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Combustion Instability in Lab-Scale HREs with Swirl Injectors: Pre- and Post-Chamber Effects

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Abstract. Combustion instability in hybrid rocket engines (HREs) remains a significant challenge, leading to pressure oscillations, vibrations, and potential engine failure. This study aims to mitigate instability while optimizing performance and safety by investigating the effects of oxidizers swirl injector, pre-combustion chamber, and post-combustion chamber lengths. Using paraffin-based fuels and oxygen, the methodology is based on experimental lab-scale firing tests to analyze the impact of these parameters on combustion dynamics. The research integrates combustion theory, fluid dynamics, and chamber design to identify optimal configurations that reduce instability and enhance fuel regression rates. The study culminates in a proposed engine design that achieves stable combustion and improved performance, offering a pathway to safer and more efficient HREs.

1. Introduction

HREs are intrinsically safer than liquid and solid rockets because their propellants are kept in distinct phases. In a typical HRE, the oxidizer is liquid or gaseous, whilst the fuel is solid. This separation considerably minimizes the risk of chemical explosions, as illustrated in Figure 1.

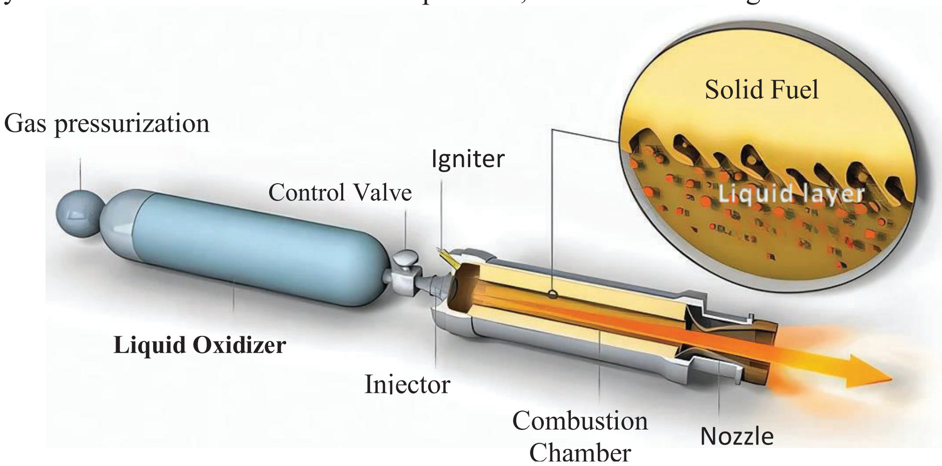

Figure 1. A traditional HRE[1].

Between 1930 and 1950, HREs were initially studied but were eventually shelved due to their low thrust and regression rates. The primary issue with conventional HREs was their diffusion-limited combustion process, which resulted in poor fuel regression rates- usually less than one-third of those achieved by solid rocket motors. While HRE is intrinsically safer and easier to handle, efforts to improve their regression rates have often compromised these advantages. For instance, increasing the burning surface area through complex multi-port fuel grain designs was a common approach. However, this led to reduced volumetric loading, lower performance, and compromised structural integrity, as illustrated in Figure 2. Additionally, fuel additives such as oxidizing agents and energetic metal particles have been tested to enhance performance. While these additives showed potential, they introduced risks of toxicity and explosion. Furthermore, the restrictive boundary layer combustion approach, depicted in Figure 3, continues to limit overall performance [2].

Figure 2. Different fuel grain designs[3].

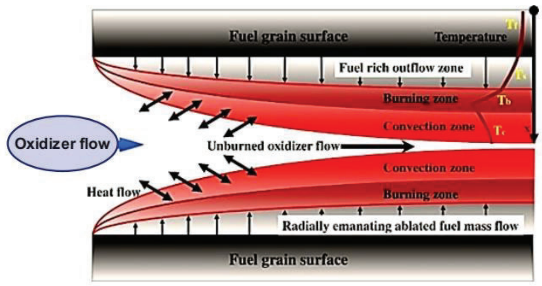

Figure 3. Boundary layer combustion [4].

A considerably more effective way is to use propellants that create a melt layer on the combustion surface. These are typically non-polymerized compounds that liquefy when heated. One apparent example is liquids or gasses at normal conditions that are frozen to create solids. Examples of this class include H_2, a deep cryogen, liquid amines, and hydrocarbons. Materials that are solids under typical conditions, on the other hand, can display the same internal ballistic behavior if a melt layer forms on the combustion surface. A researcher's group at Stanford University identified the exceptionally high burn rate characteristics of paraffin wax in the early 21st century (1999–present) [5].

The oxidizer's injection pattern into the combustion chamber (c.ch) is an important aspect in determining an HRE performance. As the oxidizer flows over the solid fuel grain surface during combustion, a turbulent diffusion boundary layer [5], [15], develops, which confines the flame. The fuel undergoes pyrolysis when heat is transferred from the flame to its surface. Pyrolysis-generated heat fluxes, on the other hand, can slow down fuel regression by preventing additional heat transfer to the fuel surface.

Historically, the resonance phenomenon has been used to describe combustion instability associated with both acoustic waves and gas flow inside the chamber; however, due to a misunderstanding of the exact coupling mechanism between the burning propellant and gas-phase oscillations, mitigation strategies for the problem were often approached in a general manner [6]. HRE developers aim to prevent oscillatory behavior before an engine enters service, but the spontaneous oscillatory motion of the gaseous combustion products within the c.ch frequently occurs. This unsteady behavior, known as "combustion instability," can become a predominant issue, as these oscillations are typically associated with the natural acoustic frequency of the chamber and can reach amplitudes of 10–30% of the mean pressure, with a resultant significant increase in mean pressure also possible [7], as shown in Figure 4.

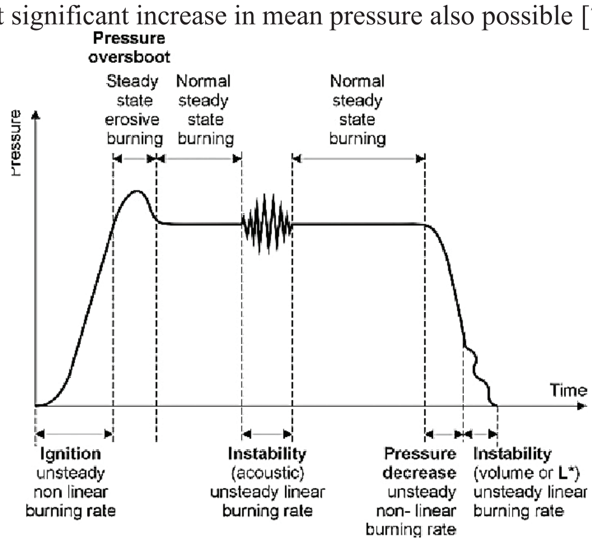

Figure 4. (P-t) History of an engine undergoing oscillatory combustion[8].

One of the reasons combustion instabilities are such a challenging problem to eliminate during the design phase is that they can arise from a variety of sources. The fundamental difficulty lies in the fact that a significant amount of energy is released over a relatively short period within a confined space. While a portion of the energy generated by the combustion process exits the chamber through the nozzle, the choked flow condition causes some of the energy to be reflected into the chamber in the form of acoustic waves[9].

Experimental studies on combustion instability in HREs have primarily focused on measuring pressure oscillations, flame flickering, and other indicators of unsteady combustion. Several mitigation techniques have been identified, including the use of baffles, acoustic dampers, and fuel additives. Baffles disrupt acoustic resonance within the c.ch, while acoustic dampers absorb pressure waves. Fuel additives can alter the combustion process, reducing the likelihood of instability[10]-[14].

Factors that have an impact on combustion instability are numerous. The present paper aims to shed more light on HRE instability with a focus on the role of engine dimensions. Paraffin-based fuel and oxygen are used as the case study propellant. A lab-scale engine is designed for this purpose. The remainder of the paper is organized as follows: the first section demonstrates the details of the experiment setup. Next results of experiments are presented and discussed. The paper finalizes the key findings and conclusions.

2. Experimental work

2.1 Fuel Grain Casting Procedure

To fabricate the fuel grains, the paraffin base fuel formulation was initially melted using an induction heater and then poured into tubular Molds. Molds were allowed to cool at ambient temperature, a process that typically took approximately six hours for the wax to solidify. X-ray imaging was performed to identify any voids, slits, or structural irregularities in the solidified fuel grain. Analysis of the imaging confirmed that the grain was free of voids, as shown in Figure 5. As a result, this method was consistently used to prepare the fuel grains throughout the experimental study.

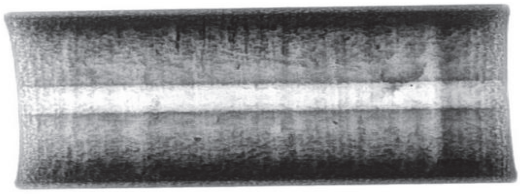

Figure 5. X-ray image of the fuel grain.

2.2 Lab-scale hybrid engine

Two lab-scale HREs used in this study are illustrated in Figure 6. The HRE was constructed from mild steel. At the aft end of the engine, a convergent-divergent nozzle with a throat diameter of 5 mm and an area ratio of 5.25 was installed. The nozzle incorporated a steel body with a graphite inlay for enhanced performance. The head end of the engine housed the injector, which delivered the oxidizer at the required injection pressure. Additionally, the engine design included both a pre-chamber and a post-chamber to optimize combustion dynamics. The two engines used differ only in lengths of c.ch. Detailed dimensions of the engine are provided in Table 1.

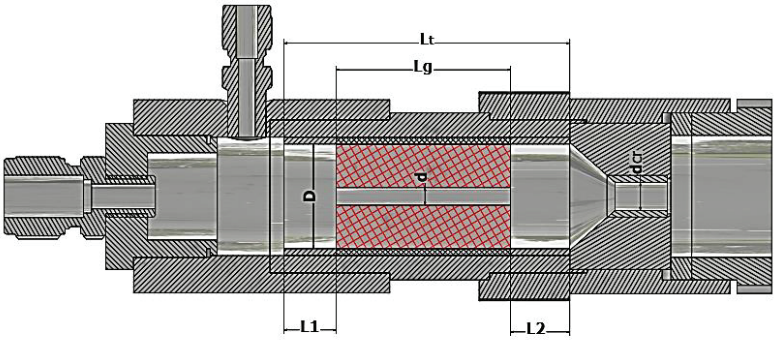

Figure 6. Lab-scale HRE.

Table 1. Dimension details of the lab-scale engines.

Parameter	Original	Modified
length of combustion chamber L_t	222 (mm)	91 (mm)
length of pre-chamber, L1	82 (mm)	15 (mm)
length of post-chamber, L2	90.5 (mm)	17 (mm)

Oxygen is injected into the engine at a rate of 5 g/s using a swirl injector as shown in Figure 7 below.

Figure 7. Swirl Injector and Swirl Injector Cross-Section

A solid composite propellant grain was used for ignition, composed of 30% HTPB (hydroxyl-terminated polybutadiene) and 70% ammonium perchlorate, along with the plasticizer di-octyl phthalate (DOP).

2.3 The experimental setup

The experimental configuration used in this investigation, as shown in Figure 8, consists of an oxygen cylinder with a maximum pressure of 151 bar. The cylinder supplied oxygen through feeding lines, which included several valves to regulate the flow and output pressure to the c.ch. To ensure consistency across all trials, the feed line pressure was controlled to maintain an oxygen pressure of 5 bar and an oxidizer mass flow rate of 5 g/s.

To control the flow of the oxidizer into the c.ch, a solenoid valve was installed at the end of the feed line, near the oxygen injection point. The propellant was ignited using a mechanism powered by a 12-volt DC power source connected to an AC/DC converter. Both the solenoid valve and the ignition system were controlled by a Select 8-channel sequential timer. The solenoid valve was opened to allow the oxidizer to enter the c.ch for the desired operating duration. During firing, a pressure transducer was used to record c.ch pressure data. The data from the pressure transducer was acquired using an NI DAQ card and NI Signal Express software.

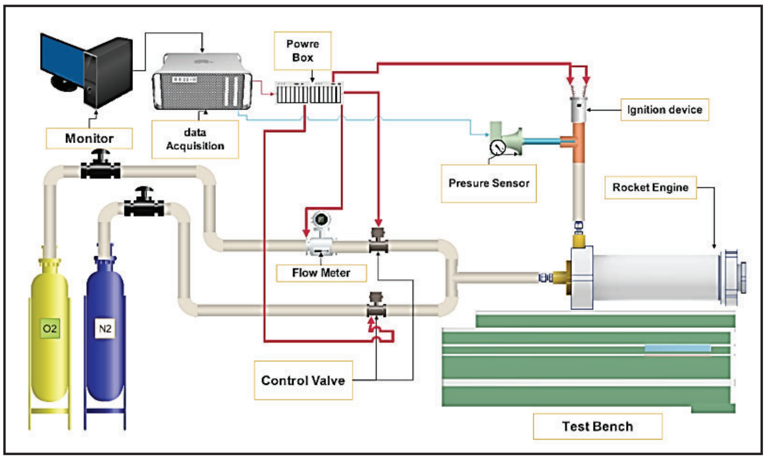

Figure 8. The layout setup of the experiment.

2.4 Investigation of Combustion Stability

The HRE's stability behavior was analyzed using the Fast Fourier Transform (FFT) approach. The FFT turns time-domain signals, such as chamber pressure (Pc), into frequency-domain representations, and vice versa. In the FFT plots, the frequency amplitudes were normalized relative to the largest amplitude recorded in the low-frequency (LF) band of the frequency spectra, as illustrated in Figure 9.

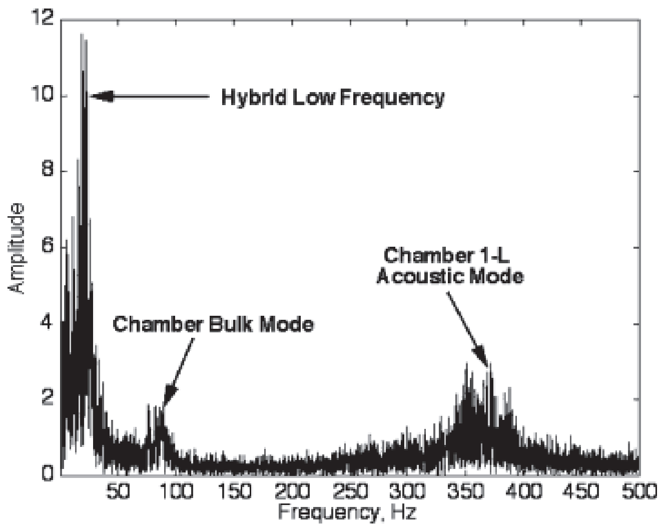

Figure 9. FFT of Pc for HRE [15].

3. Results and Discussions

3.1 Original engine

The original HRE serves as the baseline case for this investigation pre and post-c.ch. The oxidizer's mass flow rate remained constant throughout the combustion process. Figure 10 displays the Pc trends. The HRE demonstrated both non-linear and linear combustion phenomena, as inferred from the Pc data in Figure 10. Combustion is considered non-linear if the amplitude of the pressure oscillations during combustion deviates by more than 5% of the average Pc. Conversely, it is referred to as linear combustion if the pressure amplitude deviation is minimal, remaining below 5%. During non-linear combustion, strong pressure oscillations were observed, and their amplitude increased rapidly[16].

After a certain period, these pressure oscillations unexpectedly ceased, and the combustion transitioned to a linear mode, continuing until completion. Additionally, Figure 11. presents photographs of exhaust plumes corresponding to different combustion phases. Qualitatively, the size of the exhaust flame varies with changes in Pc during combustion. In Phase 2, the flame is comparatively larger, coinciding with the period of maximum amplification in Pc over the engine's entire operating duration. The evolution from non-linear to linear combustion, referred to as Phase 3, is illustrated in Figure 10. During Phase 3, a sharp decline in Pc occurred, resulting in a significant reduction in the size of the exhaust plume, as depicted in Figure 11. The exhaust flames in Phase 1 and Phase 4 were nearly identical in size, as the engine exhibited linear combustion in both stages. The variation in the size of the exhaust plume between Phase 2 and Phase 3 is attributed to abrupt changes in chamber pressure. This sudden increase and decrease in Pc are referred to as the DC shift. The DC shift phenomenon is regularly observed in solid motors and has also been documented in HRE by several researchers [14]-[22]. In HREs, the DC shift is primarily caused by sudden fluctuations in the regression rate of the solid fuel [19]. This phenomenon has been widely studied and reported in the context of HRE combustion.

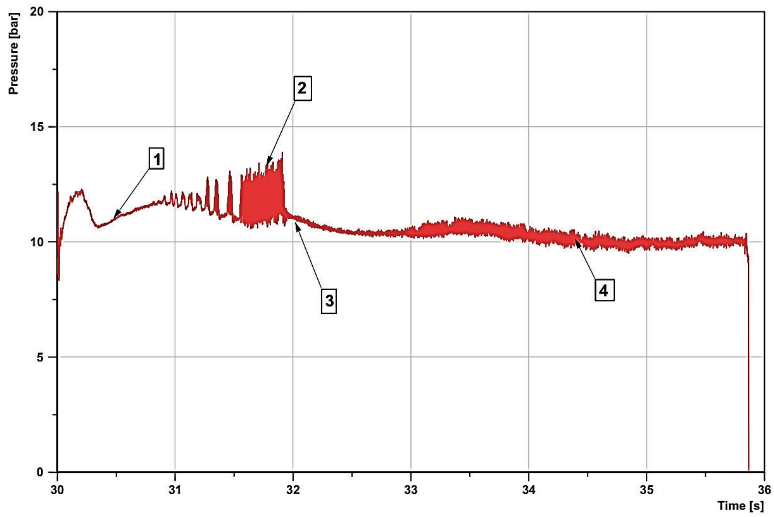

Figure 10. Pressure-time trends

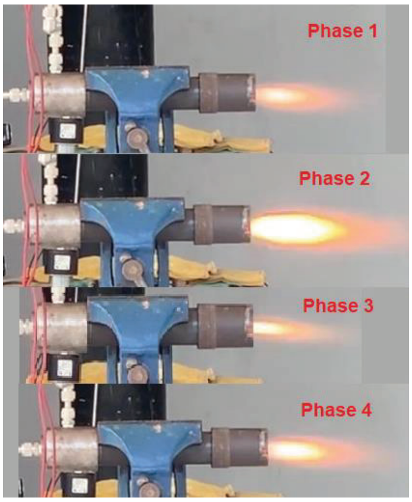

Figure 11. Exhaust flame images for the original engine test

The LF region of the FFT reveals the presence of inherent LF and bulk mode (BM) instabilities. LF instabilities are associated with frequencies ranging from 10–30 Hz, while BM instabilities correspond to frequencies between 50-200 Hz. These observed frequencies align well with the theoretically predicted frequencies presented in Table 3. Furthermore, the FFT data, as shown in Figure 12, provides additional insights into the combustion stability behavior of the HRE. Specifically, the FFT indicates the occurrence of LF instabilities (10-30 Hz) during the combustion process.

On the other hand, BM instabilities (50–200 Hz) were observed to begin after 0.8 seconds of combustion and persisted until the end of the burn. From 0.5 seconds onward, both LF and BM instabilities appeared as a single band until combustion completion. The FFT depicted in Figure 12 reveals a distinctive peak within the 350-400 Hz frequency range, which corresponds to the first longitudinal acoustic modes of the c.ch.

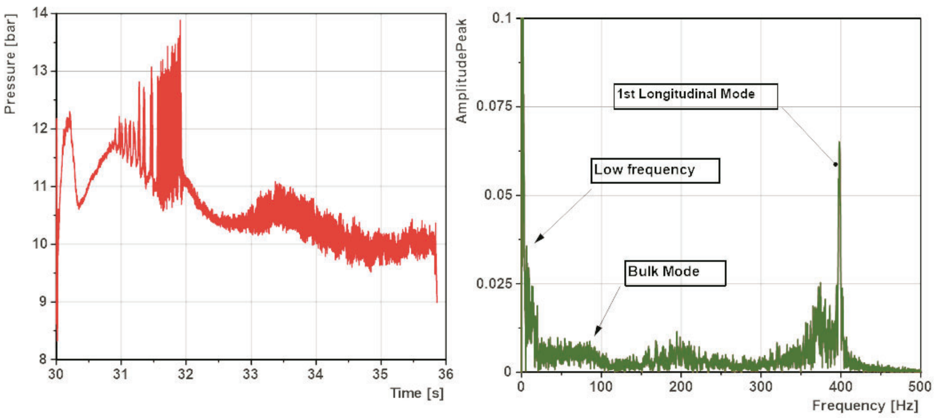

Figure 12. FFT of Pc test #1.

The frequency ranges of the acoustic modes, both empirically observed and theoretically predicted, are presented in Table 2. The experimentally determined acoustic mode frequencies show close agreement with the theoretically calculated values. Figure 12 illustrates the variation in the first acoustic modes (350–410 Hz) over the burn duration. To validate the results, the experiment was repeated, and no significant differences in frequencies or phases were observed, as shown in Figure 13 and Figure 14.

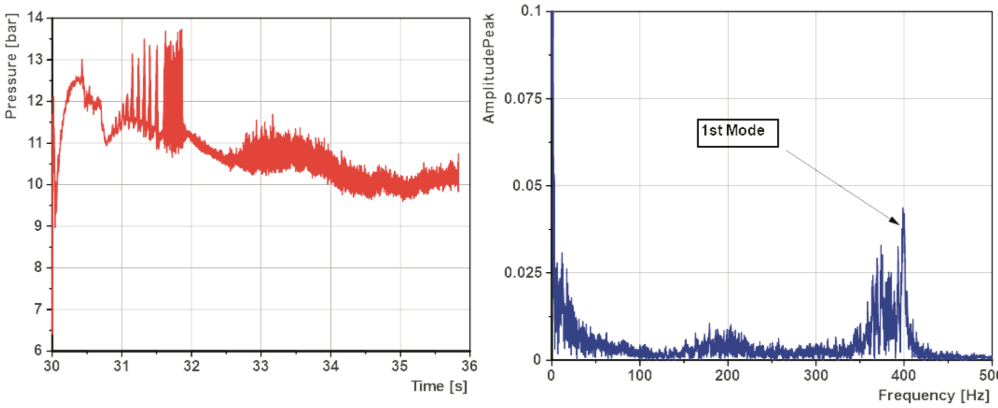

Figure 13. FFT of Pc test #2.

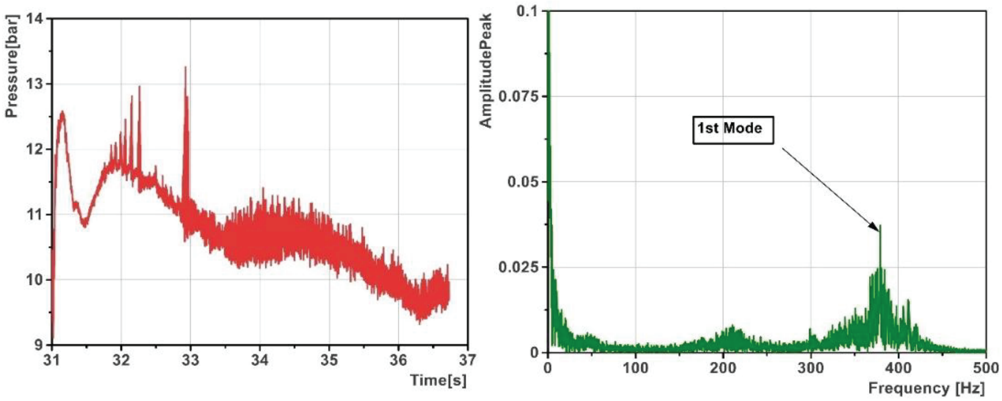

Figure 14. FFT of Pc test #3.

3.2 Effect of pre and post c.ch lengths

The pressure-time data and FFT corresponding to the modified engine are illustrated in Figure 15, and Figure 16. The analysis of these results demonstrates an impressive decrease in the amplitude of the acoustic modes. However, no notable changes were observed in the amplitude of LF and BM oscillations. As a result, the combustion process in the modified HRE appears to be more stable compared to the original engine. This enhanced stability can be attributed to the dynamics of vortex shedding at the fuel grain exit and its interaction with the nozzle walls, which resembles flow phenomena observed in cavities. Strong and self-sustaining pressure oscillations occur in such cavities as a result of the interplay between the shear layer created at the leading edge and the acoustic oscillations caused by the shear layer's impact on the trailing edge walls. The creation of this shear layer plays an important function in causing pressure oscillations within the cavity. To address this, research efforts have focused on disrupting the shear layer formation at the cavity's leading edge through the implementation of passive flow control techniques [24]. Table 2 illustrates the whole results.

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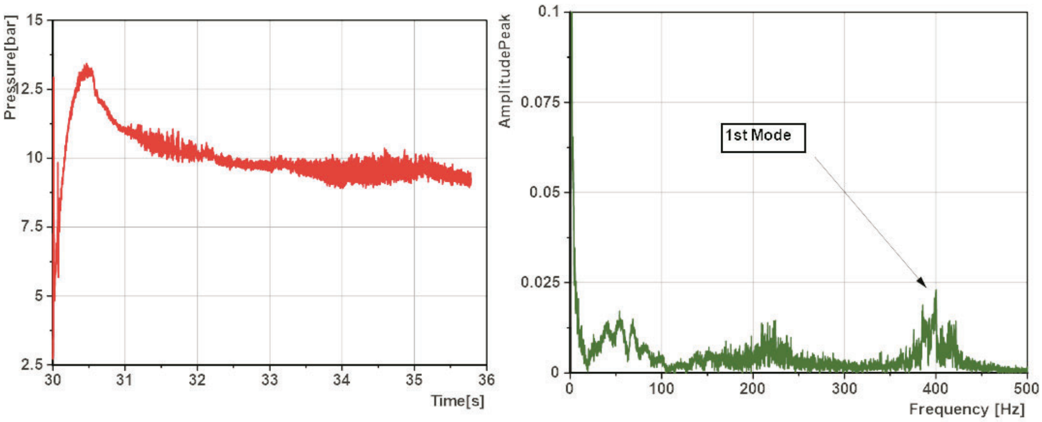

Figure 15. FFT of Pc test #4.

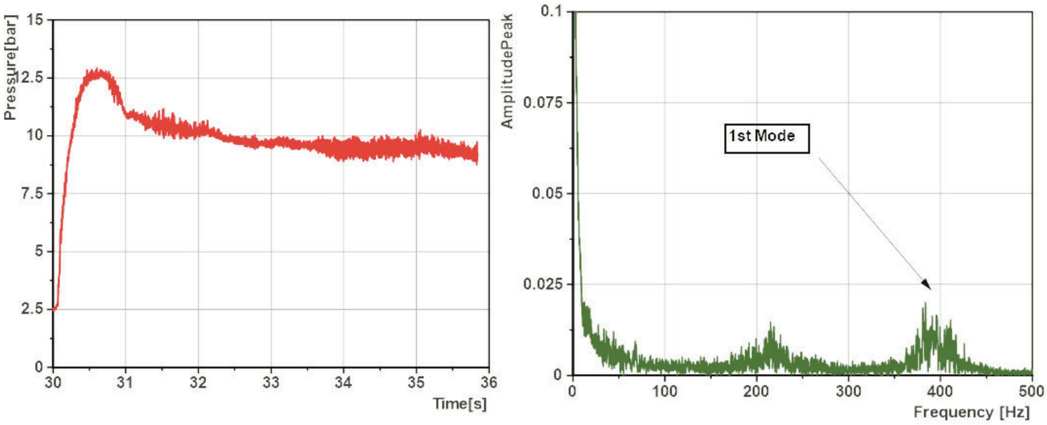

Figure 16. FFT of Pc test #5.

Table 2. Results Data.

No.	Engine Type	t_b(s)	G_{ox} (Kg/m²s)	P_{mean}*(bar)*	r`(mm/s)	1st Mode (Hz)	Amplitude
#1	Original	5.7	52.48	10.64	1.4037	409	0.067
#2	Original	5.7	49.46	10.81	1.5793	407	0.043
#3	Original	5.7	49.32	10.77	1.3995	382	0.039
#4	Modified	5.76	52.14	10.07	1.3596	390	0.021
#5	Modified	5.8	54.04	10.03	1.3823	376	0.017

4. Conclusion

The study offers significant insights into combustion instability in lab-scale HREs, highlighting its critical implications for performance and safety. By examining key factors such as fuel selection, oxidizer injection patterns, and engine design, the research seeks to address instability while enhancing combustion efficiency. The findings underscore the intricate relationship between combustion dynamics, fluid mechanics, and acoustic modes, laying the groundwork for future innovations in HREs technology.

Key conclusions reveal that combustion instability, driven by amplified pressure disturbances, presents substantial risks to HREs, including performance degradation and potential engine failure. Additionally, the selection of fuel and oxidizer, along with fuel grain geometry and injection patterns, plays a pivotal role in determining combustion stability, with paraffin-based fuels and oxygen being favored for their eco-friendly attributes and operational versatility. Experimental observations indicate both linear and non-linear combustion phases, marked by significant pressure oscillations, while FFT analysis has identified LF and BM instabilities, as well as first longitudinal acoustic modes that align closely with theoretical predictions. Furthermore, a modified engine design has shown reduced acoustic mode amplitudes, suggesting enhanced stability through optimized vortex shedding dynamics at the flow exit. The study also notes the DC shift phenomenon, where abrupt Pc changes correlate with sudden variations in the solid fuel's regression rate, a prevalent challenge in solid and HREs systems.

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