively refine the combustor key geometry components, including injector design and chamber dimensions, based on experimental feedback to enhance operating frequency, stability, and overall performance.

SO5 Vacuum Validation:
Validate the optimized design under vacuum conditions, simulating space propulsion environments, to ensure the system's applicability in space-like conditions and for space-based missions.

Each objective is designed to progressively increase the Technology Readiness Level (TRL) of the system, ultimately targeting a level suitable for practical aerospace applications.

1.5 Research Methodology

The research methodology is systematically designed to address the specific objectives (SO) and validate the proposed hypotheses. By integrating analytical and experimental approaches, this research aims to advance the understanding and performance of PDCs for high-efficiency propulsion systems. Additionally, the methodologies prioritize leveraging existing knowledge, identifying gaps, and building upon prior research through meticulous literature review and state-of-the-art experimental techniques. The overall workflow is outlined below, in **Figure 3**.

General Methodological Approach

1. Literature Review and Knowledge Synthesis:
   - A comprehensive review of high-impact publications, including Q1/Q2 journal articles (such as Journal of Propulsion and Power, Shock Waves, Aerospace, Acta Astraonautica etc.) and A+/A conference proceedings (such ASME, AIAA, etc.), is conducted using search engines like Google Scholar, Scopus, and Web of Science. Filters such as publication year, citation count, and journal reputation were applied to ensure the relevance and quality of references.
   - The focus is on identifying what has been achieved in PDC research, analyzing gaps in understanding, and determining how this thesis could contribute to filling those gaps.
   - By examining methodologies, findings, and recommendations from prior studies, this research builds upon the foundation laid by experts in the field while addressing specific challenges unique to this thesis.
2. Instrumentation and Diagnostics:
   - Advanced diagnostic tools are carefully selected to ensure accurate and reliable measurements. High-speed Schlieren visualization, pressure and temperature transducers, and photodiodes were employed to monitor detonation wave propagation, temperatures, ignition repeatability, and operational frequency.
   - Calibration protocols are rigorously followed to minimize measurement uncertainties and ensure consistency across tests.
3. Iterative Design and Testing:
   - The research adopted an iterative approach, where experimental findings informed subsequent design improvements. This cycle of design, testing, and refinement was critical for achieving the desired performance metrics.

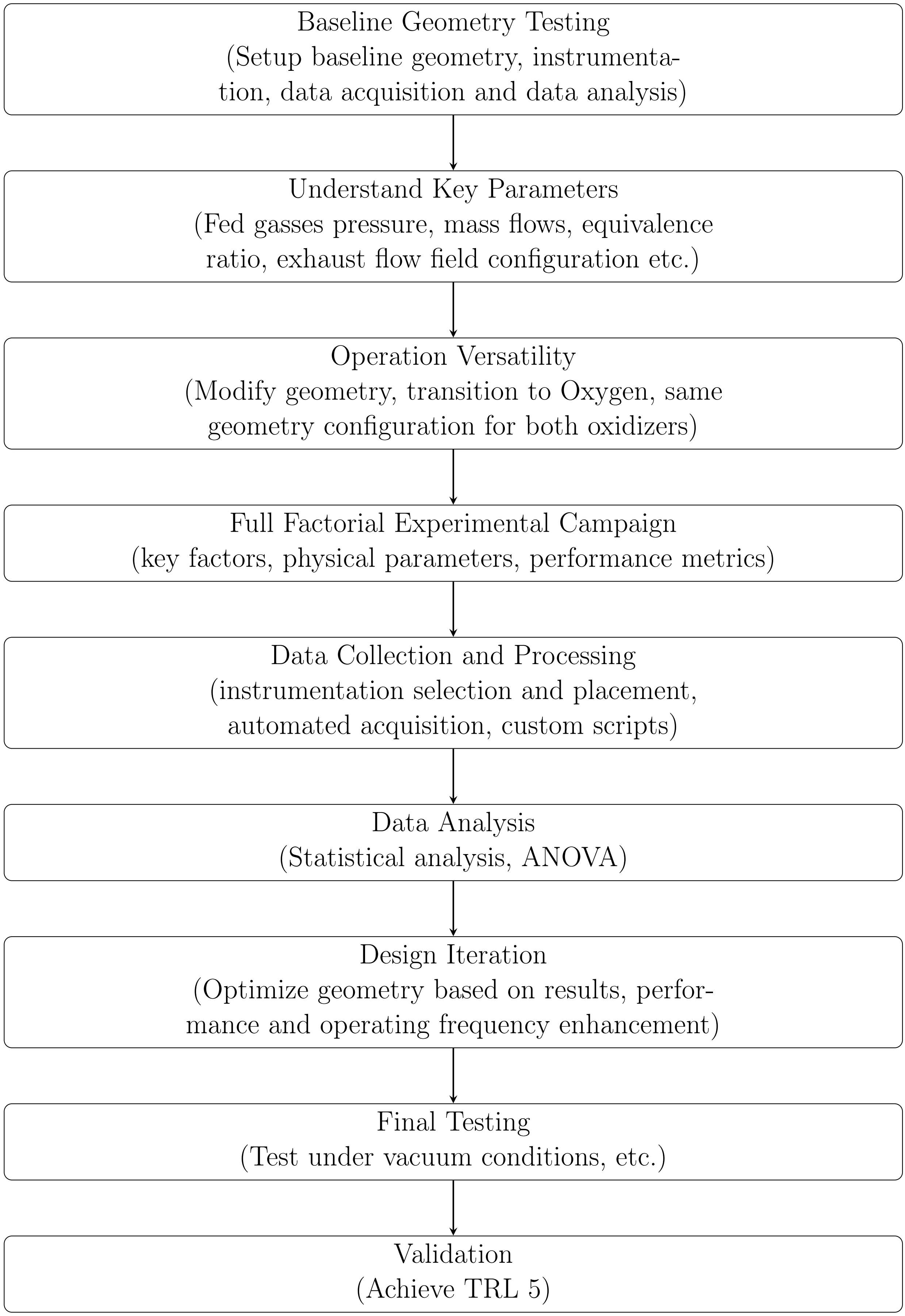


Figure 3: Overall experimental and analytical workflow for the PDC research.

4. Data Processing and Analysis:

    - Custom automated scripts are developed to handle large datasets generated during the experimental campaigns, extracting key physical parameters such as pressure, temperature, velocity and performance metrics such as thrust, specific impulse, and pressure gain.
    - Statistical tools, such as Design of Experiment (DoE), mean and variance extraction, and Analysis of Variance (ANOVA), are considered to quantify the impact of operational parameters on performance.

Objective-Specific Methodologies

1. **Objective 1:** Achieving Detonation in the Baseline Geometry with H_2/air Mixtures (TRL 3):

    - **Approach:** Experimental trials are conducted to validate the baseline geometry's capability to sustain detonation. Schlieren visualization and pressure sensors are used to observe detonation wave formation and propagation.
    - **Outcomes:** Modifications to the oxidizer inlet nozzles are introduced based on initial observations to enhance vortex strength and ensure robust detonation.

2. **Objective 2:** Adapting the Baseline Geometry for H_2/O_2 Mixtures (TRL 3):

    - **Approach:** Multiple fuel injection plate designs are tested to accommodate the higher reactivity of H_2/O_2 mixtures. Iterative testing and performance evaluation are used to identify the optimal configuration.
    - **Outcomes:** Successful repeatable detonation cycles are achieved for H_2/O_2 mixtures, demonstrating the system's adaptability.

3. **Objective 3:** Performance Mapping Through Full-Factorial Experimental Campaigns (TRL 4)

    - **Approach:** A full-factorial test matrix is designed to evaluate the impact of oxidizer and fuel pressures, spark plug frequency, and exhaust pipe length on performance. Each parameter is tested at four levels, resulting in 512 total tests.
    - **Diagnostics:** Automated data processing scripts extract means and variance of the performance metrics, while ANOVA determine the statistical significance of each parameter.
    - **Outcomes:** A comprehensive operational map of the PDC is developed, highlighting key performance trends and sensitivities.

4. **Objective 4:** Optimizing PDC Geometry for Enhanced Performance and Frequency (TRL 4)

    - **Approach:** Insights from the performance mapping inform geometric optimizations, including adjustments to combustor geometry.
    - **Validation:** Optimized configurations are experimentally tested to confirm performance improvements.
    - **Outcomes:** Enhanced operational frequency and pressure gain are achieved.

5. **Objective 5:** Demonstrating Pressure-Gain Combustion Under Low-Vacuum Conditions (TRL 5)

- **Approach:** Necessary modifications are implemented to address challenges in low-vacuum environments.
- **Validation:** Tests in a vacuum chamber simulate near-space conditions, with performance metrics monitored to assess detonation sustainability.
- **Outcomes:** Pressure-gain combustion is successfully demonstrated under low-vacuum conditions.

This thesis builds upon prior studies by adapting established methodologies to address the unique challenges associated with PDC. For instance, the detonation cell size database [16] is employed to estimate the critical dimensions required for sustaining detonation waves effectively. Additionally, previous research on turbulence enhancement [17,18,19] informed the design of flow obstacles aimed at reducing the DDT length, thereby improving overall system performance.

Beyond leveraging existing research, this thesis contributes novel insights to the field. It explores under-researched areas, such as the performance of detonation under low-vacuum conditions, a critical factor for space propulsion, introduces optimized geometries for hydrogen-fueled PDCs, and identifies a new found effect which is presented in Chapter 9. These advancements expand the current understanding of PDC operations and pave the way for more efficient propulsion systems in terrestrial, atmospheric and space applications.

2. Synthesis of Results and Implications

In this synthesis chapter, the results of this PhD Thesis are consolidated to illustrate the iterative workflow that guided the research towards meeting each specific objective. By comparing and contrasting the findings from the individual articles, it is highlighted how the sequential phases of modeling, experimental validation, and design optimization interlinked to advance the hydrogen-based PDC technology. This integrated discussion not only reinforces the theoretical frameworks and experimental approaches established in **Chapter 1** but also underscores the systematic process through which each research objective are addressed. Moreover, by tracing the evolution of the methodology and outcomes, key trends, interrelationships, and remaining challenges that point to promising directions for future research, are identified.

Please note that the figures and tables included here, as well as their captions, have been selectively summarized or adapted to focus on key insights, and some details may have been omitted for clarity and conciseness.

2.1 Experimental Investigations of Hydrogen Fuelled Pulsed Detonation Combustor

The results of this section are presented in **Chapter 2 of the PhD Thesis**, which represents the article referenced in [20], and are synthesized below.

The experimental investigations on the hydrogen-fueled PDC presented in this section primarily address **SO1: Baseline Geometry Feasibility**. The objective is to demonstrate that the baseline PDC geometry can reliably initiate and sustain detonation cycles using a hydrogen-air mixture at the designated operational frequency of 100 Hz. The study focuses on validating the combustor's performance metrics under controlled experimental conditions, providing evidence for detonation wave sustainability, cycle consistency, and the fundamental operational characteristics required to meet the baseline feasibility criterion.

Hydrogen is selected as the primary fuel due to its well-documented proneness to detonation, wide flammability range, and low auto ignition temperature, making it a highly effective candidate for pressure-gain combustion. However, its low density and high diffusivity pose challenges in storage and controlled injection. The experimental design aims to overcome some of these challenges and validate the PDC's ability to achieve stable detonation cycles with hydrogen.

The notable innovation is the use of Hartmann-Sprenger wave generators to enhance fuel-oxidizer mixing of the PDC aerodynamic system. By generating oscillatory counter-rotating vortices, this aerodynamic valve concept eliminates the need for mechanical flow restrictions, allowing for efficient and uniform mixing. The design (**Figure 4**) facilitates valveless operation, a key feature of the baseline geometry, which should ensure robust and consistent detonation cycles.

The results confirm the successful initiation and sustainment of a self-sustaining oscillatory regime in the PDC. The leading shock wave velocity (**Figure 5(a)**) is measured at 2215 m/s $\pm$ 419 m/s, providing clear evidence of stable detonation propagation. A key finding is the identification of a Mach disk structure in the exhaust plume (**Figure 5(b)**), which confirms the supersonic nature of the flow and supports the combustor's capability to operate under pressure-gain conditions.

The experimental campaign identified four distinct phases within the PDC cycle:

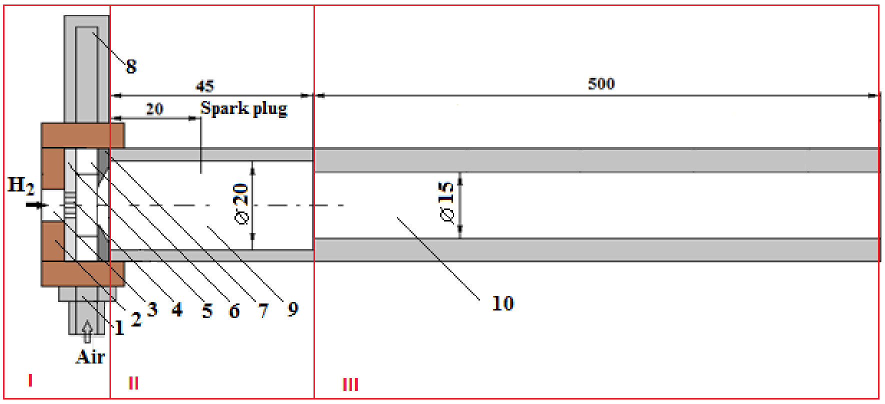
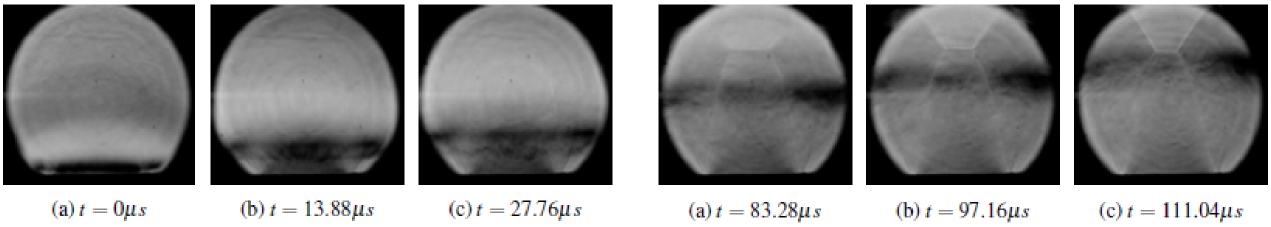


Figure 4: PDC experimental model [20].



(a) (b)

Figure 5: Exhaust pipe flow-field: (a) Leading Shock Wave, (b) Mach disk structure [20].

1. **Detonation Phase:** A rapid pressure rise followed by a sharp decrease, corresponding to the detonation wave propagation.

2. **Entrainment Phase:** Flow reversal causes the ingestion of ambient air and residual combustion gases into the combustor.

3. **Exhaust Phase 1:** Expulsion of entrained gases from the system.

4. **Exhaust Phase 2:** Trapped combustion products are expelled, resetting the system for the next cycle.

These phases were consistently observed across the operational conditions, further validating the baseline geometry's reliability in achieving pressure-gain combustion (see **Figure 6**).

The combustor achieved an operational frequency of 100.3 $Hz \pm 0.5$ Hz, matching the target baseline frequency outlined in **SO1**. This frequency consistency is critical for practical applications, as it ensures predictable and repeatable combustion cycles. Additionally, the average flow velocity during the detonation phase was measured at 706 m/s, with the maximum Mach number of the exhaust flow estimated at 1.05 ± 0.02. These findings align with the performance expectations for the baseline geometry.

Schlieren visualization, combined with static pressure measurements, provide valuable insights into the combustor's flow dynamics. Time-sequenced Schlieren images capture the development of leading shock waves, expansion waves, and the eventual transition of the flow to a subsonic regime. These visualizations further confirmed the combustor's ability to meet **SO1** requirements.

The results presented in this section strongly support the achievement of **SO1: Baseline Feasibility**, validating the PDC's ability to reliably initiate and sustain detonation cycles under

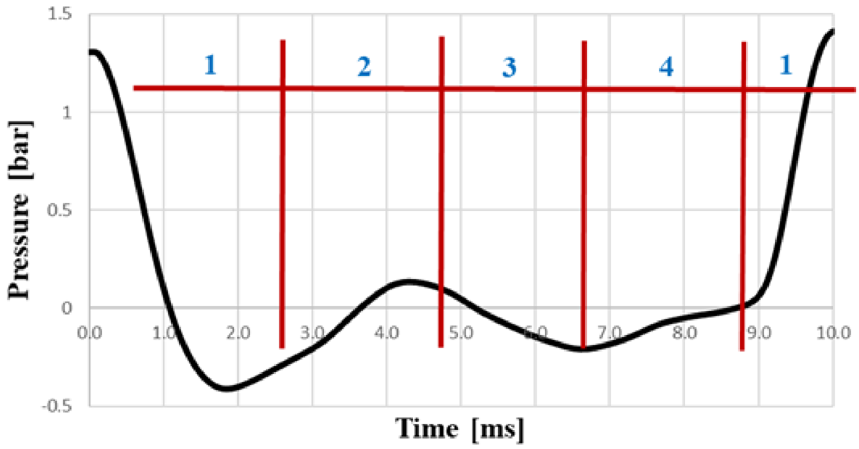


Figure 6: Relative Static Pressure over One PDC Cycle [20].

specified conditions. The integration of aerodynamic control methods for mixing, combined with the robustness of the baseline geometry, establishes a solid foundation for further exploration and optimization of pressure-gain combustion systems.

An important result of this paper [20] recommends the investigation to explore the potential for higher operational frequencies beyond the baseline frequency of 100 Hz. These advancements will contribute to the development of more efficient and scalable detonation-based propulsion architectures.

2.2 Experimental Comparison for Different Oxidizers in Hydrogen-Fuelled Pulsed Detonation Combustor

The results of this section are presented in **Chapter 3 of the PhD Thesis**, which represents the article referenced in [21], and are synthesized below.

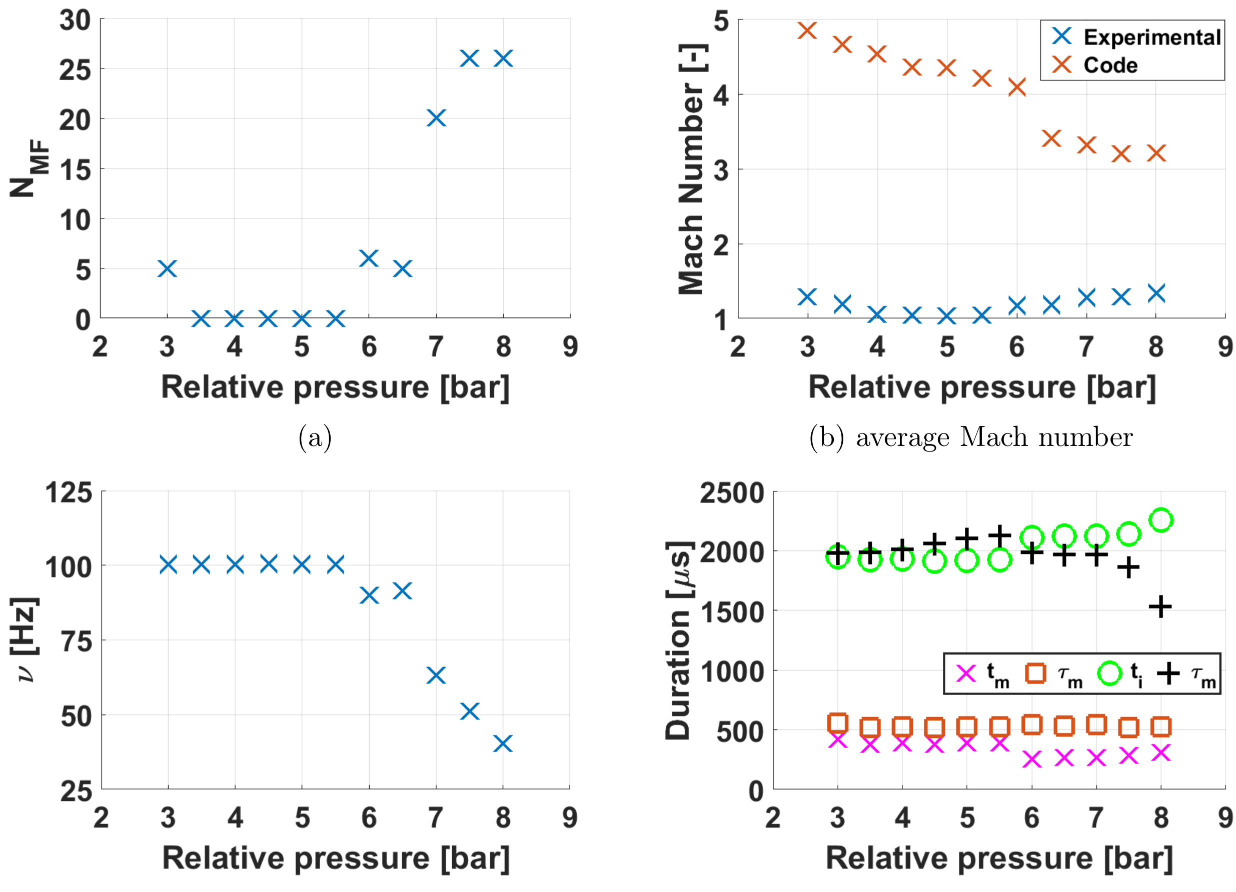
This study builds upon previous investigations of hydrogen-fueled PDC (**SO1**) by evaluating the effects of different oxidizers, air and pure oxygen, on the detonation process. The objective is to explore how the removal of nitrogen, a key component of air, influences DDT, combustion stability, and overall cycle performance. Since nitrogen acts as a diluent, its absence in the oxygen-fed cycles leads to different detonation characteristics, requiring adjustments in fuel injection and mixture preparation. This research aligns with **SO2: Adapting the Baseline Geometry for H_2/O_2 Mixtures**, by assessing whether hydrogen-fueled PDCs can sustain stable detonation cycles for different oxidizers on the same geometry. The study also reports findings of varying oxidizer conditions within the same combustor geometry.

A series of experiments are carried out using a modified test rig designed to deliver both oxidizers (air and oxygen) along a single flow line, thereby ensuring that the experimental conditions remained identical. The study compares the behavior of hydrogen-air and hydrogen-oxygen mixtures by analyzing ignition, detonation propagation, and cycle performance. The experimental setup includes the Schlieren visualization technique to capture the movement of shock waves and detonation fronts, at the outlet of the exhaust pipe offering valuable insights into flow dynamics.

Hydrogen-Air Mixture Performance

In the previous section, the PDC is evaluated under its optimal operating regime. When air is used as the oxidizer, stable detonation cycles are achieved for ERs ranging from 0.45 to

0.63. Within this interval, the combustor consistently produces repeatable detonation events, ensuring efficient combustion and controlled cycle performance. To further assess the PDC's performance and facilitate a transition to using oxygen as the oxidizer, off-design operating points are identified. Outside of the optimal ER range, the system exhibits significant irregularities, including a higher occurrence of misfires and an inability to sustain detonation. Moreover, increased air supply pressure resulted in less efficient mixing, leading to more frequent misfires and a reduced operating frequency due to a leaner mixture (see **Figure 7**).



(a)

(b) average Mach number

(c) average cycle frequency

(d) average characteristic time intervals

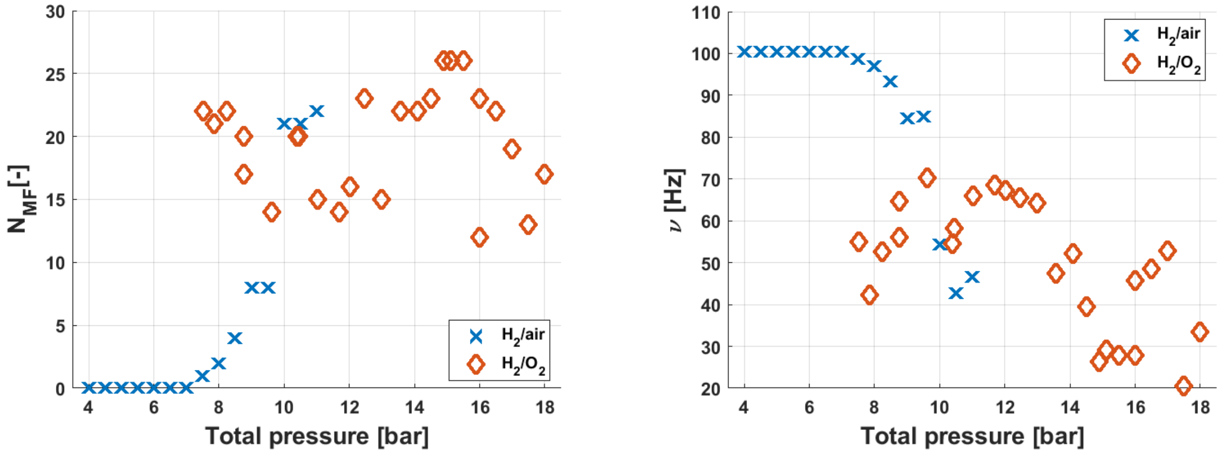
Figure 7: (a) Influence of air feed pressure on cycle repeatability (b),(c),(d) Influence of air supply total pressure on performance characteristics [21].

Transition to Oxygen as Oxidizer

The transition to pure oxygen as the oxidizer introduces new challenges. Initial trials with the baseline combustor configuration resulted in unstable detonation behavior, indicating that oxygen's higher reactivity alters the necessary conditions for successful DDT transition. To address this, modifications are made to the fuel injection system, optimizing the flow structure to accommodate the altered reaction kinetics. These adjustments leads to faster combustion products, but also to shorter entrainment phase, resulting in a higher number of misfires and reduced operating frequency, than for air operations (see **Figure 8**).

Comparative Performance of Air vs. Oxygen

A direct comparison of detonation cycle characteristics highlights key differences between the two oxidizers. The hydrogen-oxygen configuration demonstrates higher Mach numbers



(a) average number of misfires (b) average frequency

Figure 8: Cycle irregularities in hydrogen - oxygen operation [21].

and faster detonation propagation. Additionally, delayed onset of reversed flow is observed in oxygen-fed operation, indicating greater momentum retention in the exhaust flow. However, a higher rate of misfires is recorded, emphasizing the need for further optimization to achieve consistent cycle performance. The results are summarized in **Table 2**, while an example of Schlieren visualization is provided in **Figure 9**.

Table 2: Mean characteristic values for air and oxygen

Parameter	O_2		Air	
	Mean Value	C.I.	Mean Value	C.I.
$\mu[°]$	53.457	13.630	65.714	9.959
M	1.26851	0.20982	1.10530	0.09632
$t_m[\mu s]$	217.204	136.332	149.462	65.063
$t_i[\mu s]$	2310.753	474.511	1597.849	99.322
$\tau_i[\mu s]$	1331.183	613.792	1705.376	96.151

2.3 Exploring the Sustainability of Pulsed Detonation in Hydrogen-Air and Hydrogen-Oxygen Mixtures

The results of this section are presented in **Chapter 4 of the PhD Thesis**, which represents the article referenced in [22] and are going to be summarized below. The findings are part of the full factorial experimental campaign, that aims to bring the PDC up to **TRL 4**, which is **SO3: Performance Mapping Through Full-Factorial Experimental Campaigns**.

Building on earlier on-design and off-design findings for both oxidizers, the third paper examines the detonation stability of the PDC using hydrogen-air and hydrogen-oxygen mixtures, aiming to define their operational detonation limits (i.e., the operating map). The key motivation behind this research is to establish a deeper understanding of the factors influencing detonation cycle repeatability and efficiency, particularly for applications in space propulsion. The study assesses how oxidizer choice, gas-fed pressure, exhaust pipe configuration, and ignition frequency affect the operating envelope of the combustor, forming a crucial part of ongoing efforts to refine pulsed detonation technology. The experimental data associated to these findings will be presented in **Sections 2.4, 2.5 and 2.6**.

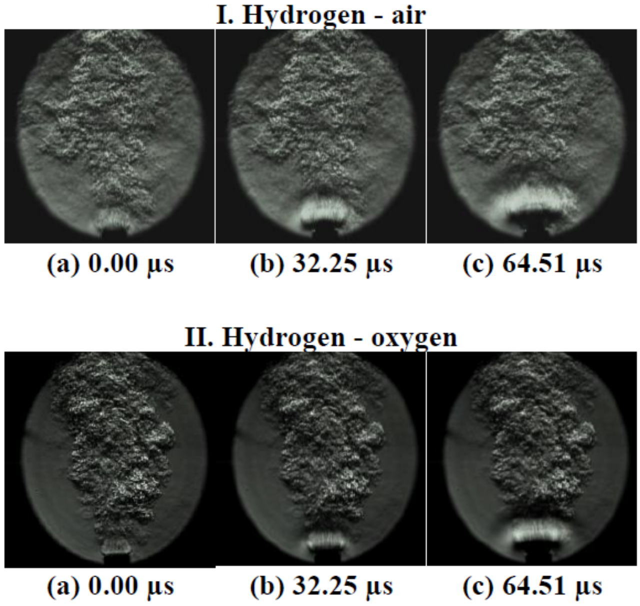


Figure 9: Leading shock wave

A series of controlled experiments are conducted using a high-pressure fuel and oxidizer supply systems, with a variable-frequency ignition system integrated into the PDC prototype. In addition, the PDC exhaust pipe is modified into a modular configuration, which enables length adaptation. A comprehensive full factorial test campaign (four factors, each with four levels - **Table 3**) is carried out, comprising 256 unique test cases designed to explore the impact of different operational parameters. The operational 3D maps for each fuel-oxidizer are presented in **Figure 10**.

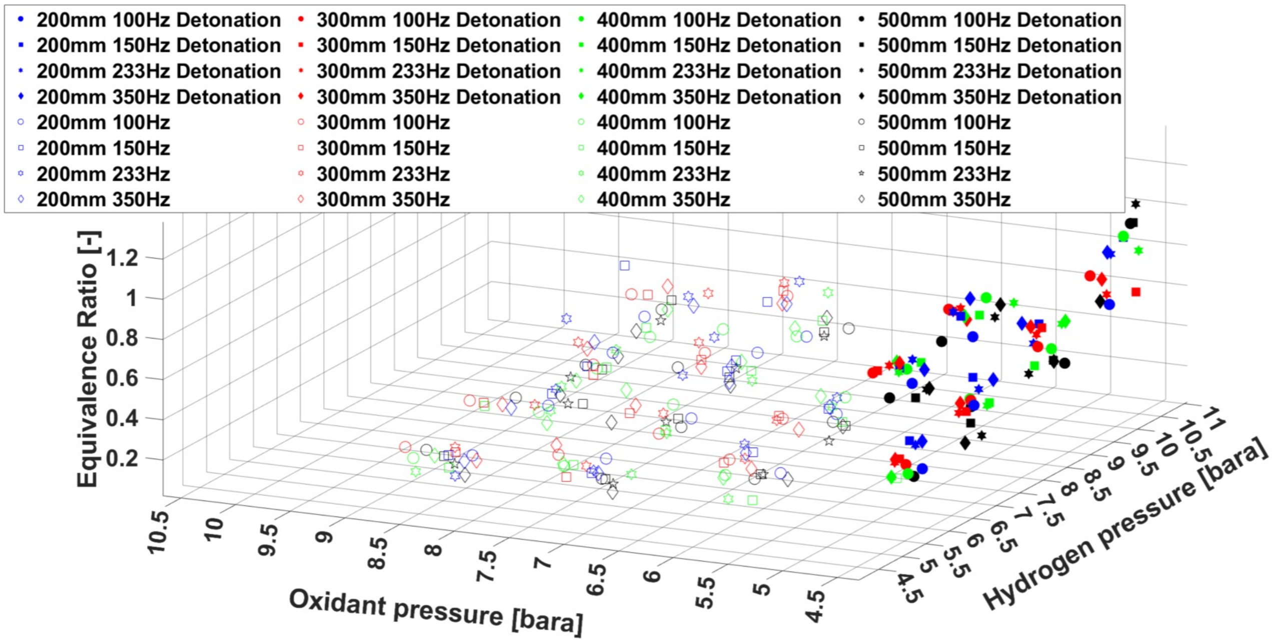
Table 3: Full factorial experimental campaign factors and levels.

Factor	**Level 0**	**Level 1**	**Level 2**	**Level 3**
Exhaust pipe length	200 mm	300 mm	400 mm	500 mm
Spark plug frequency	100 Hz	133 Hz	233 Hz	350 Hz
Hydrogen pressure	5.5 bara	7 bara	8.5 bara	10 bara
Oxidizer pressure	9 bara	7.5 bara	6 bara	4.5 bara

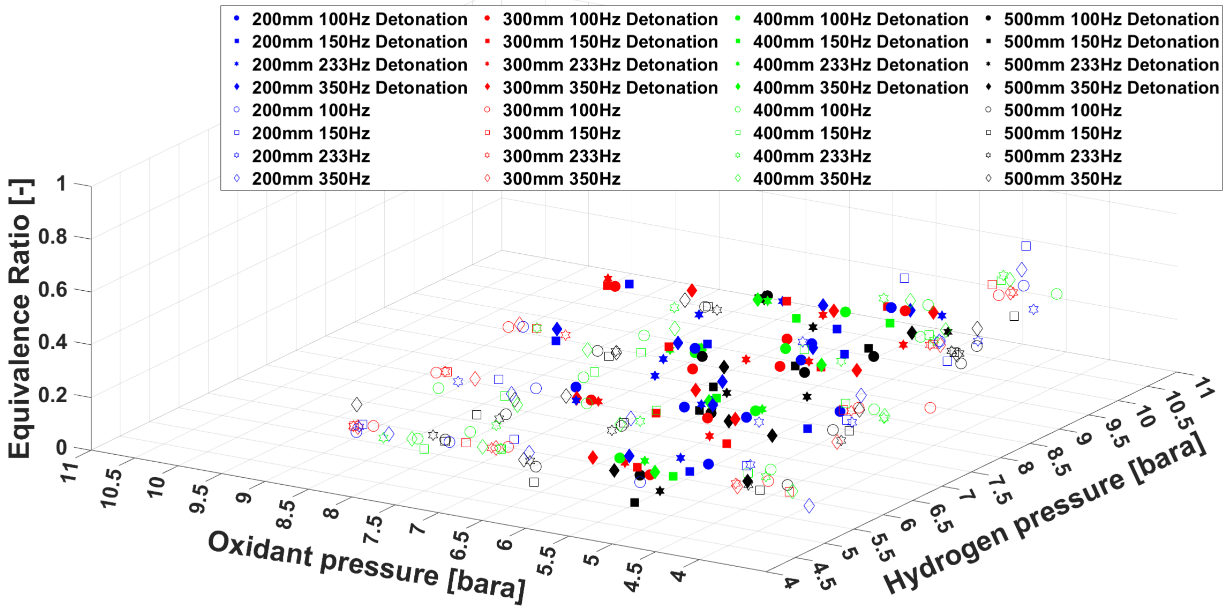
The results indicate that hydrogen-oxygen detonation cycles exhibit a wider stability window over the ER to sustain repeatable detonations. In contrast, hydrogen-air mixtures demonstrate a narrower stability margin but at the expense of lower overall detonation efficiency. Further analysis of fuel and oxidizer pressure effects highlight key trends in cycle sustainment. It is observed that the maximum pressure for achieving stable detonation is higher in oxygen-fed cycles compared to air-fed ones. When operating in the low oxidizer pressure regimes, combustion frequently transitioned into a deflagration mode, failing to achieve sustained detonation.

For air operations, the influence of oxidizer line pressure plays a central role in determining the sustainment of pulsed detonation cycles. It is determined that when the air pressure exceeded 6.5 bar, no sustainable detonation regime can be achieved. Similarly, at the other extreme, when the air pressure drops below 5 bar, sustainable detonation is not possible in most cases, with only one exception. Notably, the test which has the lowest recorded equivalence ratio of 0.319, also fails to sustain detonation, highlighting the significance of both air pressure and mixture composition in cycle stability.

In addition to air pressure, hydrogen pressure emerged as the second crucial factor influencing sustained detonation. The data shows that when the hydrogen pressure exceeded 8



(a) H_2/air



(b) H_2/O_2

Figure 10: 3D map of operational regimes envelope [22].

bar, sustainable detonation cycles is consistently achieved. This relationship can be explained by the interaction between fuel and oxidizer dynamics. Higher air pressure contributes to a stronger vortex in the premixing chamber, improving the uniformity of fuel-air mixing. At the same time, higher fuel pressure enhances the ability of the hydrogen jet to penetrate the aerodynamic valve formed by the vortex, ensuring effective mixing and improved detonation initiation.

For Oxygen operations the oxidizer line pressure has the same behavior in defining the operating envelope for sustainable detonation cycles. Within the pressure range of 4.8 to 5.4 bar, all test cases demonstrate sustained detonation, indicating a stable regime where combustion can be reliably maintained. As the pressure increases to the 5.4 to 6.4 bar range, most cases continue to exhibit sustainable detonation, though some deviations are observed. However, when the air pressure is further raised to 6.4 to 7.3 bar, the fuel line pressure becomes the determining factor for detonation stability. In this range, no sustained detonation is achieved for cases where the hydrogen pressure is below 7 bar. Beyond 7.3 bar, only specific operating regimes support sustained detonation, and these are limited to equivalence ratios above 0.069, suggesting that richer mixtures are required to compensate for the increased oxidizer flow.

In addition to the oxidizer pressure, hydrogen pressure emerges as the second crucial factor affecting detonation sustainability. When the hydrogen pressure falls below 4.8 bar, the system consistently transition into continuous deflagration mode due to the low intensity of the aerodynamic vortex controlling fuel admission. This lack of momentum prevented proper fuel-air mixing and fails to support the rapid energy release required for detonation. Conversely, for hydrogen pressures above 10 bar, all test cases result in sustained detonation, confirming that adequate fuel jet penetration and mixing intensity are essential for maintaining stable combustion cycles.

The phenomena occurring in the aerodynamic mixer of the PDC is explained in **Figure 11**. The ability to maintain a repeatable detonation cycle is strongly tied to the oxidizer line pressure, which directly impacts the velocity of the jet in the premixing chamber. This jet velocity, in turn, dictates the rotational speed of the vortices responsible for fuel-air mixing, effectively acting as an aerodynamic valve that controls fuel admission and mixture homogeneity. When the vortex intensity is low, the fuel injection process becomes uncontrolled, leading to incomplete mixing and causing the combustor to shift into deflagration mode, preventing sustained detonation.

The sustainment of pulsed detonation cycles is primarily governed by the fuel and oxidizer feed pressures, with secondary influences from the exhaust pipe length and ignition frequency. These findings emphasize the delicate balance between oxidizer dynamics, vortex formation, and fuel injection timing, all of which play a pivotal role in achieving and maintaining a sustainable pulsed detonation cycle.

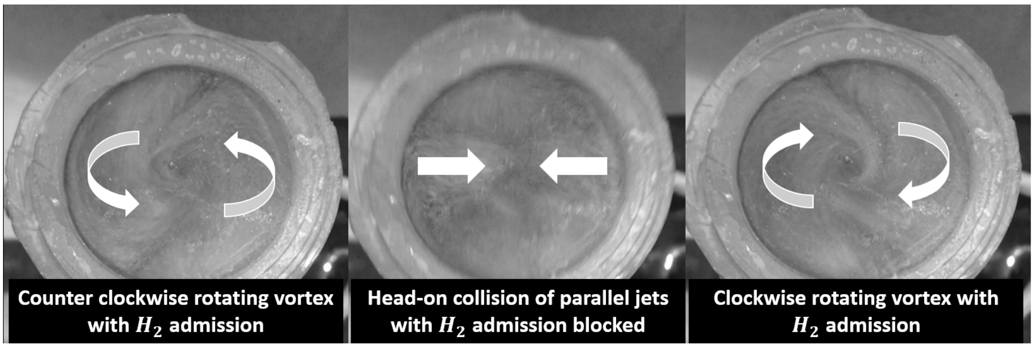


Figure 11: Visualization of flow in the mixing chamber [21].

2.5 Experimental Pressure Gain Analysis of Pulsed Detonation Engine

The results of this section are presented in **Chapter 5 of the PhD Thesis**, which represents the article referenced in [23]. This paper adds to **SO3: Performance Mapping Through Full-Factorial Experimental Campaigns** defined in the **PhD Thesis** through the investigations into the pressure gain combustion characteristics of the PDC for both mixtures.

The primary objective is to determine the operational regimes that yield maximum cycle pressure, average cycle pressure, and overall pressure gain. To achieve this, the same full-factorial experimental campaign is adopted (**Table 3**), systematically varying parameters such as oxidizer pressure, fuel pressure, exhaust pipe length, and spark plug frequency to analyze their effects on the detonation pressure characteristics. To ensure high-fidelity data collection, two high-speed Kulite ETM-HT-375 pressure sensors (K1 and K2), operating at a 20 kHz sampling rate, are employed to capture cycle behavior. The sensor placement is show in **Figure 12**. Additionally, Schlieren imaging techniques are utilized to visualize the exhaust plume configuration and to complement the data obtained from the pressure sensors.

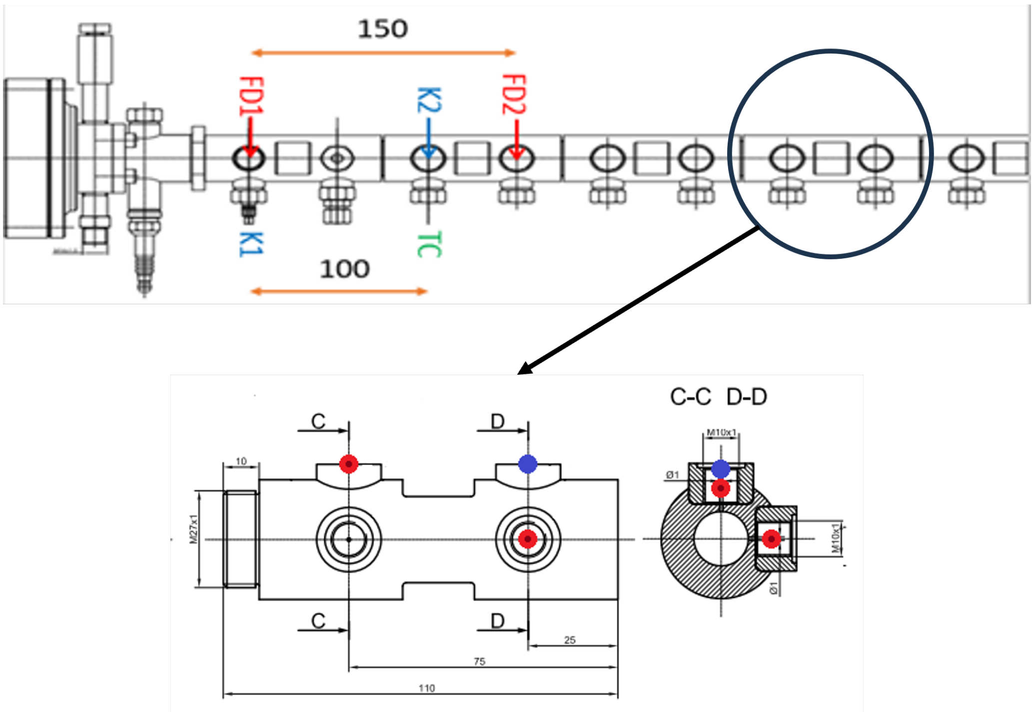


Figure 12: Instrumentation diagram. K1 and K2 mark the positions of the two Kulite probes [23].

A post processing algorithm is developed for the pressure sensors' raw signal. A signal filtering process is applied to eliminate unwanted noise while preserving the relevant pressure fluctuations associated with detonation cycles. Once the data is cleaned, the algorithm identified peak pressures within each detonation cycle, using a threshold-based detection method to separate valid detonation peaks from sensor noise. This allows for accurate measurement of maximum pressure, average pressure, dominant frequency and cycle-averaged pressure gain, which are calculated by comparing the pressure levels at the start and end of each detonation cycle. A moving average filter is then applied to highlight overall trends in pressure characteristics behavior. An example of the output of the pressure sensors is provided in **Figure 13**.

Additionally, the algorithm assesses cycle stability, measuring variations in peak pressures across successive detonation events. This analysis revealed operational conditions that led to stable or unstable detonation cycles, providing insight into the influence of oxidizer pressure, exhaust pipe length, and ER on detonation consistency.

The results indicate that the PDC achieves its highest maximum and average cycle pressures when the oxidizer line is held at a total of 6 bar and the fuel line at 10 bar. This holds true whether using air or oxygen. Moreover, the ideal exhaust pipe length differs between the oxidizers: 500 mm for air and 300 mm for oxygen. Analysis of the operating frequency data shows that setting the spark plug frequency to 100 Hz yields optimal performance in both cases.

When experiments are conducted at a fixed ER, it is observed that increasing either the exhaust pipe length or the oxidizer pressure results in higher average and peak pressures,

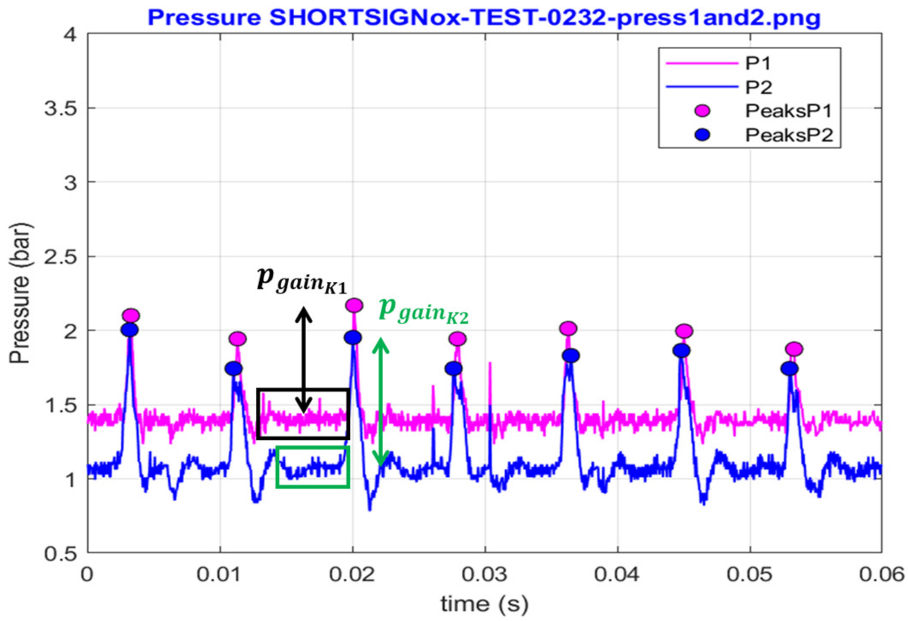


Figure 13: Pressure gain example [23].

whereas changes in the spark plug frequency have a minimal effect. Specifically, at lower oxidizer pressures there is an optimal ER that decreases as the exhaust pipe length is extended, with pressure cutoffs measured at 4.5 bar for air and 6.0 bar for oxygen. At elevated oxidizer pressures, however, this trend reverses, and a particular ER emerges that corresponds to the lowest observed values for both average and maximum pressures. This suggests that further investigation is warranted to understand the PDC's behavior at very low fuel mass flow rates.

Additionally, the thruster's operating frequency is primarily determined by the spark plug setting, although misfires during detonation initiation often lead to actual frequencies lower than the target. As expected, the design frequency of 100 Hz minimizes the occurrence of misfires. In off-design conditions, the data indicate that with air as the oxidizer the system can sometimes approach a spark plug frequency of 150 Hz. In other scenarios, while the spark plug may be driven above the design frequency, misfires prevent the system from fully matching that frequency, due to the unmatched operating frequency of the aerodynamic system. Finally, lower ERs are linked to a higher incidence of misfires across both experimental campaigns. Notably, shorter exhaust pipes tend to reduce misfire occurrences when using air and at high oxygen pressures, whereas longer exhaust pipes perform better under low oxygen pressure conditions.

2.5 Experimental Thrust and Specific Impulse Analysis of Pulsed Detonation Combustor

The results of this section are presented in **Chapter 6 of the PhD Thesis**, which represents the article referenced in [24]. This paper disseminates the results of thrust and specific impulse data that are obtained from the full factorial experimental campaign of the PDC (described in **Table 3**), for both mixtures. These findings are part of **SO3: Performance Mapping Through Full-Factorial Experimental Campaigns**.

The experimental setup includes a load cell system designed to capture thrust measurements of the combustor (**Figure 14**). Additionally, data from the mass flow meters, which provide physical parameters of the fed gasses is collected to correlate detonation behavior with impulse generation.

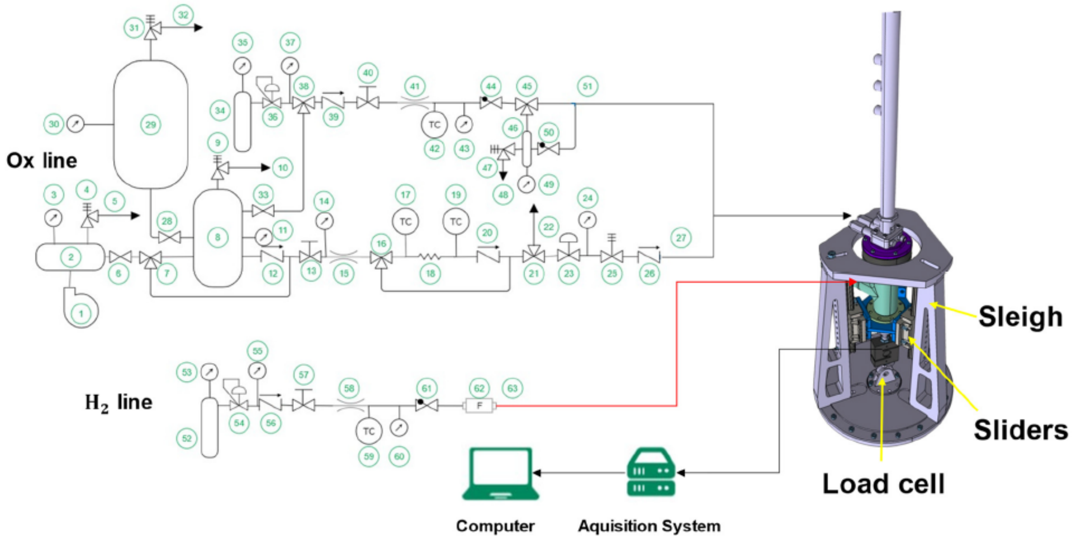


Figure 14: Schematic of the experimental set-up [24].

The results show that higher time-averaged thrust and specific impulse values are observed when using a hydrogen-air mixture compared to hydrogen-oxygen. This outcome is primarily due to the initial PDC design, which is optimized for air as the oxidizer. When transitioning to hydrogen-oxygen operation, only minimal modifications, mainly adjustments to the fuel injection system, are made to maintain a baseline configuration capable of sustaining high-frequency detonation regimes.

The thruster's operating frequency is largely dictated by the spark plug settings, though misfires during detonation initiation often lead to lower than expected frequencies. As anticipated, a spark plug frequency of 100 Hz minimizes misfires. When operating off-design, experimental results indicate that with air as the oxidizer, the PDC can occasionally reach 150 Hz. However, in other cases, frequencies above the design value are achieved sporadically but never fully match the spark plug frequency due to misfires.

Performance metrics for the hydrogen-oxygen mixture generally show lower values, particularly in terms of thrust and total specific impulse, as these parameters are significantly influenced by the frequency of misfires.

For the hydrogen-air mixture, time-averaged thrust values increase with both ER and oxidizer pressure. The optimal PDC operation is achieved with a 400 mm exhaust pipe length, which yields the highest thrust values across different oxidizer pressure levels—except at a spark plug frequency of 233 Hz. A similar trend is observed for both total and fuel-specific impulse, where peak performance is also associated with the 400 mm exhaust pipe length, with the same exception. This behavior is attributed to the decoupling between the aerodynamic flow system and the ignition frequency.

In contrast, for the hydrogen-oxygen mixture, the highest time-averaged thrust is recorded with a 200 mm exhaust pipe. This is due to the higher energy release of the hydrogen-oxygen reaction, which is more affected by heat transfer to the exhaust pipe walls. Consequently, shorter exhaust pipes reduce energy dissipation, leading to higher thrust levels.

For both oxidizers, increasing the ER enhances performance. However, the interactions between oxidizer pressure, spark plug frequency, and exhaust pipe length differ. When using air, low oxidizer pressures and shorter exhaust pipes result in higher performance at increased ignition frequencies, while higher oxidizer pressures and longer exhaust pipes are more effective at lower frequencies. For oxygen, thrust levels tend to be higher at lower oxidizer pressures when paired with smaller exhaust pipes and lower ignition frequencies. Meanwhile, total specific impulse improves with increasing oxidizer pressure and longer exhaust pipes. The highest fuel-specific impulse is consistently obtained with a 500 mm exhaust pipe across all tested conditions.

2.6 Complete Thruster Performance Parameters

The results of this section are presented in **Appendix C of the PhD Thesis**, which supplements and concludes **SO3** by providing a detailed analysis of additional performance parameters not covered in **Chapters 5 and 6 of the thesis**. These results are not included in the thesis chapters as they have not yet been published but are planned for future publication. These include wave velocities, cycle temperatures, and statistical analysis of the influences of operational factors on pulsed detonation thruster (PDT) performance. The figures and tables referenced have been selectively summarized to focus on key insights, with some details omitted for clarity and conciseness.

To comprehensively assess the PDC cycle performance and to advance the PDC to **TRL 4**, a full set of parameters is recorded, including oxidizer and fuel pressures, mass flow rates, ER, maximum and average cycle temperature, shock wave velocity, combustion wave velocity, thrust (**Section 5**), maximum and average cycle pressure and operating frequency (**Section 4**). While **Chapters 5 and 6 of the thesis** primarily focused on pressure, operating frequency and thrust, **Appendix C** extends the analysis to include parameters that further characterize the detonation process.

Cycle Temperature Analysis

The maximum and average cycle temperatures are recorded using a high-speed temperature sensor installed on the exhaust pipe (denoted TC in **Figure 12**). However, due to the rapid sensor heating rate, temperature measurements are constrained to limited cycles. This can be seen in **Figure 15**.

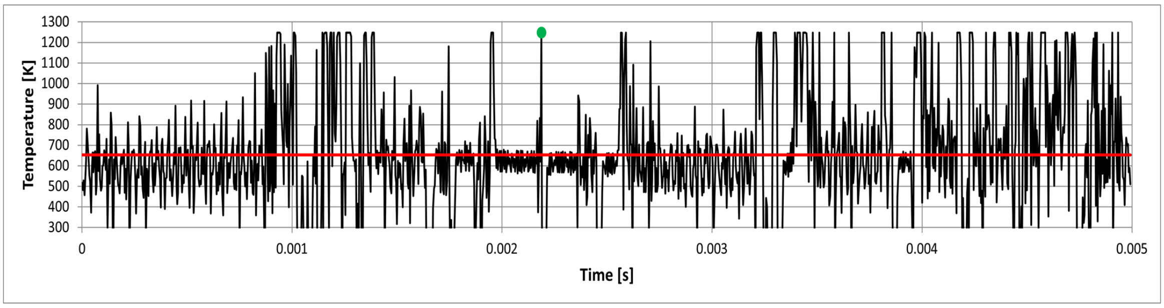


Figure 15: Selection of the characteristic maximum and mean temperature. Example. The maximum value is marked by the green dot, and the average value by the red line.

For hydrogen-air operations, the highest recorded temperature is 1247 K, achieved for a 500 mm exhaust pipe at 233 Hz spark plug frequency. For hydrogen-oxygen operation, the highest recorded temperature was 1266 K, measured at 400 mm exhaust length and 233 Hz frequency.

The temperature profiles exhibited distinct trends with exhaust pipe length, oxidizer pressure, and ER, with longer pipes generally resulting in reduced peak temperatures at high oxidizer pressures.

Wave Velocity Analysis

The shock wave velocity (W_s) and combustion wave velocity (W_c) are determined using high-speed pressure sensors and photodiodes (denoted FD1 and FD2 in **Figure 12**), respectively. These sensors are positioned along the exhaust pipe to measure the time delay between peak signals and calculate wave velocities. The results reveal that oxidizer pressure and ER play dominant roles in influencing these velocities.

Results show that shock wave velocity generally increases with ER up to a peak value, beyond which it stabilizes or slightly decreases. Higher oxidizer pressures result in lower shock wave velocities but increased combustion wave velocities, improving wave coupling and detonation intensity. Longer exhaust pipes contribute to stronger wave coupling by reducing the velocity difference between the two waves.

Statistical Analysis of Parameter Influence

A four-factor ANOVA analysis [25] is performed to quantify the influence of exhaust pipe length, spark plug frequency, fuel pressure, and oxidizer pressure on key performance metrics. This statistical method allows for the estimation of the effects of the key factors on a specified set of responses. The complete results and the implementation of ANOVA is thoroughly descried **Appendix C of the PhD Thesis**. An example of the ANOVA study is provided in **Table 4**.

A brief overview for both oxidizers shows that thrust is primarily influenced by exhaust pipe length and oxidizer pressure, with minor contributions from spark plug frequency. Maximum cycle pressure and average cycle pressure are largely dictated by oxidizer pressure and ER, with less contributions from fuel pressure. Cycle temperature trends follow similar influences, with oxidizer pressure being the dominant factor. Shock wave velocity is mainly determined by oxidizer pressure and ER, while combustion wave velocity is most affected by oxidizer pressure and fuel pressure interactions.

Table 4: ANOVA table for the maximum cycle pressure for H_2/air.

Factor	SS	DF	MS	Test	F	Result	% SS
F1: Length	0.213	3	0.071	1.69	2.717	N	0.042
F2: Frequency	0.178	3	0.059	1.41	2.717	N	0.035
F3: Fuel pressure	55.311	3	18.437	437.36	2.717	Y	10.774
F4: Oxidizer pressure	345.885	3	115.295	2734.97	2.717	Y	67.378
F1 × F2	0.215	9	0.072	1.998	1.998	N	0.042
F1 × F3	0.648	9	0.072	1.998	1.998	N	0.126
F1 × F4	0.978	9	0.108	1.998	1.998	N	0.190
F2 × F3	0.428	9	0.048	1.998	1.998	N	0.082
F2 × F4	0.619	9	0.034	1.998	1.998	N	0.120
F3 × F4	101.735	3	33.104	268.14	2.717	Y	19.818
F1 × F2 × F3	1.383	27	0.051	1.624	1.624	N	0.268
F1 × F2 × F4	1.451	27	0.052	1.624	1.624	N	0.281
F1 × F3 × F4	1.122	27	0.041	1.624	1.624	N	0.217
F2 × F3 × F4	1.381	27	0.051	1.624	1.624	N	0.265
Error	8.315	81	0.042	-	-	-	0.665
Total	513.351	255					99.335

2.7 Experimental Investigations on the Impact of Hydrogen Injection Apertures in Pulsed Detonation Combustor

The results discussed in this section are detailed in **Chapter 7 of the PhD Thesis**, which corresponds to the article cited in [26]. This paper, along with **Section 8**, addresses **SO4: Optimizing PDC Geometry for Enhanced Performance and Frequency**. Building on the findings from SO3, the next step towards achieving TRL 5 is to explore strategies for further enhancing the PDC's performance.

The aerodynamic system is based on two aerodynamic concepts, the Jet in Cross-Flow technique [27] (JICF) and Hartmann-Sprenger wave generators [28]. This study explores the first concept through the impact of hydrogen injection aperture size on the performance of the PDC, for both mixtures. The investigation focuses on how variations in fuel injector diameters influence key combustion parameters such as maximum, average cycle pressure, pressure gain, thrust, and specific impulse. By assessing these variables, the study aims to refine fuel-oxidizer mixing strategies and enhance overall combustor performance.

During the experimental campaign, three injector aperture sizes (see **Figure 16**) are evaluated (0.7 mm, 0.8 mm, and 0.9 mm), while varying the oxidizer pressure (4.5–9.0 bar) and fuel pressure (5.5–10.0 bar). This selection of parameters is driven by the insights obtained in SO3.

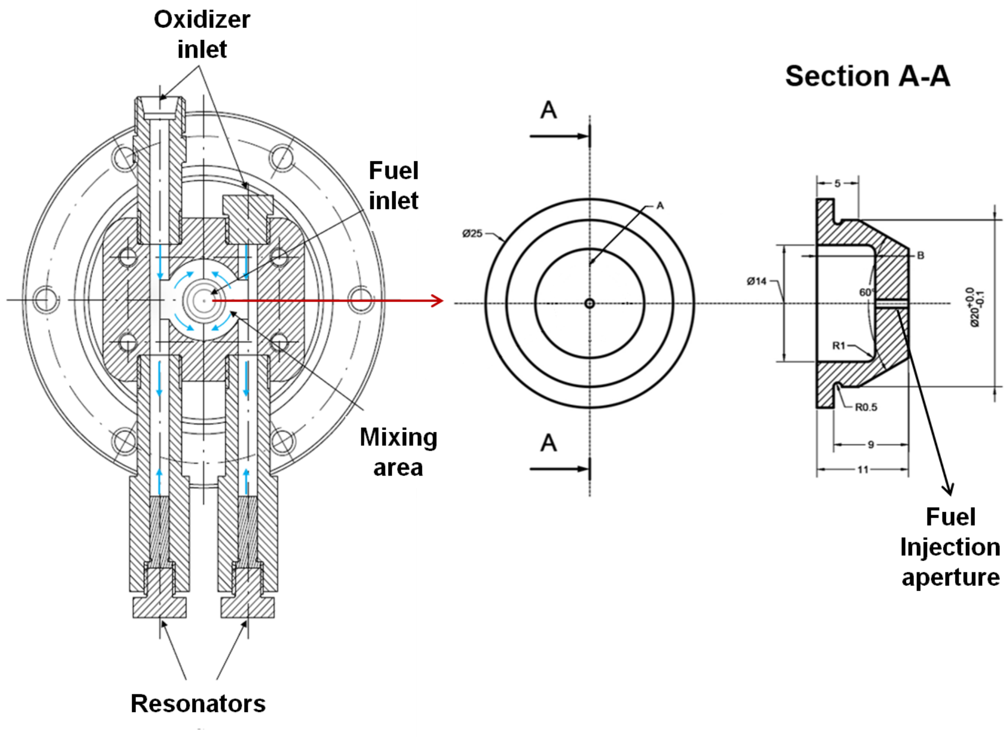


Figure 16: The aerodynamic system of the PDC: mixing diagram and fuel injection section.

Data acquisition include the same high-speed pressure sensors (as described in **Section 4**) positioned along the detonation channel and the same load cell system ((as described in **Section 5**) for thrust measurement. The ignition system is maintained at a constant frequency of 100 Hz, ensuring consistency across all tests.

The experiments revealed that the injector size has a significant impact on the maximum pressure generated during detonation. At lower oxidizer pressures, smaller apertures (0.7 mm) lead to higher maximum pressures because they promote better fuel entrainment into the vortex, thereby optimizing mixing. In contrast, larger injectors tend to produce excessively rich mixtures under these conditions, which results in deflagration rather than detonation. As the oxidizer pressure increases, however, the JICF effect becomes more pronounced, and larger injectors (0.9 mm) are required to supply sufficient fuel mass for effective mixing. At elevated pressures (7.5 and 9 bar), the intensified vortex necessitates a higher fuel mass flow to achieve successful detonation, and in these cases, 0.9 mm injectors deliver the highest maximum pressures. This trend underscores the increasing importance of effective fuel-oxidizer mixing as oxidizer pressure rises.

When focusing on the mean cycle pressure, it becomes evident that JICF has a major influence on the non-detonation phases, such as the filling and mixing stages. At lower pressures, the size of the injector is critical for ensuring efficient mixing; yet, as oxidizer pressure grows, the dominant influence of the JICF effect means that injector size becomes less significant. Moreover, pressure gain, defined as the ratio between peak and average pressures, increases with ER, especially when larger injectors are employed at higher oxidizer pressures. While 0,7 mm and 0.8 mm injectors show only a modest rise in pressure gain, they fall short of the performance achieved with 0.9 mm, indicating that smaller injectors cannot sustain optimal mixing as oxidizer pressure increases.

Time-averaged thrust measurements, however, do not always mirror the pressure trends. The presence of misfires, failed detonation cycles, introduces significant variability; even when peak pressures are high, frequent misfires reduce the overall time-averaged thrust. This is particularly apparent at higher oxidizer pressures, where proper mixing and detonation are more sensitive to injector performance. Since thrust is directly related to the momentum change produced during combustion, a higher incidence of misfires results in lower average thrust over time.

The relationship between total specific impulse and the JICF behavior is also clear. At lower pressures, the weaker vortex allows smaller injectors (0.7 mm) to achieve higher total specific impulse by effectively penetrating the flow and ensuring efficient mixing. However, as oxidizer pressure increases and the vortex intensifies, larger injector openings (0.9 mm) become necessary to maintain efficient fuel entrainment and combustion. Injectors that cannot meet the demands of a stronger vortex experience a decline in total specific impulse due to poor mixing and inefficient fuel utilization.

Similarly, the fuel-specific impulse results highlight the importance of selecting the correct injector size relative to the oxidizer pressure. As pressure increases, larger injectors facilitate more effective mixing, which is critical for converting the fuel's chemical energy into thrust. Conversely, smaller injectors struggle under high-pressure conditions, leading to a significant drop in fuel-specific impulse and overall performance.

A trade-off emerges when considering the overall impact of the JICF process on PDC performance. At lower oxidizer pressures, the smallest injector (0.7 mm) delivers favorable performance in terms of pressure gain and thrust due to its lower mass flow requirement—an advantage for space applications where minimizing propellant mass is crucial. In contrast, at higher oxidizer pressures, the largest injector (0.9 mm) outperforms the others in pressure gain and thrust, though this benefit comes at the cost of requiring higher mass flow rates, which can increase overall system mass and costs.

2.8 Frequency Enhancement of the Pulsed Detonation Combustor

The results of this section are presented in **Appendix E of the PhD Thesis**, which represents a submitted article to Proceedings of ASME Turbo Expo 2025 Turbomachinery

Technical Conference and Exposition, with ID GT2025 – 152698, titled "EXPERIMENTAL ANALYSIS OF OPERATING FREQUENCY ENHANCEMENT AND PRESSURE CHARACTERISTICS IN A PULSED DETONATION COMBUSTOR ", with the following authors: **Andrei Vlad Cojocea**, Mihnea Gall, Ionut, Porumbel, George Vrabie, Tudor Cuciuc, Daniel Eugeniu Crunțeanu. While this work is under review, the full paper cannot be included here, due to copyright issues. No further modifications are expected, and the findings reflect the completed scope of the thesis.

The study adds to **SO4: Optimizing PDC Geometry for Enhanced Performance and Frequency** and complements the work summarized in **Section 7**. The research investigates the enhancement of operating frequency and pressure characteristics of the PDC through aerodynamic tuning via geometric modifications. The primary objective is to determine how adjustments to Hartmann-Sprenger resonator - HSR (depicted in **Figure 17**) length and exhaust pipe length impact detonation cycle frequency, cycle pressure ratio, and pressure gain. By systematically varying these parameters, the study aims to optimize PDC performance for high-frequency propulsion applications.

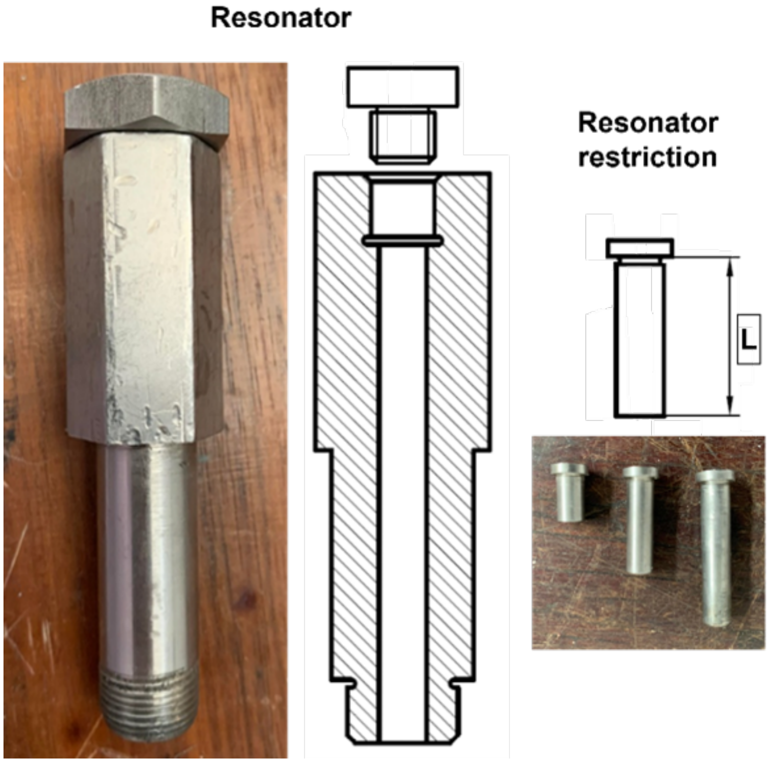
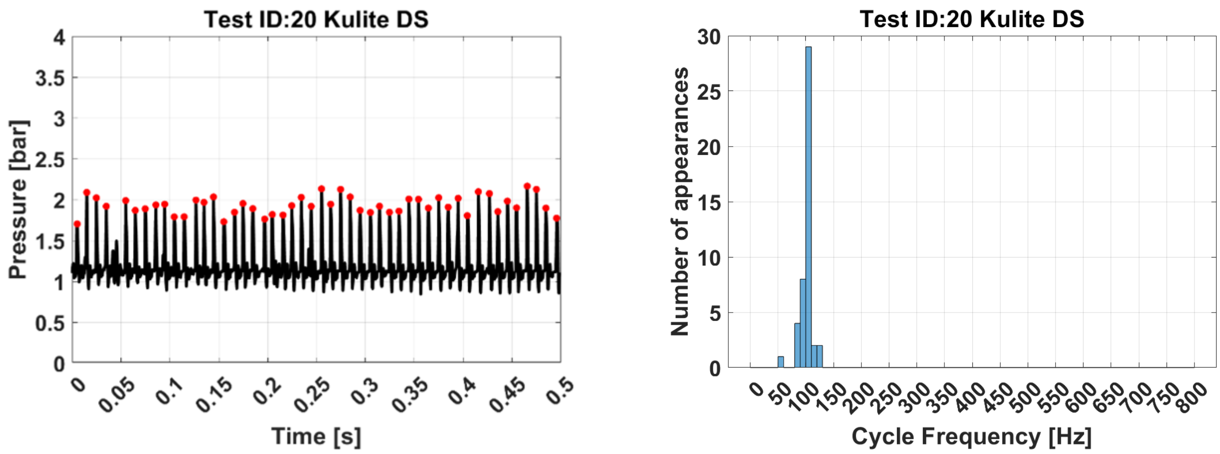


Figure 17: HSR and its restriction schematics.

The same high-speed Kulite ETM-HT-375 pressure sensors are used to record the detonation cycle characteristics, capturing maximum and average cycle pressures, operating frequency, and pressure gain performance. Throughout the experimental campaign, the spark plug frequency is kept constant at 100 Hz. In addition, to isolate the effects of geometry variations, the gasses' fed pressure is also kept constant (10 bara for the fuel and 4 bara for the oxidizer).

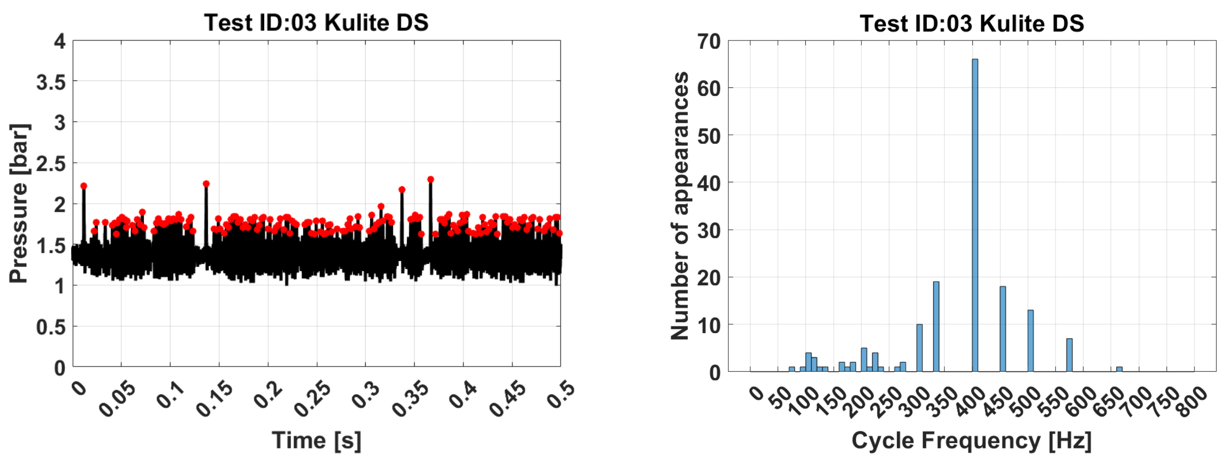
After filtering and accurately identifying the detonation pressure peaks, the pressure signals are subjected to statistical analysis (see **Figures 18, 19**). At low-frequency operations (**Figure 18(a)**), all features of the PDC cycle are clearly distinguishable. However, at high-frequency operations (**Figure 19(a)**), the refilling phase becomes nearly imperceptible, and the pressure signal transitions into a pattern resembling a shock wave train, which can be interpreted as the effect of an aerodynamic Shchelkin spiral.

The study demonstrates that aerodynamic tuning through resonator design and exhaust



(a) (b)

Figure 18: Low frequency pressure data example.



(a) (b)

Figure 19: High frequency pressure data example.

geometry modifications can significantly enhance the operating frequency and pressure performance of the PDC experimental model, making it a promising candidate for advanced aerospace propulsion and energy systems. In experiments with air as the oxidizer, the residence time of the detonation wave in the exhaust pipe proves critical: too short a pipe results in incomplete combustion, while an overly long pipe diminish the operating frequency. For oxygen, however, shorter exhaust lengths are sufficient to extract the maximum energy, due to the faster reaction rates.

The results reveal that maximum pressure, cycle pressure ratio, and pressure gain generally increase with exhaust pipe length at the downstream sensor for both oxidizers, although upstream pressure trends differ. Resonator length is also crucial: an optimal pressure gain is achieved at a normalized resonator length of 0.8, with contrasting effects on mean and maximum pressures between air and oxygen operations. Decreasing the resonator length generally raises the operating frequency, especially when combined with changes in exhaust pipe length for air. For oxygen, both parameters must be adjusted to realize a significant frequency increase. Although the target of 1000 Hz was not reached, most configurations resulted in an overall increase in frequency. For air operations the maximum achieved frequency is 300 Hz, while for oxygen is 400 Hz.

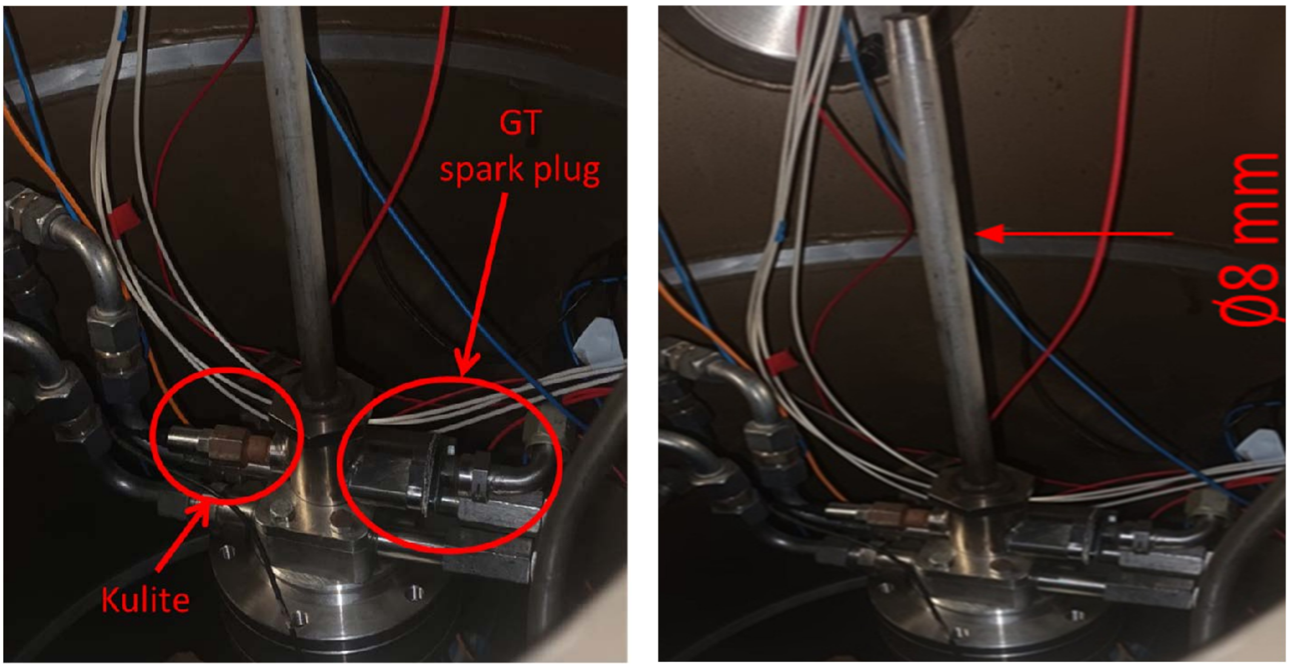
The findings also highlight that as the operating frequency rises, the cycle's refilling time shortens, transitioning the detonation process toward a more continuous mode but at the expense of reduced maximum pressure, which adversely affects both cycle pressure ratio and pressure gain. Optimizing these parameters simultaneously remains a challenge.

2.9 Experimental Study on Ignition and Pressure-Gain Achievement in Low-Vacuum Conditions for a Pulsed Detonation Combustor

The results of this section are presented in **Chapter 9 of the PhD Thesis**, which represents the article referenced in [29]. These findings build on all previous milestones and culminate in meeting **SO5: Demonstrating Pressure-Gain Combustion Under Low-Vacuum Conditions**, thereby achieving **TRL 5**.

This study investigates the feasibility of operating the PDC under near-vacuum conditions, focusing on ignition stability, pressure gain trends, and shock wave propagation. Given that the ultimate goal of this PhD Thesis is develop a PDC for space propulsion, it is essential to determine how it performs in reduced-pressure environments.

Drawing on the insights from **Sections 4–6**, which define the PDC operating map, and **Sections 8 and 9**, which identify strategies to enhance pressure-gain combustion, the necessary modifications are implemented to achieve pressure gain under low-vacuum conditions. These modifications include implementing an exhaust pipe with a reduced diameter and the shortest length tested, as well as employing an alternative spark plug that delivers higher energy output under vacuum conditions. The altered PDC model is presented in **Figure 20**.



(a) (b)

Figure 20: PDC prototype inside the vacuum chamber [29].

The experimental campaign is conducted in a vacuum chamber, where the ambient pressure is reduced to 15 mbar to simulate near-space conditions. The PDC is fueled with a hydrogen-oxygen mixture, with fuel and oxidizer supplied at pressures of 7.5 bar and 5.5 bar, respectively, corresponding to an ER of 0.048. Two high-speed pressure sensors (Kulite ETM-HT-375), positioned inside both the PDC ignition chamber and the vacuum chamber, allow real-time monitoring of pressure fluctuations.

The PDC successfully completes six pressure-gain combustion cycles (**Figure 21**), as recorded via both pressure sensors and Schlieren imaging. These pressure-gain spikes indicate the presence of six distinct detonation waves. Combustion was initiated at a vacuum level of approximately 103 mbar (**Figure 22**), and the pressure-gain process (**Figure 23**) persisted for about 0.5 s before an explosion occurred (**Figure 24**). This explosion was caused by the accumulation of unburned fuel inside the vacuum chamber, a result of the spark plug's lower ignition frequency, which operates below the engine's design specification. As a result, more gas products were expelled without being ignited, leading to the buildup of unburned fuel. Schlieren imaging confirms the occurrence of pressure-gain cycles at a frequency of 11.97 Hz. While the leading pressure wave is not directly visible due to the low pressure, its effects on the flow structure can be clearly identified.

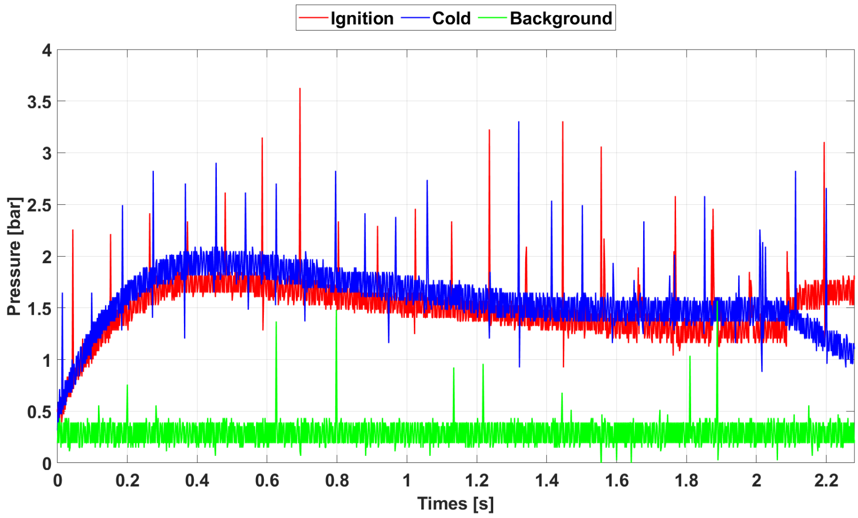


Figure 21: Pressure signals during the full PDC vacuum operation test: red line - combustion, blue line - cold flow, green line - pressure inside the vacuum chamber [29].

Several technical challenges are encountered during the experiments. Maintaining signal integrity is difficult due to elevated noise levels, partially attributed to the wiring connections through the vacuum chamber walls. Additionally, the limited capacity of the vacuum chamber restricts the duration of low-pressure operation, impacting on the overall data collection and the ability to gather more robust results.

To capture shock wave dynamics and combustion flow structures, the Schlieren visualization technique is employed as well. A Phantom VEO 710L high-speed camera, operating at 77,000 fps, is positioned downstream of the detonation channel to record flow-field evolution. The results can be seen in **Figure 25**, where A represents the Mach diamonds, B is the combustion front, C is the shock wave. Unlike the detonation cycles observed under atmospheric conditions, the reverse flow regime is absent under vacuum.

The research presented here significantly contributes to bridging the gap between ground-based experiments and the eventual development of a PDC for space applications. Future work should continue refining the design of the PDC to operate in extreme environments, focusing on optimizing fuel efficiency, reliability, and scalability. Ultimately, the goal is to advance the technology toward a fully operational space propulsion system capable of delivering performance benefits in space. By addressing these challenges, the research will bring PDC technology closer to achieving a functional space-based propulsion system capable of utilizing pressure-gain combustion for more efficient spacecraft propulsion.

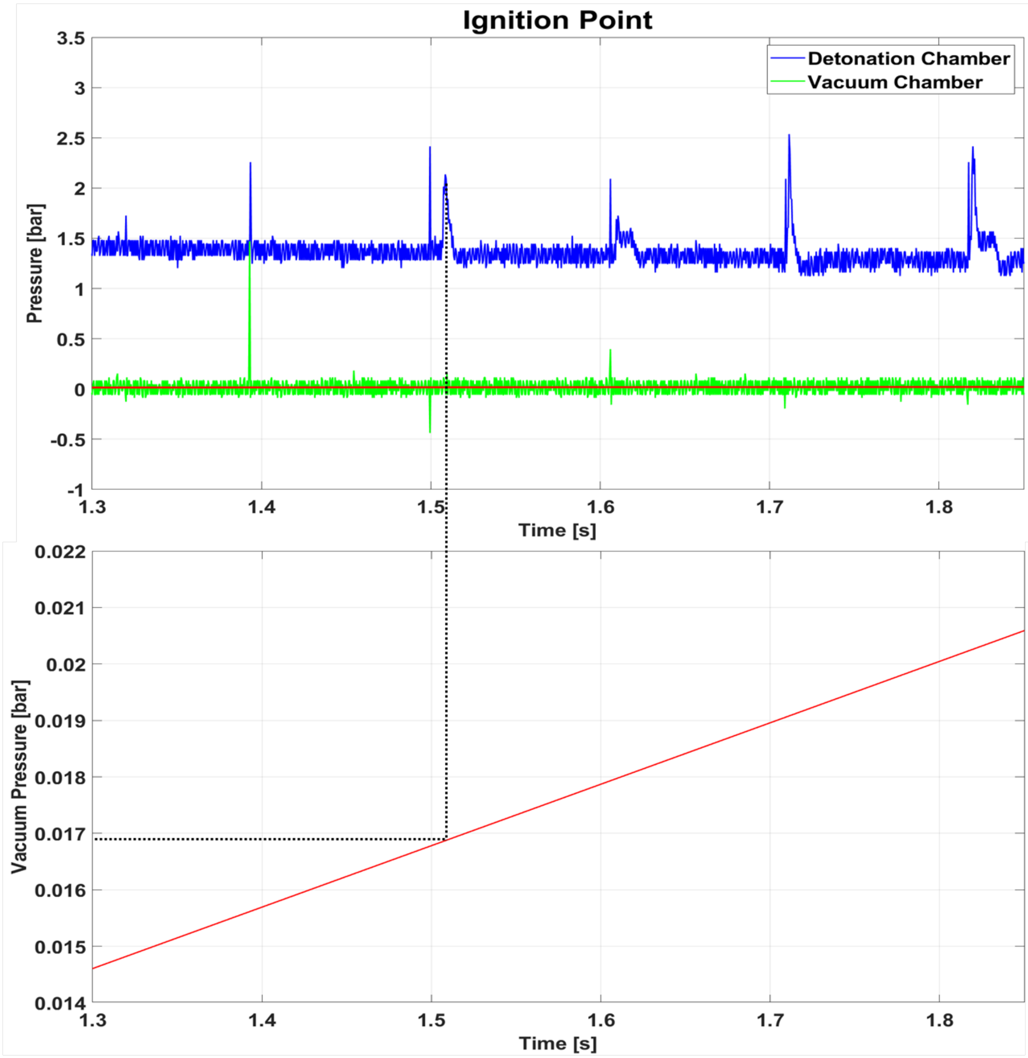


Figure 22: Pressure signals during PDC ignition [29].

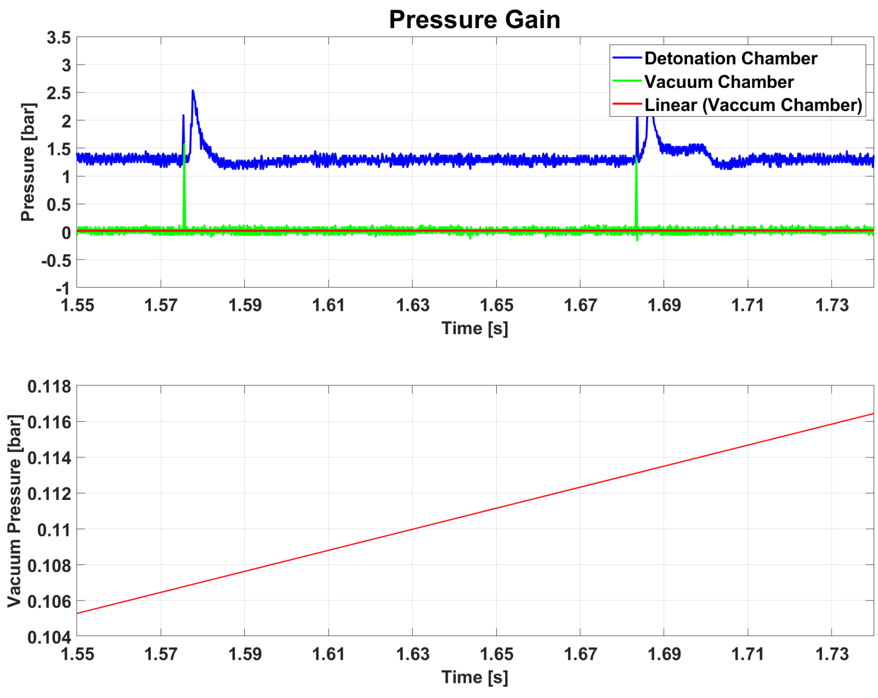


Figure 23: Pressure signals during PDC operation [29].

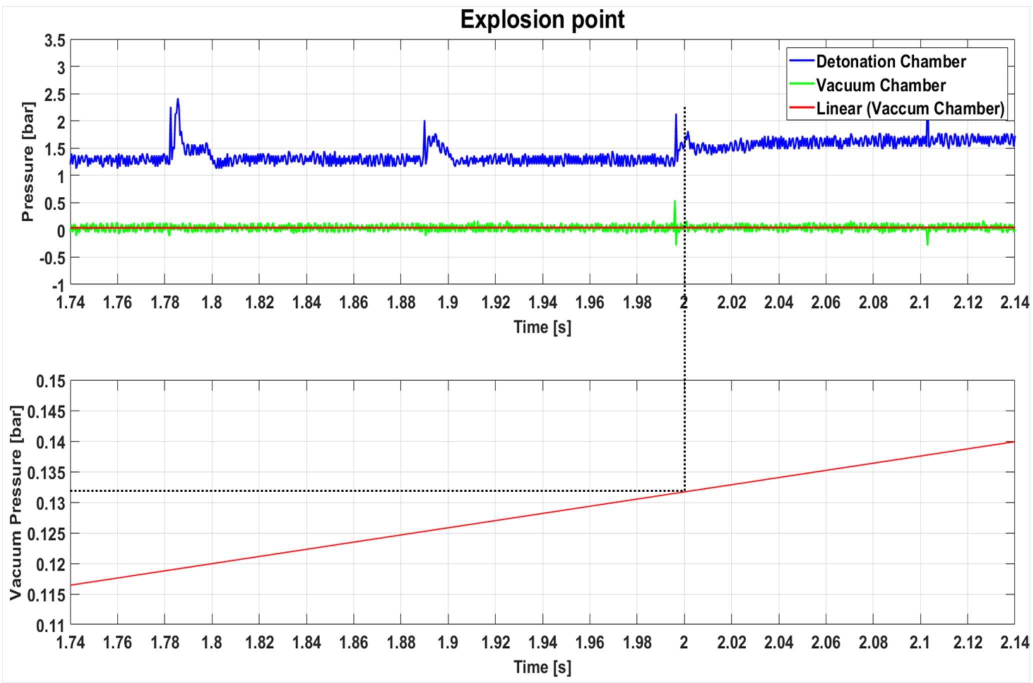


Figure 24: Pressure signals during the explosion [29].

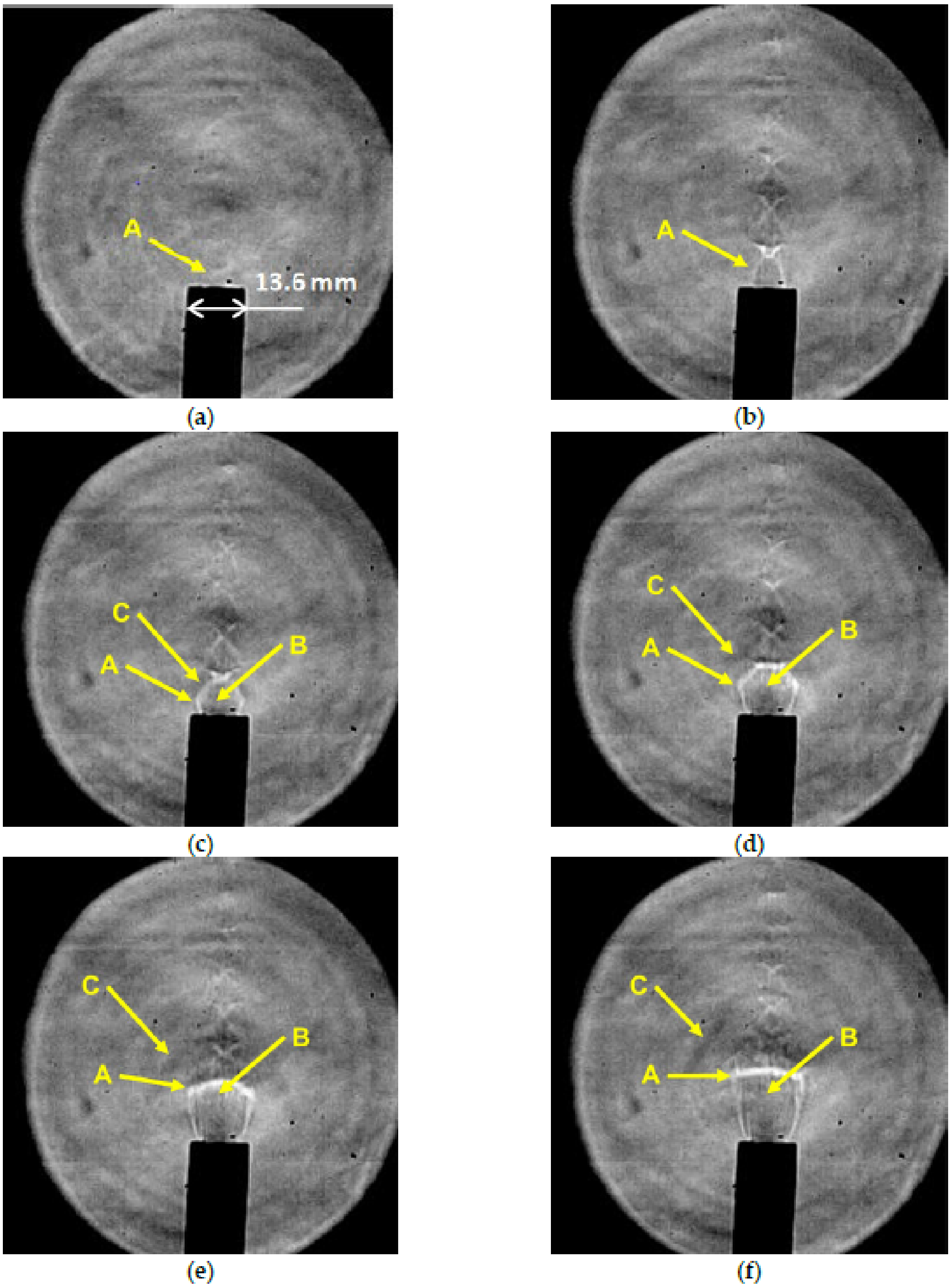


Figure 25: Schlieren images of the flow exiting the PDC around the cycle ignition moment under vacuum conditions; (a) $-1.953\mu s$; (b) $-12.99\mu s$; (c) 0.00 μs; (d) 12.99 μs; (e) 25.58 μs; (f) 38.97 μs [29].

Conclusions and Personal Contributions

3.1 General Remarks

The Pulsed Detonation Combustor is rigorously investigated through multiple experimental campaigns aimed at achieving operational capability with two distinct oxidizers, thereby expanding its potential applications and **advancing its Technology Readiness Level to 5**. To define the operational envelope for each oxidizer, two extensive full-factorial experimental campaigns are conducted under atmospheric conditions. These campaigns systematically examined the influence of four critical parameters: oxidizer and fuel feed pressures, spark plug ignition frequency, and exhaust pipe length, each varied across four levels. The results of these experiments are comprehensively documented and analyzed.

For the atmospheric campaigns, the thruster's performance is evaluated using ten key response metrics: oxidizer mass flow rate, fuel flow rate, thrust, maximum and mean cycle pressures, maximum and mean temperatures, shock and combustion wave velocities, and thruster operating frequency. This exhaustive dataset, derived from a meticulously designed experimental test matrix, served as a robust foundation for subsequent optimization efforts.

Building on these results, the combustor geometry is further optimized to enhance pressure gain and operating frequency. The optimization process yielded demonstrable improvements in performance, as evidenced by detailed pressure and thrust data.

The final phase of experimentation involved testing under vacuum chamber conditions to simulate space-like environments. This critical campaign focuses on a single test case with fixed parameters, including oxidizer and fuel pressures, exhaust pipe length, and spark plug frequency. The findings from this campaign represent a significant step toward evaluating the PDC's feasibility for applications beyond atmospheric operations.

This systematic investigation underscores the complex interplay between operational parameters and combustor performance, highlighting the importance of both atmospheric and vacuum testing in advancing PDC technology. Further details on the experimental setup, data acquisition methods, and results are provided in **Appendices C - E of the PhD Thesis**, where comprehensive tables and figures offer a deeper insight into the findings.

3.2 Maximum Values

Over the entire set of 256 test cases, the recorded maximum values for thrust, pressure, temperature, shock and combustion wave velocities for each of the first two experimental campaigns, under atmospheric conditions, are presented in **Table 5**.

3.3 Thruster Operational Envelope

The operational envelope for H_2/air under atmospheric exhaust conditions is primarily governed by the fuel and oxidizer pressures, although the exhaust pipe length and spark plug frequency also influence thruster performance. The air line pressure plays a crucial role in determining the velocity of air jets entering the premixing chamber, thereby affecting both the intensity of the central vortex, which acts as an aerodynamic valve for hydrogen admission, and the quality of fuel/air mixing. At high oxidizer pressures above 6.5 bar, sustainable operating

Table 5: Centralized recorded maximum values.

Response	Hydrogen / Air		Hydrogen / Oxygen	
	Maximum value	**Test Case**	**Maximum value**	**Test Case**
Thrust [N]	28.9	2032	27.1	2332
Pressure [bar]	5.18	2032	3.22	1332
Temperature [K]	1247	3213	1266	2302
Shock wave velocity [m/s]	1429	0122	1429	0331
Combustion wave velocity [m/s]	633	1323	923	0230

regimes are not observed, as disrupted mixing dynamics hindered proper detonation. In the intermediate oxidizer pressure range (5–6.5 bar), the thruster's operation depended on the fuel line pressure, with sustainable detonation cycles achieved for fuel pressures above 7.5 bar. At lower oxidizer pressures below 5 bar, the ER became the decisive factor. For instance, Test Case 2103, with an ER of 0.318, fails to achieve detonation, whereas cases with higher ERs succeed irrespective of fuel line pressure. The lower ER limit for PDC operation increases with the air line pressure and decreases with the fuel line pressure.

For oxygen under atmospheric exhaust conditions, the same parameters influence the sustainability of the detonation cycle, but the exhaust pipe length exerts a more pronounced effect. At high oxidizer pressures above 7.3 bar, sustained detonation requires an ER above 0.069; below this threshold, detonation could not be achieved. For ERs exceeding 0.069, fuel pressures above 10 bar consistently support proper operation, and a short exhaust pipe (200 mm) facilitated successful detonation even at lower fuel pressures. In the upper-intermediate range (6.4–7.3 bar), the fuel line pressure becomes critical, with some uncertainty for ERs between 0.069 and 0.072, where a few test cases fail to sustain detonation. In the middle range (5.4–6.4 bar), the limiting factor is the ER, with regimes below 0.06 failing to ignite and those above 0.2 transitioning into continuous detonation. Uncertainty persists near the ER boundaries, particularly between 0.06 and 0.07 on the lean side and 0.17 and 0.2 on the rich side.

In the lower-intermediate range (4.7–5.4 bar), all test cases achieve sustainable pulsed detonation. However, in the low oxidizer pressure range below 4.8 bar, most cases transition into continuous deflagration due to insufficient vortex strength to control the aerodynamic valve. Despite this, three borderline cases manage to sustain detonation, highlighting the intricate interplay between oxidizer and fuel pressures, equivalence ratio, and design parameters. These findings underscore the complexity of determining the operational envelope of the PDC and the importance of finely tuned design and operating conditions.

3.4 Statistical Analysis

An ANOVA statistical analysis has been carried out for both H_2/air and H_2/O_2 campaigns, under atmospheric exhaust conditions (results presented in **Chapters 5, 6** and in **Appendix C**). The findings are centralized in **Table 7** for air, and **Table 8** for Oxygen. The oxidizer and fuel mass flow rate have not been subjected to the statistical analysis for obvious reasons. The definitions of the factors referred to in these tables are provided in **Table 6**:

The analysis of the experimental campaigns conducted under atmospheric exhaust conditions reveal the influence of various operational parameters on the ten measured response metrics. For both air and oxygen oxidizers, the oxidizer mass flow rate increases with rising oxidizer pressure and exhaust pipe length, with the latter effect being more pronounced at

Table 6: Definitions of factors and responses used in the ANOVA Analysis.

F1	Exhaust pipe length
F2	Spark plug frequency
F3	Fuel line set pressure
F4	Oxidizer line set pressure
F1xF2	Correlation of Exhaust pipe length and Spark plug frequency
F1xF3	Correlation of Exhaust pipe length and Fuel line set pressure
F1xF4	Correlation of Exhaust pipe length and Oxidizer line set pressure
F2xF3	Correlation of Spark plug frequency and Fuel line set pressure
F2xF4	Correlation of Spark plug frequency and Oxidizer line set pressure
F3xF4	Correlation of Fuel line set pressure and Oxidizer line set pressure
F1xF2xF3	Correlation of Exhaust pipe length, Spark plug frequency, and Fuel line set pressure
F1xF2xF4	Correlation of Exhaust pipe length, Spark plug frequency, and Oxidizer line set pressure
F1xF3xF4	Correlation of Exhaust pipe length, Fuel line set pressure, and Oxidizer line set pressure
F2xF3xF4	Correlation of Spark plug frequency, Fuel line set pressure, and Oxidizer line set pressure
Y1	Thrust (mean cycle value)
Y2	Maximum cycle pressure
Y3	Mean cycle pressure
Y4	Maximum cycle temperature
Y5	Mean cycle temperature
Y6	Shock wave velocity
Y7	Combustion wave velocity
Y8	Operating frequency

lower oxidizer pressures. Conversely, oxidizer mass flow rate decreases as the ER increases, while the fuel mass flow rate rises accordingly. Thrust measurements, though influenced by variations in fuel line rigidity during testing, generally exhibit a positive correlation with ER in the air/hydrogen campaign. However, this trend is less evident in the oxygen/hydrogen tests, likely due to the narrower ER range explored. For both campaigns, higher oxidizer pressures result in increased thrust due to elevated flow rates.

Exhaust pipe length and spark plug frequency also significantly impact thrust performance. In the air campaign, maximum thrust values are observed with longer pipes (400 mm and 500 mm) at high oxidizer pressures, while shorter pipes (200 mm and 300 mm) combined with higher spark plug frequencies (233 Hz and 350 Hz) perform better at lower oxidizer pressures. For oxygen, the influence is reversed. At low oxidizer pressures, short pipes pair with a spark plug frequency of 100 Hz producing higher thrust, whereas longer pipes deliver better results at 350 Hz. The effects of these factors diminish at higher oxidizer pressures for both oxidizers.

At high oxidizer pressures (above 6 bar), the maximum cycle pressure increases with both ER and oxidizer pressure for both campaigns, confirming its direct relationship with thrust. At lower oxidizer pressures, however, the increase in maximum cycle pressure with high ERs (above 0.6 for air and 0.15 for oxygen) is less significant, with some cases even showing slight decreases. This reduction is particularly evident in air tests at a spark plug frequency of 233 Hz and in oxygen tests across all off-design frequencies (150 Hz, 233 Hz, and 350 Hz), especially with shorter pipes. Mean cycle pressure exhibit similar trends, with a notable dip at 6 bar oxidizer pressure in the air campaign. Deviations from the expected trend of increasing mean pressure with ER are observed for long pipes (400 mm and 500 mm) in the air campaign and 300 mm pipes in the oxygen campaign. Peak mean pressures occur at intermediate ERs, between 0.5 - 0.7 for air and around 0.5 for oxygen, most prominently in air tests at a spark plug frequency of 150 Hz.

Table 7: Centralized Anova Results for H_2/air campaign.

Response	F1	F2	F3	F4	F1xF2	F1xF3	F1xF4
Y1	N	Y	N	Y	N	N	N
Y2	N	Y	N	Y	N	N	N
Y3	N	Y	N	Y	Y	N	N
Y4	Y	Y	Y	Y	Y	N	N
Y5	Y	Y	Y	Y	Y	N	N
Y6	N	Y	Y	Y	N	N	N
Y7	N	Y	Y	Y	N	N	N
Y8	N	Y	N	N	N	N	N
Response	F2xF3	F2xF4	F3xF4	F1xF2xF3	F1xF2xF4	F1xF3xF4	F2xF3xF4
Y1	N	Y	N	N	N	N	N
Y2	N	N	N	N	N	N	Y
Y3	Y	N	N	N	Y	Y	N
Y4	Y	Y	Y	Y	Y	Y	Y
Y5	Y	Y	Y	Y	Y	Y	Y
Y6	N	N	N	Y	N	N	N
Y7	N	N	N	Y	N	N	N
Y8	N	N	N	N	N	N	N

Maximum cycle temperature increase with both ER and oxidizer pressure for short pipes (200 mm) in the air/hydrogen campaign, but these effects diminish as pipe length increases. For long pipes (400 mm and 500 mm), maximum temperature decreases with oxidizer pressure, with a peak ER corresponding to maximum temperature identified. For oxygen, maximum temperature generally rises with ER, but the trend is minimal for the shortest (200 mm) and longest (500 mm) pipes, with greater variability for intermediate lengths. Pipe length significantly influence temperature behavior. For air, increasing pipe length reduces the ER corresponding to maximum temperature, while for oxygen, maximum temperature increases directly with pipe length. Higher spark plug frequencies slightly shift the ER for maximum temperature upward in air tests, but no consistent effect is observed for oxygen.

Mean temperature profiles are also affected by pipe length due to heat absorption by the metal walls. For short pipes (200 mm), mean temperature trends align with maximum temperature trends for both ER and oxidizer pressure in air tests but are negligible for oxygen. For longer pipes, the behavior becomes more complex, as detailed in **Appendix C**.

Detonation wave velocity, calculated from time delays between pressure sensors and photodiodes placed along the exhaust pipe, indicate decoupling between the shock wave and the combustion wave. For air, this decoupling is less severe at mid-range pipe lengths (400 mm) and ERs between 0.6 - 0.7. For oxygen, stronger coupling is observed with shorter pipes (200 mm and 300 mm), with the best results at 300 mm and ERs between 0.1 - 0.15. Increasing oxidizer pressure improves coupling by decreasing shock wave velocity and increasing combustion wave velocity. Spark plug frequency has minimal effect on decoupling. Detonation velocities in regions of strong coupling are approximately 600 m/s for both campaigns.

The thruster's operating frequency is primarily driven by the spark plug frequency but often falls short due to misfires. The design frequency of 100 Hz produces the fewest misfires for both oxidizers. Oxygen tests demonstrate good performance at higher frequencies (150 Hz and 233 Hz), whereas air tests show increased misfires at 233 Hz. For off-design frequencies, optimal ERs are around 0.5 for air and 0.15 for oxygen. Longer exhaust pipes helped reduce misfires and increase the operating frequency for both oxidizers.

Table 8: Centralized Anova Results for H_2/O_2 campaign.

Response	F1	F2	F3	F4	F1xF2	F1xF3	F1xF4
Y1	Y	Y	Y	N	N	Y	Y
Y2	Y	N	Y	Y	Y	N	Y
Y3	Y	N	Y	N	N	Y	N
Y4	Y	Y	N	Y	Y	N	N
Y5	Y	Y	N	Y	Y	N	N
Y6	N	N	N	N	Y	Y	N
Y7	N	N	N	N	Y	Y	N
Y8	N	N	N	N	N	N	N
Response	F2xF3	F2xF4	F3xF4	F1xF2xF3	F1xF2xF4	F1xF3xF4	F2xF3xF4
Y1	N	N	N	N	N	N	N
Y2	N	N	N	N	N	N	N
Y3	N	N	N	N	Y	Y	Y
Y4	N	Y	N	N	N	N	N
Y5	N	Y	N	N	N	N	N
Y6	Y	Y	N	N	N	N	N
Y7	Y	Y	N	N	N	N	N
Y8	N	N	N	N	N	N	N

3.5 Schlieren Analysis

Both campaigns carried out under atmospheric conditions allow the identification of four stages during a PDC cycle (**Chapters 2, 3 and 5 of the thesis**):

1. Detonation, when the pressure rises fast, reaches a high peak, then drops equally fast.
2. Entrainment of surrounding air and previously exhausted gas due to flow reversal.
3. Exhaust of the gas entrained in the device during the previous phase.
4. Exhaust of the gas trapped inside the device.

Summarizing the Schlieren data, **Table 9** presents the 30-cycle average of the main parameters characterizing the detonation cycle for both air and Oxygen as oxidizer for Test Case 0032.

The maximum Mach number in the flow is higher for Oxygen, and the time to reach the maximum flow speed also increases. The start of the reversed flow occurs later for Hydrogen - Oxygen than for Hydrogen - air combustion, and its duration appears to be shorter. The reverse flow tends to vanish for some cycles in Oxygen. The operating frequency follows the spark plug frequency and drops apparently for Oxygen as an effect of the significant number of misfires.

Table 9: Mean flow characteristics values estimated from Schlieren visualizations.

Parameter	Hydrogen / Air	Hydrogen / Oxygen
Mach angle	66	53
Mach number	1.1	1.3
Shock wave velocity [m/s]	699	668
Mean flow velocity [m/s]	149	217
Time to reach maximum velocity [μs]	149	217
Time to flow reversal [μs]	1598	2311
Duration of flow reversal [μs]	1705	1331
Cycle frequency [Hz]	70.3	100.4

3.6 Enhanced Performances

The two follow-up experimental campaigns, detailed in **Chapter 7** and in **Appendix E**, are conducted to enhance the PDC's output. The first experimental campaign focuses on improving performance metrics, including thrust, pressure, total specific impulse, and fuel-specific impulse, under atmospheric conditions, with the results summarized in **Table 10**. The second campaign aims to optimize the operating frequency, with findings presented in **Table 11**.

The first experimental campaign (**Chapter 7**) complements the ANOVA study by highlighting the pivotal role of fuel injector size in optimizing PDC performance. Consistent with the ANOVA findings, the fuel injection opening size, which governs the fuel mass flow rate, emerges as a critical factor influencing detonation behavior, maximum pressure, and thrust efficiency. Its impact varied with different oxidizer pressures, demonstrates a clear dependency on the oxidizer mass flow rate. The results align with the observed trade-offs in injector performance: at low oxidizer pressures, smaller injectors excel in generating favorable performance metrics. These injectors optimize fuel entrainment and mixing while requiring lower mass flow rates, making them suitable for applications such as space propulsion, where minimizing fuel and oxidizer storage is essential.

Table 10: Performance output for baseline geometry and optimized geometry.

Parameter	Baseline	Enhanced	Total increase [%]
Fuel pressure [bar]	10	10	-
Oxidizer pressure [bar]	9	9	-
ER [-]	0.09508	0.10126	106.499
Thrust [N]	4.4447	16.067	361.486
Total specific impulse [s]	21.615	71.629	331.385
Fuel specific impulse [s]	1840.324	5730.731	311.397
Maximum cycle pressure [bar]	2.239	3.633	162.259
Mean cycle pressure [bar]	1.239	1.714	94.7538
Pressure Gain [%]	180.660	309.412	171.267

Conversely, at higher oxidizer pressures, the study corroborates the superior performance of larger injectors. These injectors maintain efficient mixing and detonation under intensified jet-in-cross-flow (JICF) conditions, resulting in higher maximum pressure and thrust. However, this performance gain comes at the cost of significantly increased mass flow rates, highlighting the inherent trade-off between achieving elevated performance metrics and the practical constraints of storage and operational efficiency.

These findings validate the insights derived from the ANOVA analysis, emphasizing the intricate interplay between injector geometry and operating conditions. They underscore the necessity for carefully tailored injector designs that balance performance and practicality to meet the specific requirements of different applications.

The second experimental campaign (**Appendix E**) builds upon the ANOVA analysis by further exploring the influence of exhaust pipe length and resonator geometry on PDC performance, particularly in terms of operating pressure and frequency. While the ANOVA study indicates that exhaust pipe length has some influence on performance, its effect is limited compared to other factors. In contrast, the operating frequency of the spark plug shows very little impact in the ANOVA results, emphasizing its minor role in influencing performance metrics.

The variation in resonator length introduced in the second campaign adds significant value to the findings, proving its substantial influence on operating frequency and pressure gain. The results demonstrate that normalized resonator lengths provide an optimal balance between pressure gain and frequency for both oxidants. This highlights the complementary relationship between exhaust pipe and resonator geometry in enhancing detonation dynamics and energy extraction, aligning with and expanding upon the ANOVA study's observations.

Table 11: Operating frequency for baseline geometry and optimized geometry.

	Operating frequency [Hz]
Baseline	
Hydrogen / Air	100
Hydrogen / Oxygen	100
Optimized	
Hydrogen / Air	300
Hydrogen / Oxygen	400

3.7 Vacuum Operations

Several design modifications are necessary to achieve sustained pressure gain combustion cycles in the PDC. These include replacing the spark plug with a more powerful one and reducing the exhaust pipe diameter from 15 mm to 8 mm (details are provided in **Chapter 8**. With these adjustments, several cycles of pressure gain combustion under rarefied atmospheric exhaust conditions are successfully recorded using both pressure sensors and Schlieren visualizations. The combustible mixture ignits at a vacuum level of approximately 103 mbar, sustaining the pulsed pressure gain combustion process for about 0.5 seconds before it is disrupted by an explosion caused by the accumulation of unburned mixture in the exhaust pipe.

Schlieren visualizations of the flow outside the exhaust pipe confirm the presence of pressure gain cycles at a frequency of 11.97 Hz. While a leading pressure wave is no longer directly visible, it can be identified indirectly through its effects on flow structures. Comparing to detonation cycles observed during operation under atmospheric pressure, the reverse flow regime is absent, as expected under vacuum conditions.

3.8 Personal Contributions

In pursuit of the **general objective of the thesis, advancing the PDC from TRL 2 to TRL 5**, I systematically addressed each of the thesis specific objectives, making significant contributions to experimental design, data analysis, and facility upgrades. These efforts not only resolved key technical challenges but also provided critical insights into the operation and optimization of PDC systems.

At the outset, I focused on validating whether the baseline PDC geometry could achieve detonation with an H_2/air mixture at the design frequency of 100 Hz (**SO1, TRL 3**). Schlieren flow visualizations revealed the absence of a sustained detonation regime, prompting a detailed analysis of the combustor's performance. By identifying the need to **reduce oxidizer pressure port sizes** to enhance flow velocity and vortex strength, critical for hydrogen entrainment and blocking hydrogen admission, **I implemented** a key modification that enabled successful detonation. This achievement is facilitated by developing basic image processing software [30], for which I contributed significantly. The software identifies critical supersonic flow features, aiding in the diagnostic process. This milestone validated the baseline geometry's viability and is presented in **Chapter 2 of the PhD Thesis**.

Building on this success, transitioning to H_2/O_2 mixtures exposed new challenges due to Oxygen's faster reaction kinetics (**SO2, TRL 3**). To address this, **I designed and tested several fuel injection plates**, iterating on parameters such as injector port size and alignment to improve vortex penetration and mixing. After multiple configurations, **I identified a design that supports repeatable detonation cycles with oxygen**. This demonstrates the adaptability of the PDC to different oxidizers, confirming its potential for diverse applications, from atmospheric flight to space missions where oxygen storage is feasible. These findings are detailed in **Chapter 3**.

To define the operational map and better understand the PDC's performance, **I organized and executed a comprehensive full-factorial experimental campaign under atmospheric exhaust conditions (SO3, TRL 4)**. **I developed a 4-parameter, 4-level test matrix** (spanning 256 configurations per oxidizer, totaling 512 tests with H_2/air and H_2/O_2), **participating in data acquisition throughout the campaign**. To manage the extensive dataset, **I created automated subroutines for data processing and visualization**. These tools enable efficient extraction of key metrics, such as equivalence ratio, thrust, cycle pressures, wave velocities, and operating frequency. **I conducted a detailed ANOVA study** to assess the impact of critical parameters (fuel and oxidizer pressures, spark plug frequency, and exhaust pipe length) on PDC performance. This analysis not only quantifies parameter influences but also lays the groundwork for future modeling efforts, providing essential insights into flow and combustion dynamics. The outcomes of this work are detailed in **Chapters 4 – 6** and **Appendix C**.

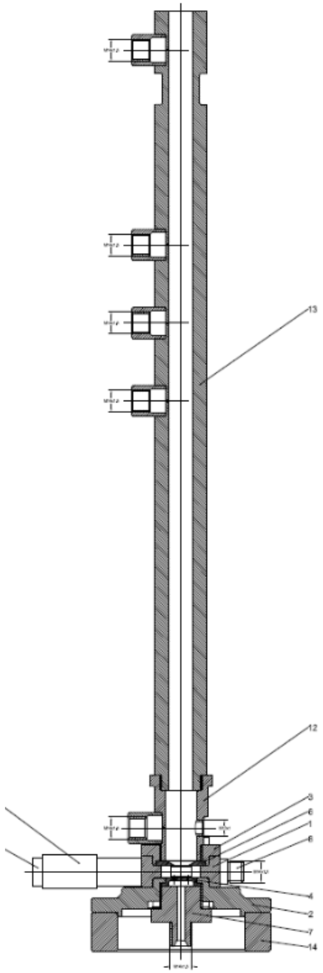
Using the insights gained, **I proposed targeted modifications to the fuel injection plate to optimize performance for both oxidizers (SO4, TRL 4)**. Additionally, I conducted a detailed investigation into the influence of geometric factors, such as resonator and exhaust pipe lengths, on operating frequency and combustion repeatability. **This study led to the observation of a groundbreaking phenomenon: a resonance effect that can be interpreted as an aerodynamic Schelkin spiral**. This novel discovery not only sheds light on previously uncharacterized flow dynamics within PDCs but also underscores the critical role of resonance in enhancing detonation repeatability and efficiency. These refinements led to significant performance improvements, as documented in **Chapter 7** and **Appendix E**. The interplay between these geometric optimizations, experimental findings, and the identification of this unique phenomenon highlights the importance of tailoring PDC designs to meet specific operational demands while advancing the scientific understanding of supersonic internal flow mechanisms.

Finally, **I addressed the critical transition to low-vacuum conditions to assess the PDC's viability for space applications (SO5, TRL 5)**. Initial attempts to achieve ignition in rarefied environments were hampered by insufficient spark energy and suboptimal flow dynamics. By replacing the spark plug with a more powerful unit and reducing the exhaust pipe diameter from 15 mm to 8 mm, **I successfully recorded multiple cycles of pressure gain combustion at a vacuum level of approximately 103 mbar**. Although unburned mixture accumulation eventually led to an explosion, this experiment marked a significant breakthrough in demonstrating pressure gain combustion in low-vacuum conditions. These findings, detailed in **Chapter 8**, represent a critical step forward, as existing literature lacks evidence of such achievements in detonation combustors. **This milestone highlights the PDC's potential for near-term aerospace missions and its readiness for TRL 5**.

Additionally, **I contributed to upgrading the detonation testing facility to expand its research capabilities**. Specifically, **I assisted in designing, identifying necessary components and building a methane fuel line**, enabling experiments with hydrogen-methane mixtures, which are safer and more practical for cryogenic storage in space applications compared to hydrogen alone. This facility enhancement, discussed in **Appendix B**, aligns with the thesis objective of advancing the TRL of PDC technology for space propulsion.

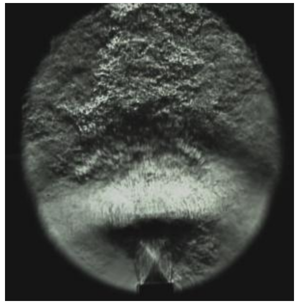
Collectively, these contributions embody the core mission of this thesis: to develop and optimize a novel propulsion system with supersonic internal flow, advancing the PDC concept from TRL 2 to TRL 5. Through iterative design improvements, extensive experimental campaigns, and facility upgrades, **I have demonstrated the viability, versatility, and scalability of PDC systems**. The extensive dataset and validated optimizations provide a strong foundation for future research, ensuring that the PDC technology continues to evolve toward higher readiness levels and eventual deployment in real-world applications. My work contributes significantly to advancing the state-of-the-art in pressure-gain combustion, a promising field with transformative implications for aerospace and energy systems. An illustrative overview of this PhD Thesis is presented in below.

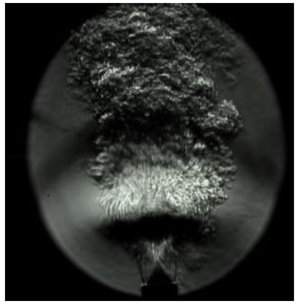
Baseline PDC

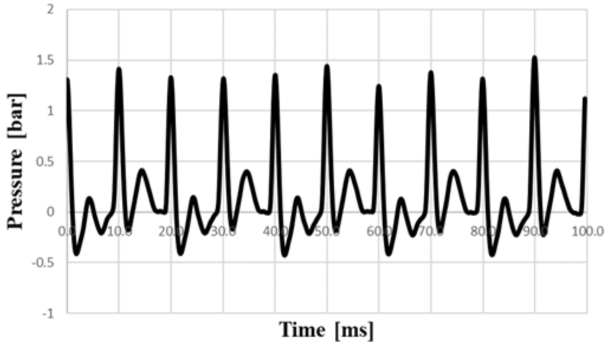


SO1 & SO2

H_2/air H_2/O_2







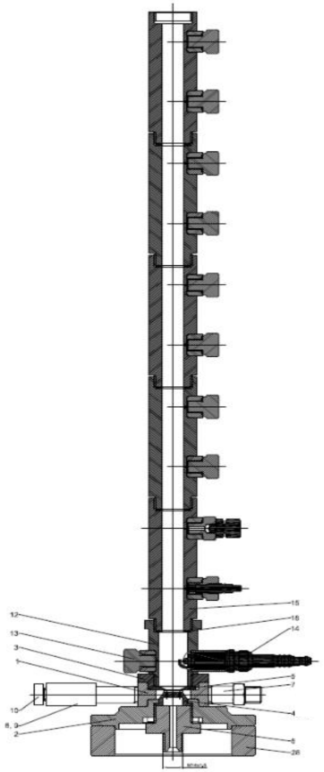
PDC modification to achieve SO1 & SO 2:

- oxidizer inlet narrow
- fuel inlet adapted

(Chapters 2 & 3 of the PhD Thesis)

SO3

Refined Geometry

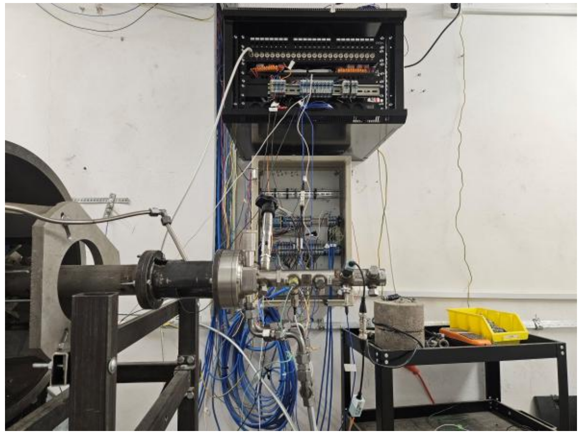


PDC refinement for instrumentation:

- Full factorial test matrix (512 tests)
- Operational map both oxidizers
- ANOVA study

(Chapters 4,5, & 6 of the PhD Thesis)

Refined Geometry

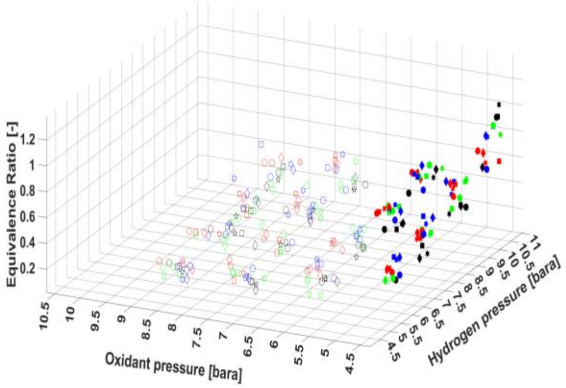


Start – TRL 2 **TRL 3** **TRL 3**

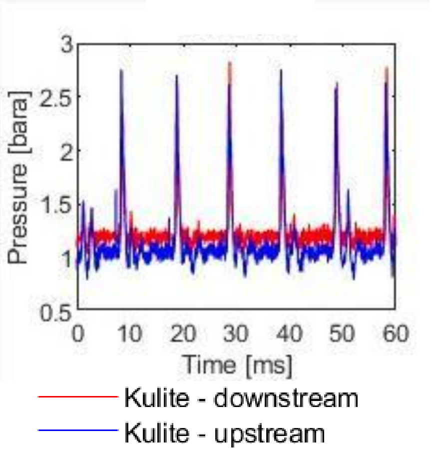
Continued next page

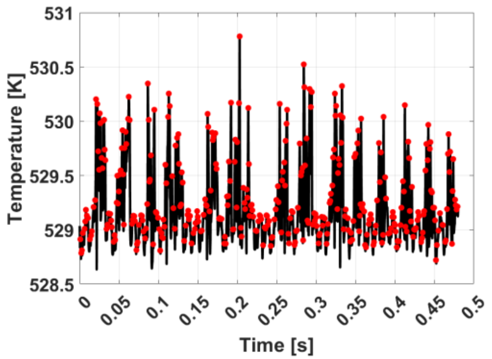
SO3

Results

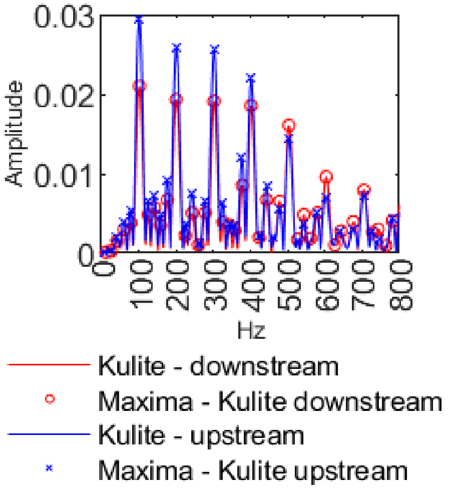


Pressure

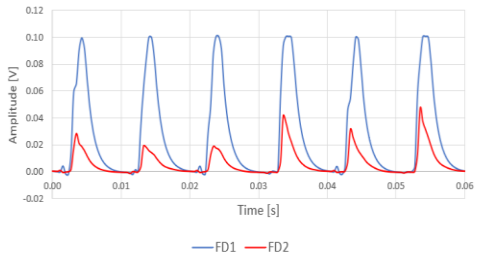




FFT analysis

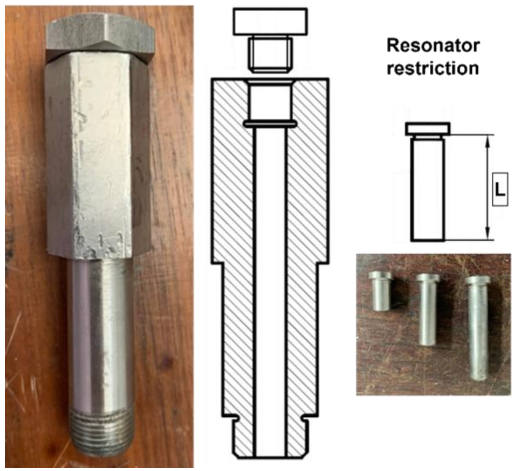


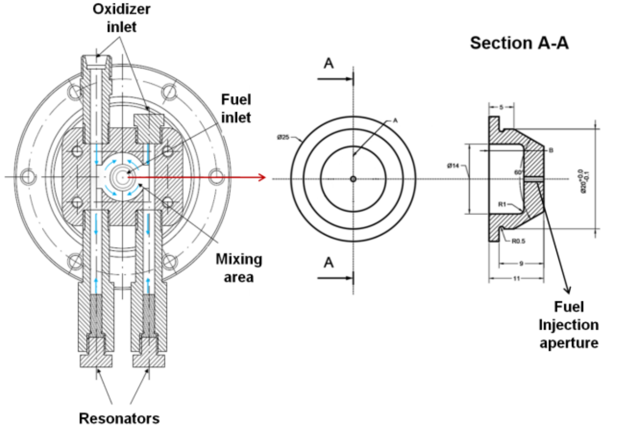
Photodiodes



SO4

Geometry optimization





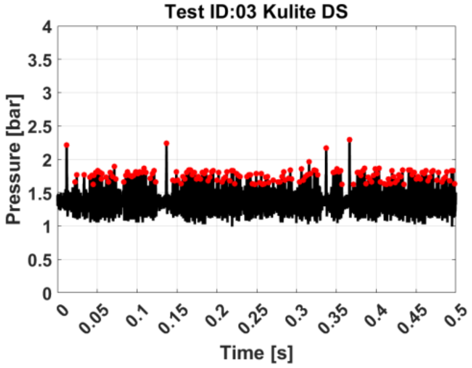
PDC geometry optimization:

1. Fuel injection place alternation
   - Thrust enhancement (361 %)
   - Pressure gain enhancement (171%)
   - Maximum cycle pressure (162 %)

2. Resonator and exhaust pipe optimization
   - Operating frequency enhancement
     - for H_2/air - 300 %
     - for H_2/O_2 - 400 %

- **Resonator phenomenon observed (NEW) – aerodynamic Schelkin Spiral**

(Chapter 7 & Appendix E of the PhD Thesis)



TRL 4

TRL 4

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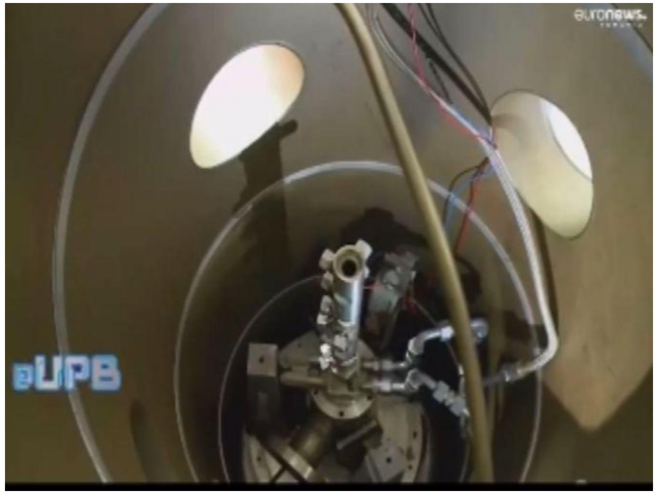
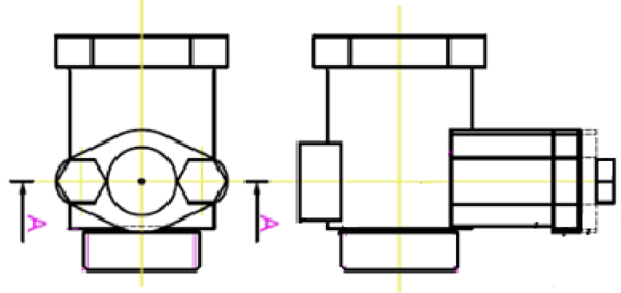
SO6

New geometry for vacuum conditions

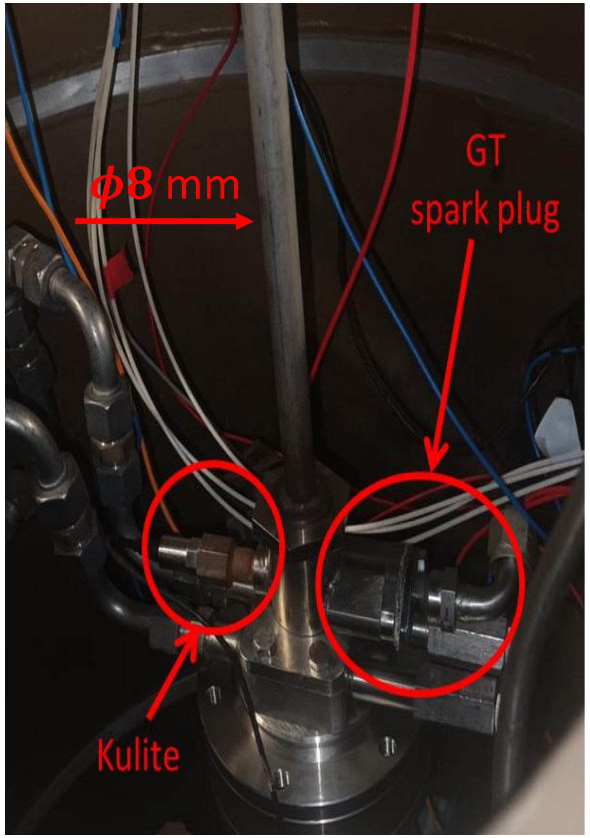
Initial design



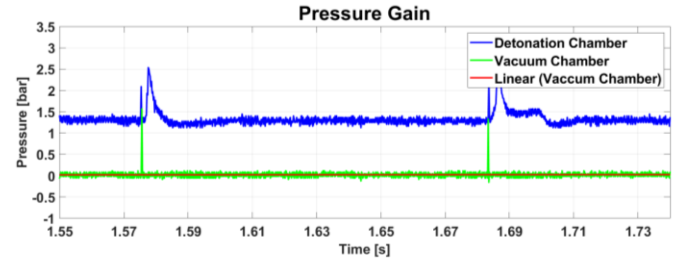
Spark plug adaptation

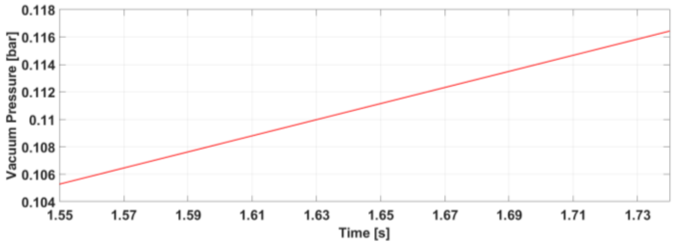


Final design



Results





Pressure gain under low vacuum conditions (~103 mbar):

- Geometry transformation (exhaust pipe, detonator)
- Multiple pressure gain cycles observed
- **Findings included in Euronews documentary by eUPB:**

https://m.youtube.com/watch?v=iJ4D7wQ1m-Unb&fbclid=IwAR01KMWx_mRM8MGZ9Ay4eR2G7_Oq0WwSqEWTU5NQPeIQ9dNOnhFDdcoPwPE

END – TRL 5

Bibliography

[1] F. Brahimi and M. Guemmadi, 2023. "Thermodynamic and Environmental Comparison of Various Recuperated Cycles for Gas Turbine Applications", 47–58, ISBN: 978-981-97-6148-7, https://doi.org/10.1007/978-981-97-6148-7_6.

[2] K Kailasanath, 2000. "Review of propulsion applications of detonation waves", *AIAA journal*, 38, 1698–1708, https://doi.org/10.2514/2.1156.

[3] University of Texas at Arlington Aerodynamics Research Center, 2024. Pulsed Detonation Engines. https://arc.uta.edu/research/pde.htm Accessed: 7th October 2024.

[4] European Commission, 2019. European Green Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan_en Accessed: 7th October 2024.

[5] SpaceX, 2024. Starship. https://www.spacex.com/vehicles/starship/ Accessed:7th October 2024.

[6] NASA, 2021. Next Generation of Orion Spacecraft in Production for Future Artemis Missions. https://www.nasa.gov/missions/next-generation-of-orion-spacecraft-in-production-for-future-artemis-missions/ Accessed: 7th October 2024.

[7] E. J. Gutmark, 2021. "Pressure Gain Combustion", *Shock Waves*, 31, 619–621, https://doi.org/10.1007/s00193-021-01053-3.

[8] D. L. Chapman, 1899. "VI. On the rate of explosion in gases", *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 47, 90–104, https://doi.org/10.1080/14786449908621243.

[9] E. Jouguet, 1905. "On the propagation of chemical reactions in gases", *J. Math. Pures Appl*, 1, 347–425.

[10] Y. B. Zeldovich, 1950. On the theory of the propagation of detonation in gaseous systems. Technical Report, FM 00-7.

[11] R. Vutthivithayarak "Analysis of pulse detonation turbojet engines". PhD Thesis. Texas, USA: University of Texas at Arlington, 2011.

[12] E. Wintenberger and J. E. Shepherd, 2006. "Thermodynamic cycle analysis for propagating detonations", *Journal of propulsion and power*, 22, 694–698, https://doi.org/10.2514/1.12775.

[13] Kenneth K Kuo, 1986. Principles of combustion, ISBN: 9780471046899.

[14] S. R. Turns, 1996. Introduction to combustion, ISBN: 9871259025945.

[15] J. H. Lee, R. Knystautas, and A. Freiman, 1984. "High speed turbulent deflagrations and transition to detonation in H2-air mixtures", *Combustion and flame*, 56, 227–239, https://doi.org/10.1016/0010-2180(84)90039-7.

[16] J. Shepherd, 2002. Detonation Database. https://shepherd.caltech.edu/detn_db/html/db.html Accessed: 9th October 2022.

[17] S.M. Frolov, V.A. Smetanyuk, V.S. Aksenov, and A.S. Koval', 2017. "Deflagration-to-detonation transition in crossed-flow fast jets of propellant components", vol. 476, 153–156, https://doi.org/10.1134/S0012501617090019.

[18] J. Chambers and K. Ahmed, 2017. "Turbulent flame augmentation using a fluidic jet for Deflagration-to-Detonation", *Fuel*, 199, 616–626, https://doi.org/10.1016/j.fuel.2017.03.023.

[19] M. Cooper, S. Jackson, and J.E. Shepherd, 2000. Effect of deflagration-to-detonation transition on pulse detonation engine impulse. Technical Report, FM 00-3.

[20] A. V. Cojocea, T. Cuciuc, I. Porumbel, M. Gall, B. Gherman, and D. E Crunţeanu, 2022. "Experimental Investigations of Hydrogen Fuelled Pulsed Detonation Combustor", vol. 86007, V03BT04A020, ISBN: ISBN: 978-0-7918-8600-7, https://doi.org/10.1115/GT2022-82393.

[21] G.I. Vrabie, D.C Asoltanei, **Cojocea, A.V.**, M. Gall, T. Cuciuc, and I. Porumbel, 2023. "Experimental Comparison for Different Oxidizers in Hydrogen Fuelled Pulsed Detonation Combustor", *Turbo Scientific Journal*, X(2), 37–53, https://comoti.ro/wp-content/uploads/2024/01/Vol-X-No-2-2023.pdf.

[22] **Cojocea, A. V.**, T. Cuciuc, I. Porumbel, M. Gall, G. Vrabie, and D. Asoltanei, 2024. "Stability Exploration of Pulsed Detoantion in Hydrogen-Air and Hydrogen-Oxygen Mixtures", https://www.3af-spacepropulsion.com/images/DOCUMENTS/SP2024_PRELIMINARY_PROGRAMME.pdf.

[23] A. Bogoi, T. Cuciuc, A. V. Cojocea, M. Gall, I. Porumbel, and C. E. Hrițcu, 2024. "Experimental Pressure Gain Analysis of Pulsed Detonation Engine", *Aerospace*, 11, 465, https://doi.org/10.3390/aerospace11060465.

[24] A.V. Cojocea, I. Porumbel, M. Gall, and T. Cuciuc, 2024. "Experimental Thrust and Specific Impulse Analysis of Pulsed Detonation Combustor", *Applied Sciences*, 14, 5999, https://doi.org/10.3390/app14145999.

[25] R. W Shonkwiler and F. Mendivil, 2009. Explorations in monte carlo methods, ISBN: 978-3-031-55964-8.

[26] A.V. Cojocea, I. Porumbel, M. Gall, and T. Cuciuc, 2024. "Experimental Investigations on the Impact of Hydrogen Injection Apertures in Pulsed Detonation Combustor", *Energies*, 17, 4918, https://doi.org/10.3390/en17194918.

[27] Bo Zhang, 2024. "Enhancing detonation propulsion with jet in cross-flow: A comprehensive review", *Progress in Aerospace Sciences*, 101020, https://doi.org/10.1016/j.paerosci.2024.101020.

[28] T. Cuciuc, C.E. Hritcu, G.G. Ursescu, I. Porumbel, and C.F. Cuciumita, 2017. Valveless Pulsed Detonation Chamber Controlled by Hartmann Oscillators.

[29] A.V. Cojocea, M. Gall, G.I. Vrabie, T. Cuciuc, I. Porumbel, G. Ursescu, and D.E. Crunţeanu, 2024. "Experimental Study on Ignition and Pressure-Gain Achievement in Low-Vacuum Conditions for a Pulsed Detonation Combustor", *Technologies*, 12, 252, https://doi.org/10.3390/technologies12120252.

[30] G. I. Vrabie, A. V. Cojocea, M. Gall, C. Anton, D.C. Asoltanei, and I. Porumbel, 2024. "Towards the development of an algorithm for automatic analysis and detection of shock waves in the schlieren visualization technique.", *INCAS Bulletin*, 16, ISSN: 2066-8201, https://doi.org/10.13111/2066-8201.2024.16.4.12.