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Experimental methodology for the characterization of a hydrogen-fuelled Pressure Gain Combustor

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Abstract. Gas turbines have been a key technology in many industrial sectors for over 50 years and they will continue to play a crucial role in the energetic scenario. Nevertheless, these systems are approaching their efficiency limits and performance improvements are becoming increasingly difficult to achieve. In this context, Pressure Gain Combustion (PGC) has emerged as a promising technology: replacing the isobaric combustion with a quasi-isochoric process creates a rise in total pressure across the combustion chamber, enhancing their potential performances. However, it is a complex process influenced by combustion chemistry, heat transfer, and fluid dynamics, and its unsteadiness increases the complexity of measurement campaigns. Thus, several challenges still need to be addressed for its development.

This paper shows the experimental methodology followed to characterize an innovative deflagrative-based PGC fuelled with 100% hydrogen. Dynamic pressure sensors were installed inside, upstream, and downstream of the combustion chamber and acquired at a high frequency (1 MHz) to describe in detail the process.

Downstream the combustor, an orifice simulated the pressure drop across the turbine. Different fuel pressure has been tested, varying the operating parameters and the position of the pressure sensors inside the chamber. For each configuration, a detailed analysis of the mean pressure trends and cycle-to-cycle variation was carried out and will help optimize the system in the following tasks of the project. The experimental methodology described can be used to better investigate the physics of Pressure Gain Combustors and allow complete exploitation of their potentiality in terms of work extracted, resource consumption, and pollutant emission.

Keywords: Pressure Gain Combustion, Hydrogen, Experimental Analysis, Deflagrative combustion

1. Introduction

Gas turbines have been a central technology in industrial sectors such as power generation, marine, and aerospace for over 50 years. Given their significant global footprint, improvements in energy consumption and pollutant emissions could have an extremely high impact on the environment and help to reach the targets set by the EU energy transition policies.

The highest loss source in conventional gas turbines occurs during the combustion phase when total pressure decreases causing a reduction of work potentiality [1][2]. In this context, Pressure Gain Combustors (PGC) fit perfectly: these systems replace the isobaric combustion with a quasi-isochoric process in which total pressure rises across the combustion chamber. From a theoretical point of view, many authors proved the thermodynamic benefits of PGC by means of the Humphrey cycle analysis [3]. Due to their potentially enhanced performances over conventional combustion, the interest in PGC has increased considerably in this decade and many investigations have been performed with both detonation and deflagration-based combustors [4]. Thanks to a higher theoretical gain in stagnation pressure, detonation systems gained higher attention. However, the absence of shock waves and lower vibrations makes deflagration processes more easily integrated into conventional gas turbine technology [5]. Most of the existing studies for deflagration-based approaches focus on acoustically resonant devices. These include the so-called pulsejets [5], Resonant Pulse Combustor (RPC) [6], and Shockless Explosion Combustors (SEC) [7][8]. Except for minor differences, these technologies are all based on the same principle of operation: the coupling between acoustic and thermal oscillation creates (1) a naturally aspirated combustor and (2) a pressure rise during the combustor phase. Various authors analyzed this topic, investigating the influence of different geometry layouts, operating parameters, and ignition characteristics on the performances. In all cases, the coupling between heat release and pressure wave is pivotal to optimize the process.

This paper focuses on an innovative deflagration-based PGC owned by Finno Exergy Oy, published in the cited patent [9]. Instead of relying on the coupling of acoustic and thermal oscillation, the quasi-isochoric process is entrusted to the combustor geometry itself: confining the flow inside the chamber allows a pressure rise during the combustion phase. It is a new concept inspired by pistonless internal combustion engines: timed valves on the upstream side of the combustor control scavenging and intake phases while the outlet is constantly open. In literature, there are very few similar systems: the only comparable one is the work of the PPrime Institute group [10][11][12], which analyzed a pistonless Constant Volume Combustor (CVC) from both a numerical and experimental point of view. In their system, inlet and outlet rotary valves ensure the constrained volume, while Finno Exergy combustor exploits an approximate Constant Volume Combustion (a-CVC) for the absence of the exhaust valve. The state of the art on this topic is still limited since from the Author's knowledge there is a lack of similar studies under development.

Some of the authors previously cited highlight the analogy between a deflagrative PGC and an internal combustion engine (ICE). Anand [13] drew a parallel between fluidic piston movement in a pulsejet and an actual piston in ICE: the author defines the different operating phases using the idea of the Top Dead Center (TDC) from automotive engines field and affirms that pulsejet operates in a grey region between compression ignition and homogenous charge compression ignition engines. The similarities are even stronger with constant volume chambers, where opening and closing of valves separates the scavenging, suction, combustion, and exhaust phases. Labarrere [13] investigated volumetric efficiency, heat losses to chamber walls, ignition, and influence of residual gases in a CVC chamber and highlights its similarities with a turbo-charged piston engine with a fixed piston position. Given the vast knowledge of combustion and ignition processes in ICE world for both numerical, experimental and data analysis, this parallelism can bring significant added value to the advancement of these novel combustors.

Given the uniqueness of Finno Exergy combustor, the experimental methodology needed for its characterization had to be developed. Not only it exploits an unprecedented type of process, never tested by anyone else, but also, by operating 100% with pure hydrogen, its development has the potential to reduce the environmental impact of turbogas systems. The experimental campaign carried out with the first prototype proved the capability of the system; it is described in [15]. However, the presence of two turbochargers for the pressurized air supply and work extraction increased the test bench complexity. In the campaign described here, the focus is fully on the combustion phase, to allow a better understanding of the process and decrease uncertainties created by additional components. For its clear characterization, inspiration was taken from similar Pressure Gain Combustor analysis and from ICE applications. Tools typically used in internal combustion engines application were applied for both the experimentation and the post-processing analysis. The methodology applied was able to give an insight into this novel technology and the issues emerged will orientate the following project developments.

2. Experimental set-up & methodology

In this chapter, after describing the general working principle of Finno Exergy combustor (Section 2.1), the methodology followed to perform the tests is given (Section 2.2). In addition, Section 2.2 reports the lists of the control parameters varied during the tests, and the instrumentation installed.

2.1. Combustor

Figure 1 shows a scheme and picture of the combustor tested. It is composed by two chambers in series connected by a restricted section, as described in [9]. Henceforth, we will refer to the first and second chambers as "top" and "bottom" respectively. In addition, for manufacturing issues the combustor tested was composed of two twin elements in parallel; from now onwards they will be indicated as "right" and "left" side.

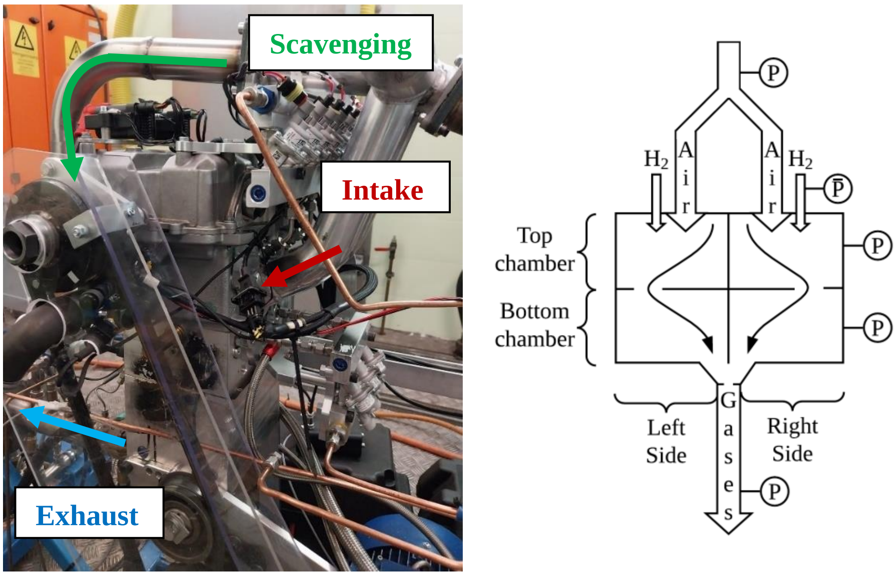

Figure 1: Finno Exergy combustor.

The combustion process consists of repeating working cycles described by four subsequent phases, highlighted in Figure 2:

a. Combustion: a controlled ignition source positioned in the top chamber starts the combustion process. The flame front propagates in all the combustor according to an a-CVC process, thanks to an accurate design geometry that confines the flow. Once reached the bottom chamber, the fuel-air mixture completes the combustion in a lean environment. In the present paper, ignition occurs at zero degree (Figure 2).
b. Exhaust: combustion gases go out through an open output channel placed in the bottom chamber. This phase continues until scavenging valves are opened.
c. Scavenging: air flows by a first set of inlet valves (called "scavenging valves") placed in the top chamber and scavenges combustion products of the previous cycle.
d. Intake: air and fuel are introduced in the first chamber by a second set of inlet valves (called "intake valves"). This phase finishes with the ignition control signal that starts again the cycle. Scavenging and intake phase overlaps during a portion of the cycle.

Before discharging the flow in the ambient, its temperature is lowered with a custom-made heat exchanger.

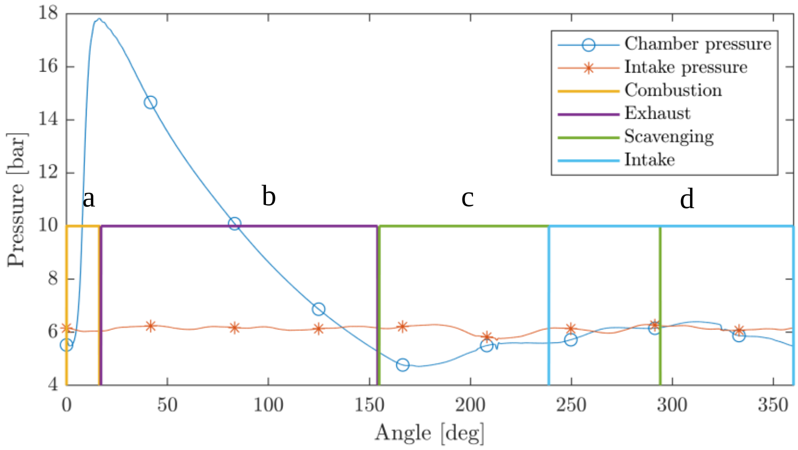

Figure 2: Cycle phases.

2.2. *Experimental methodology*

In the experimental campaign described in this paper, the focus was fully on the characterization of the combustor. The test bench was equipped as follows: the supply line consisted of air at 5 barg and hydrogen at 12 barg. The air pressure was fixed, while the hydrogen one could be slightly varied from one test to the other (+- 0.5 bar). An injection rail consisting of IG4 Dakota HP injectors was responsible for the hydrogen inlet. The fuel was injected indirectly, right before the top chambers: this allows a more homogeneous mixture than the one obtained with direct injection but, on the other hand, limits the correct management and control of the combustion process. An electric motor was responsible for the intake valve opening and a Hall sensor monitored its angular position. As in two-stroke engines, each revolution corresponded to a combustion event, identified by the four typical combustion phases previously introduced. The acquisition of the angular position allowed to control injection, spark plug, and intake valve closing timings. In this way, the mean cycle and phases shown in Figure 2 could be adjusted from test to test. The test bench layout was simplified from the previous campaign (reported in [15]): at the time, two turbochargers were responsible for the pressurized air supply and for the work extraction quantification. In the latest tests instead, a calibrated orifice had the role to simulate the pressure drop across the turbine. This decreased complexity and uncertainties created by additional components. Different test configurations could be analyzed by varying the parameters shown in Table 1. The timing values are omitted for confidentiality.

Table 1: Parameters varied during the tests.

Type of parameter	Parameter	Range
Timing	Injection Duration	[ms]
	Injection End Timing	[deg]
	Spark Plug Timing	[deg]
	Intake Valve Closing	[deg]
	Rotational Speed	600 – 730 [rpm]
Supply Pressure	Hydrogen Supply Pressure	11.5 - 12.4 [bar]

At the beginning of each test, the timings were set according to the desired conditions. Then, after opening the air line, the rotational speed was increased until the target value. Lastly, the fuel line was opened, and combustion started. The variables acquired were:

- Upstream the PGC:
    - Intake air dynamic pressure: Kulite XTL-123B-190M;
    - Hydrogen supply average pressure: FINJECTOR MKS-20-1-8-C;

- Inside the PGC:
  - Dynamic pressure: piezoelectric type, AVL GR14D;
  - Dynamic pressure: piezoelectric type, AVL GR12D;
  - Angular position;
- Downstream the PGC:
  - Exhaust dynamic pressure: iAir Cooled Pressure Transducer Kulite EWCTV 312 (M).

The AVL INDIMICRO, an acquisition system typical of internal combustion engines application, was installed to acquire data at high frequency (1 MHz) and monitor the run in real-time. It was responsible for pressures dynamics (analog) and the angular position signal (digital) acquisition. The Ethernet interface transferred data in real time to a connected laptop and, with the data acquisition software IndiCom, the variables were monitored and saved.

In the experimental campaign, firstly the optimal timings reported in Table 1 were found. With optimal we consider operating parameters that create higher pressure gain, avoid auto-ignition, and provide a stable operation. An example can be seen in Figure 3, which shows intake and bottom chamber pressure trends for five consecutive cycles. It can be noted that during the cycles there are some sparks in the curves, especially for the intake trend (red-star curve): this was probably due to mechanical and electronic interference in the acquisition system.

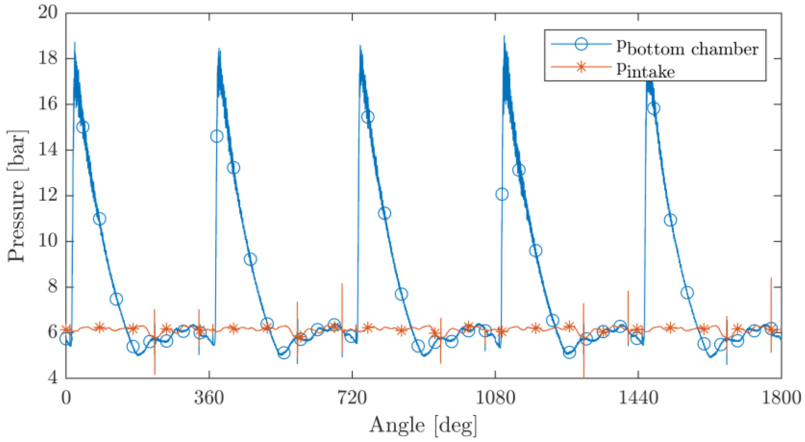

Figure 3: Bottom chamber and intake pressure in five consecutive cycles

Since the pressure sensors used in the chamber were piezoelectric, it was needed to impose an offset pressure value for each cycle. Thus, at degree 270, i.e. when both scavenging and intake valves are open and air is flowing inside the combustor, the chamber pressures were imposed equal to the value measured at the intake. This is a common technique used in internal combustion engines experimentation.

The analysis then included:

1) Variability between left and right side, done by installing the piezoelectric pressure sensors in the left and right top chamber respectively.
2) Variability between top and bottom chambers, done by installing the piezoelectric pressure sensors in the left side, one in the top and one in the bottom chamber.
3) Sensitivity analysis, done through the investigation of the mean-cycle pressure trends as function of hydrogen supply pressure and rotational speed.

The analysis was done in terms of mean cycle and deviation from it: for each run, the angular position signal was used to cut the cycles and obtain the mean trend of all the variables. The parameters of interest monitored were:

- Pressure Gain (PG), defined as the percentage increase of the mean chamber pressure with respect to the intake:

$$PG = \frac{\overline{P_{chamber}} - \overline{P_{intake}}}{\overline{P_{intake}}} \cdot 100 \quad [\%]$$

- Cycle-to-cycle variation (σ_{trend}), defined as the variability of cycle pressure trends from the mean-cycle during combustion, i.e. in the first 90 degrees after ignition. In the present paper ignition occurs at degree zero. It was computed as the standard deviation of each cycle from the mean trend:

$$\sigma_{cycle} = \frac{\sum_{i=1}^{s}(p_i - \overline{p_i})^2}{s}$$

With: i = sample; s = number of samples in the 90 degrees after ignition. Then:

$$\sigma_{trend} = \frac{\sum_{j=1}^{n} \sigma_{cycle_j}}{n}$$

With: j = cycle; n = number of cycles per run.

- Emptying angle, defined as the cycle angle at which the chamber pressure reaches its minimum:

$$\theta_{emp} = \theta(\min(P_{chamber}))$$

- Emptying time, defined as the cycle time at which the chamber pressure reaches its minimum:

$$t_{emp} = t(\min(P_{chamber}))$$

3. Results & Discussion

3.1. Variability between left and right element

To analyze deviations between the sides, the chamber pressure sensors were installed on the top left and top right chambers respectively. Figure 4 shows mean chamber pressure (black) and the pressure trace of all the cycles in the run (grey) for the left and right chamber. The vertical dashed lines identify the portion of the rotation where cycle-to-cycle variation was computed (first 90 degrees). A higher variability in the right element is evident; it was experienced in all the runs, as demonstrated by the higher cycle-to-cycle variation (). Figure 5 shows instead the mean trends of intake, left, right, and exhaust pressure. The left chamber (blue) gave higher peak and a faster emptying. Analogous results were found for all tests. The parallel combustion elements are alike from the intake up to the exhaust section, in both geometry, injection line and control system. Thus, the reason of this variation is not easily identifiable. Although the elements are identical, the whole system is complex and consists of numerous components that can introduce noise or actual differences in the process. These disturbances may be of mechanical nature, for example due to uneven amount of fuel distribution, variations in the valve closings, in the sensors installation sites, or in the ignition source positions, or of electrical nature, for example related to the ignition control signal sent to the system. They do not significantly affect the average cycle but strongly influence the pressure peaks during the combustion phase. The source of this noise is still under investigations and will be identified in the future phases of the project.

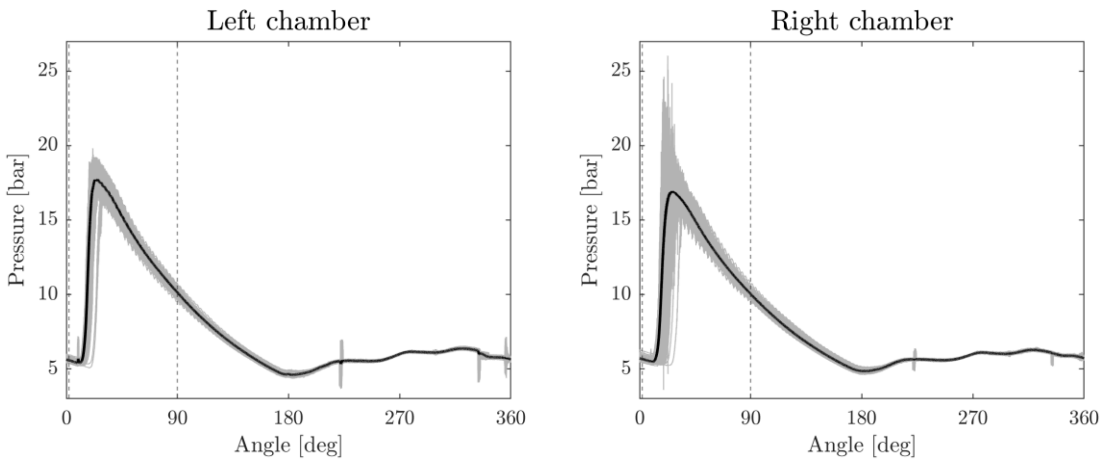

Figure 4: mean (black) and cycles (grey) pressure in left and right elements.

Table 2: Cycle-to-cycle deviation in the first 90 degrees left and right elements.

Test	σ_{trend} Left [bar]	σ_{trend} Right [bar]
1	0.32	0.60
2	0.31	0.47
3	0.43	0.80
4	0.33	0.91
5	0.67	0.91

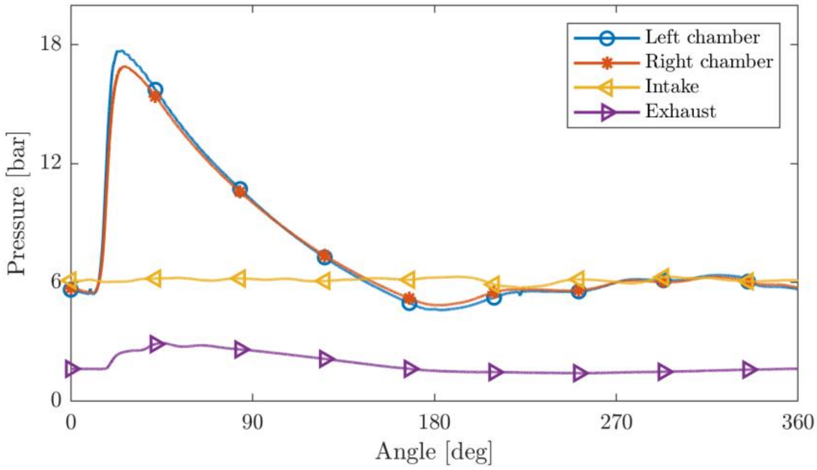

Figure 5: Mean pressure trends for Test n.4.

3.2. Variability between top and bottom chamber

The same analysis was done to investigate differences between top and bottom chamber. Figure 6 shows the cycle-to-cycle variation: in this case the variability between the two is lower, being 0.33 bar in the top and 0.45 bar in the bottom. From the mean pressure trends (Figure 7), it can be noted that there is no delay in the combustion phase: the pressure rises simultaneously in the top and bottom chamber. This result is reasonable, since pressure fluctuations travel at the speed of sound and the chamber characteristic dimensions are quite small. However, the peak reached in the bottom one (red-star) is slightly lower. This result seems to indicate that a small amount of pressure losses is generated during the expansion of the hot gases from the top chamber to the bottom one.

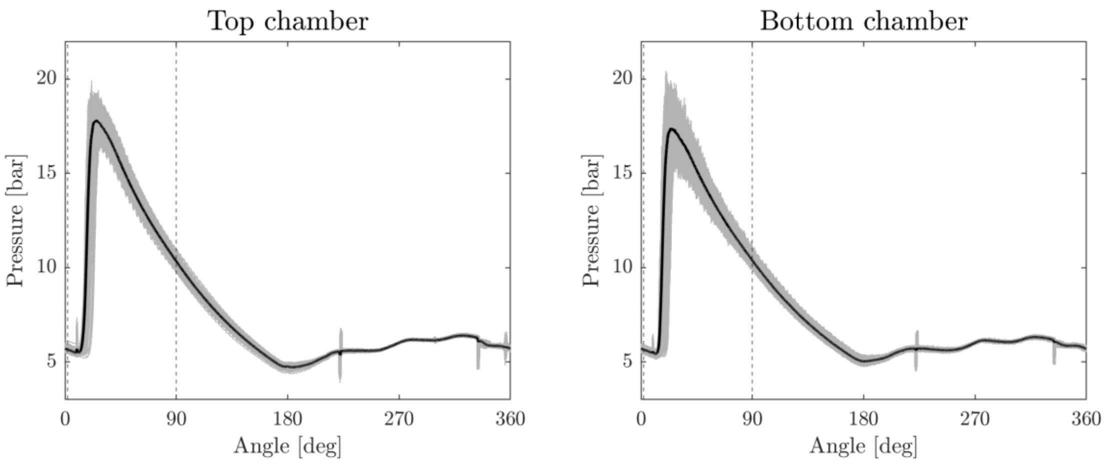

Figure 6: Mean (black) and cycles (grey) pressure in top and bottom chambers.

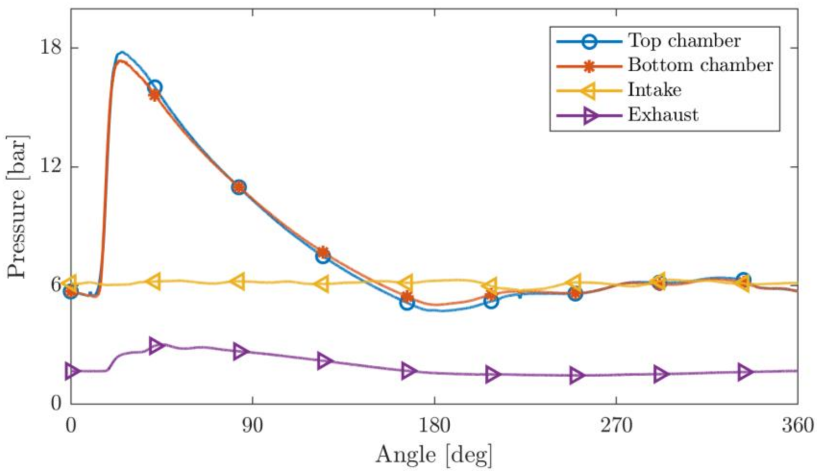

Figure 7: Mean pressure trends for top and bottom chamber.

3.3. Sensitivity analysis

Lastly, the influence of hydrogen supply mean pressure and rotational speed (rpm) was examined. This analysis was performed by looking at the mean cycle of the top left chamber since it was a variable acquired in all test cases. **Figure 8** shows all mean trends (grey). The blue stars indicate the peak pressure value, while the red triangles the minimum value reached after the combustion, i.e. the emptying angle θ_{emp} (left) and time t_{emp} (right). It can be noted that, for all cases, there is no delay in the combustion phase: the pressure rise as function of time is perfectly synchronized (Figure 8 left). Instead, the peak pressure value changes from run to run. Looking at the red triangles, both the emptying time and angle varied during the campaign. Thus, the parameters investigated are peak pressure value, emptying time, and emptying angle.

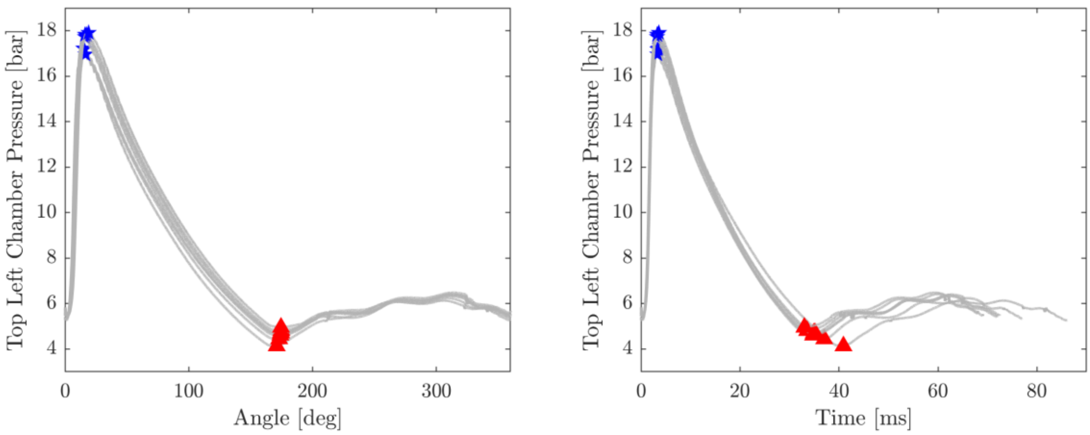

Figure 8: Mean trends in angle based (left) and time based (right)

To investigate the effect of the coupling of rotational speed and fuel pressure on the three chosen variables, we can observe the contour plots in **Figure 9**. The direction of the isolines is an indication of which parameter is predominant in the variable analyzed. The emptying time and angle are function only of velocity. The former decreases with rpm: this is reasonable since, increasing the rotational speed, all the cycle phases take less time to complete. On the contrary, the emptying angle slightly increases with rpm, going from 171 to 175 degrees. This result may indicate that, in the cases tested with lower speed, we didn't reach the optimal timings introduced in Table 1. Indeed, keeping constant the cycle-degree at which scavenging valves open, the optimal emptying angle should be constant: if the exhaust gas flows out too slowly, the chamber pressure remains higher than the intake value when scavenging phase starts, and some exhaust gases may flow in the opposite direction (backflow). On the other hand, if the exhaust gases flow out too quickly, the potentiality of the system is not fully exploited: it is an indication that there could be more room to increase the hydrogen supply pressure or to go faster. The higher emptying angle that ensures a stable operation is considered the optimal one.

As expected, increasing the fuel pressure rises the pressure peak reached inside the chamber. There is also a moderate influence of rpm: this is probably due to the better timings obtained with higher velocities, as previously explained.

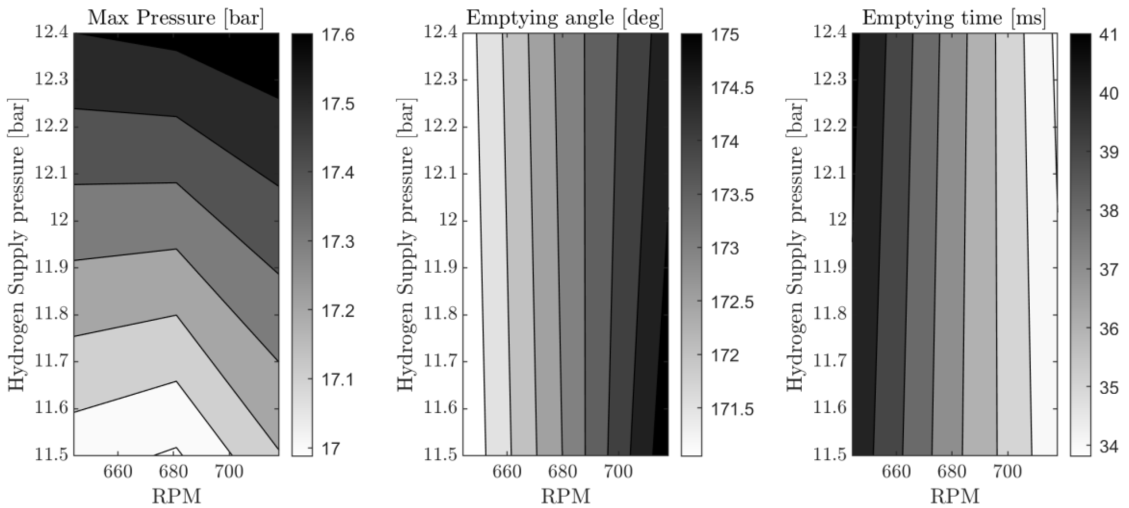

Figure 9: Peak pressure (left), emptying time (center) and emptying angle (right) parametric study.

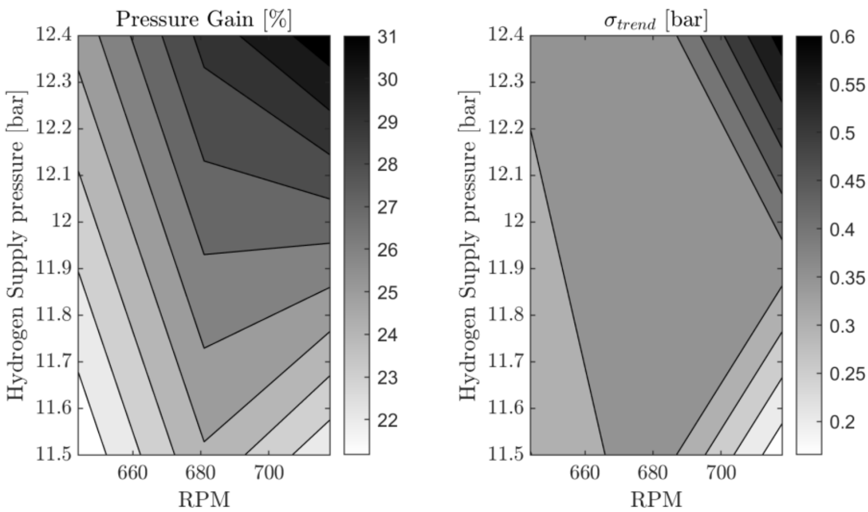

Figure 10: Pressure Gain and cycle-to-cycle variation parametric study.

Lastly, **Figure *10*** shows the Pressure Gain and the cycle-to-cycle variation as function of mean hydrogen supply pressure and rotational speed. The Pressure Gain is the main parameter of interest in PGC combustors since it is the indication of the potentiality of the system. All the values obtained during the experimental campaign, from 21 to 31 %, are considerably higher than those reached in the current state of the art. This is an additional proof of the actual novelty and the capability of the system. Higher

PG was obtained with higher fuel pressure and rotational speed. However, this was the case that gave also higher cycle-to-cycle variation.

4. Conclusion

This paper presents the methodology to experimentally investigate and characterize a novel kind of pressure gain combustor. The activity was carried out by taking advantage of the similarities between the system investigated and an internal combustion engine, and by harnessing the vast knowledge available in the field, from both an experimental and post-processing point of view. Being able to run with 100% hydrogen gave an additional value to the campaign. An indicating system and sensors typically used in ICE applications were installed during the experimental campaign to analyze and monitor the characteristic variables of the process. Results are then presented highlighting the differences between parallel and subsequent chambers. It was noted that, despite an analogous geometry, the left and right side of the combustor experienced different conditions, especially in terms of higher cycle-to-cycle variation. For what concerns the top and bottom chambers, the restrictor between the two influences the pressure peak since some pressure losses are generated during the expansion of the hot gasses through the connective element. Instead, it does not affect the time at which pressure rises during the combustion. Lastly, a sensitivity analysis showed how the pressure peak, pressure gain, and cycle-to-cycle variation are function of both rotational speed and hydrogen supply pressure. These results can give an insight in the combustion phenomena occurring in this novel combustor.

Despite the evident thermodynamic benefit of the Humphrey cycle with respect to conventional Brayton, some crucial challenges still need to be exploited for complete development and future diffusion of Pressure Gain Combustors. Indeed, having a pulsed flow at the turbine inlet causes a significant reduction in its efficiency, and the theoretic cycle advantages decrease drastically. However, in the author's opinion, interest in PGC will exponentially increase in the near future thanks to its potential. There is for sure still room for advanced research: a correct integration between a pulsed flow and the turbine is one of the major challenges to be addressed, and the upcoming developments of the project will include this aspect. From the experimental point of view, a more detailed analysis of air and fuel flows entering the system and an emission investigation will give additional information on the combustor characterization.

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