Notes on Numerical Fluid Mechanics
and Multidisciplinary Design 152

Rudibert King
Dieter Peitsch *Editors*

Active Flow and Combustion Control 2021

Papers Contributed to the Conference "Active Flow and Combustion Control 2021", September 28–29, 2021, Berlin, Germany

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Preface

The efficient conversion of energy to serve societal needs for mobility and improved lifestyle enjoys continuous attention since decades and especially in recent years by initiatives like ‘Fridays for Future’ and others. However, striving for more efficiency poses challenges for conventional energy conversion systems such as gas turbines. Thermodynamically, conventional configurations are limited in terms of further efficiency improvements by maximum temperature allowances to avoid unwanted emissions and ensure sufficient lifetime.

Since many years, energy research in Berlin has focused on the improvement of both the efficiency and effectivity of technical systems. Active flow control (AFC) demonstrated a strong potential to save costs for land, sea, and air vehicles already by reducing drag and increasing lift. The successful collaborative research center CRC 557 Control of turbulent shear flows at Technische Universität Berlin, funded by the Deutsche Forschungsgemeinschaft (DFG), led to a strong recognition of this approach and resulted in a series of conferences, where the findings were discussed with experts in the field. In parallel, pressure gaining combustion (PGC) promised a significant chance to increase thermal efficiency of gas turbines. However, these approaches of more efficient thermodynamic cycles introduce the challenge of unavoidable unsteadiness for adjacent components. In order to increase the operability range of combustors, compressors, and turbines, the effect of highly dynamic processes has thus moved into the focus of research activities.

In order to wide up the view onto the potential of PGC, the CRC 1029 substantial efficiency increase in gas turbines through direct use of coupled unsteady combustion and flow dynamics was proposed, which was granted by DFG in 2012 for a first 4-year period and continued for a second funding period in 2016. The objective is to achieve a higher thermodynamic efficiency of gas turbines, while keeping the additional control and aerodynamic challenges within bounds. Multidisciplinarity has been proven to be required definitely, which is expressed in this volume by the combined authorships from various disciplines. Thermodynamic understanding of energy conversion together with experimental and numerical fluid mechanics needs to be combined with mathematics and control theory in order to create the overall picture. The reduction in amplitude of pressure waves traveling within the system was achieved by the introduction of concepts like the shockless explosion combustion (SEC). Included in this volume are as well results for rotating detonation combustion (RDC), which in this context appears to be a promising concept for the future as well.

A series of successful conferences was set up in the past to convey the results of this detailed research, bringing together recognized experts in these various fields. Starting in 2006 and 2010 with 'Active Flow Control I and II', an interdisciplinary discussion was initiated in the community. This approach was followed later by adding the specific challenges of controlling unsteady combustion in the conferences 'Active Flow and Combustion Control' in 2014 and 2018. The present volume contains most of the presentations given at 'Active Flow and Combustion Control 2021'. The successful format of the preceding conferences was unchanged with invited lectures and single-track sessions only. Not all presenters could prepare a manuscript for this volume, but it still presents a well-balanced combination of theoretical, numerical, and experimental state-of-the-art results of active flow and combustion control.

The papers presented within this volume deal with all different aspects of flow and combustion control. They show the high potential of active measures within the flow and combustion regime, which is partially already demonstrated and partially predicted, when it comes to an improved operation of gas turbines overall and their individual components. While the practical demonstration of the overall concept in an interacting environment of compressor, combustor, and turbine is still pending, the basic understanding of the relevant parameters and influence coefficients is available by now.

All papers in this volume have been subjected to an international review process, supported by an International Program Committee. We would like to express our sincere gratitude to all involved reviewers: B. Atakan, H.-J. Bauer, A. Bauknecht, M. Bellenoue, M. Bohon, B. Boust, J. Braun, T. Breiten, F. di Mare, N. Djordjevic, M. Eck, D. Greenblatt, T. Grönstedt, F. Haucke, M. Heinkenschloss, E. Kaiser, R. Klein, M. Lemke, R. Liebich, R. Mailach, J. Moeck, S. Müller, R. Niehuis, N. Nikiforakis, B. Noack, K. Oberleithner, C.O. Paschereit, H. Pitsch, R. Radespiel, J. Reiss, M. Samimy, H.-P. Schiffer, P. Stathopoulos, J. Wild, D. Williams.

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The members of CRC 1029 are indebted to their respective hosting organizations, TU Berlin and FU Berlin, for the continuous support, and to Springer and the editor of the series Notes on Numerical Fluid Mechanics and Multidisciplinary Design, W. Schröder, for handling this volume.

Last but not least, we are indebted to Mario Eck and especially Steffi Stehr for their irreplaceable support in organizing and administrating CRC 1029, organizing the conference and compiling this volume.

September 2021

Dieter Peitsch
Rudibert King
(Chairmen of AFCC 2021 and CRC 1029)

Contents

Part I: Constant Volume Combustion and Combustion Control

Pressure Gain and Specific Impulse Measurements in a Constant-Volume Combustor Coupled to an Exhaust Plenum

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Abstract. In the framework of air-breathing propulsion, the thermodynamic cycle of turbomachines is likely to be adapted to pressure-gain combustion (PGC) technology, which raises integration challenges. In this study, a constant-volume combustion chamber, fed with air and isooctane, was experimentally coupled to a nozzle assembly featuring a plenum with variable volume and throat diameter. The spark-ignited, direct-fueled combustion chamber allowed for time-resolved measurements of combustion pressure and axial thrust, as well as direct imaging of the reacting flow. The main parameters that drive the cyclic operation of the facility – regarding combustion dynamics and thrust generation – have been recorded as a function of the exhaust geometry, including the air stagnation pressure, the air/fuel equivalence ratio, and the cycle frequency. The pressure gain measured in the exhaust plenum proves to be a relevant parameter of the PGC facility, by representing the increase in stagnation pressure upstream of a turbine in turbomachine applications. The cycle frequency directly drives the pressure gain that reaches up to 31% in our constant-volume combustion facility, which yields an outstanding increase in specific impulse by up to 23% compared to conventional constant-pressure combustion.

Keywords: Pressure-gain combustion · Engine performance · Airbreathing propulsion

1 Introduction

The thermodynamic cycles of current turbomachines are based on a constant-pressure heat release (Joule-Brayton cycle). Thermodynamic cycles in which the pressure rises through the combustion phase (Humphrey-Atkinson) hold a theoretical potential for substantial efficiency gain. Many solutions on how to implement Pressure-Gain Combustion (PGC) exist in the literature. These include rotating or pulsed detonation [1], the auto-ignition of a stratified mixture [2], a confined deflagration in a piston engine [3] or piston-less chambers [4–9].

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The latter was investigated in recent works both experimentally [5] and numerically [6, 7] by LES on a combustion chamber in which the inlet and exhaust systems are rotary valves. The combustion chamber is operated with indirect injection where liquid isooctane is injected upstream of the intake valves in a carburation chamber. The authors addressed the cycle stability including the analysis of both the ignition phenomena and the cycle-to-cycle variation of the flame propagation. Studies on this prototype did not address the effect of the exhaust plenum pressure as it remained equal to the atmospheric pressure. However, downstream pressure is relevant for further integration in a turbomachine, as the turbine operates downstream of the combustion chamber and extracts work from exhaust gases while restraining the flow. The turbine presence could therefore induce the buildup of higher backpressure in the exhaust plenum. Moreover, the unsteadiness of the pulsating exhaust flow can be detrimental to turbine efficiency [10]. To overcome this, the flow unsteadiness should be levelled by introducing either an exhaust plenum with a volume adapted to the combustion chamber or a pulse converter manifold. In a previous study conducted on another CVC device [11], the authors investigated the influence of fixed back pressure on the overall combustion process. Higher back pressure, without or with limited scavenging of the chamber, led to a higher residual burnt gas dilution, which strongly slowed down the combustion and reduced the combustion peak pressure.

Thrust measurement has been previously suggested to measure the performance of such devices [12]. Thus, this article aims at investigating the effect of an exhaust plenum of adjustable volume and throat on the combustion and propulsive properties of a CVC combustor operated in a cyclic, pulsed regime. Particularly, the objectives of this study are to characterize the pressure gain of the facility and its specific impulse in the corresponding conditions. The influence of the main operating parameters will be sought, such as plenum volume, throat diameter, cycle frequency, equivalence ratio and air stagnation pressure.

2 Experimental Setup and Diagnostics

The device investigated in this study is a piston-less constant-volume combustion chamber, as thoroughly described in a previous study [5]. Its basic principle is the opening and closing of intake and exhaust ports by rotating valves that generate two cycles per revolution, so that a single cycle lasts 180° of the valve angle θ. The combustor (see Fig. 1a) is fed with hot, pressurized air generated by an electrical heater (100 kW, up to 200 °C), a dome pressure regulator (up to 0.5 MPa) and a Coriolis mass flow meter (Endress-Hauser 80F40, 0.5% uncertainty). The diameter (80 mm) and volume (65 L) of the air feedline are such that the intake pressure (P_{in}) measured in the intake plenum remains independent of the combustion chamber pressure fluctuations. The pressure sensors used in the intake plenum (P_{in}), combustion chamber (P_{cc}) and exhaust plenum (P_{ex}) are absolute water-cooled piezoresistive sensors, respectively Kistler 4007, 4011 and 4049 (0.2% uncertainty).

The nozzle diameter is selected using two nozzles based on the ISO9300 design with respective throat diameters of 10 and 20 mm, a toroidal convergent and a conical divergent of expansion ratio 1.4 (see Fig. 1b). Meanwhile the combustion chamber volume is fixed (V_{cc} = 0.65 L), the exhaust plenum volume V_{ex} can be chosen by adding spacers upstream of the nozzle. This study involves an exhaust plenum which volume V_{ex} is either: equivalent to the combustion chamber volume V_{cc}, equal to half of it (0.3 L), or higher (1 L). The device assembly (chamber, intake and exhaust plenums) is heated by maintaining a steady airflow at T_{in} = 180 °C. The chamber wall temperature is measured by a K thermocouple, T_w = 100–130 °C. Each test features the cyclic operation of the combustor during up to 4 s, to obtain more than 50 combustion cycles per test.

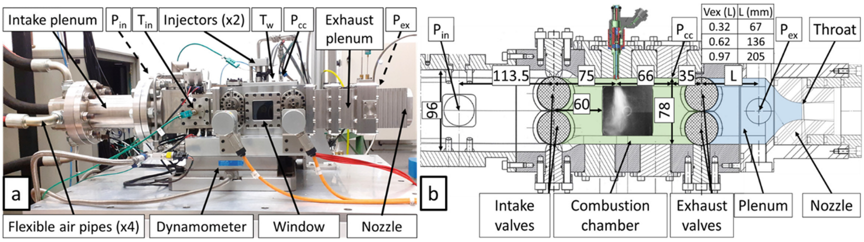

Fig. 1. a) Constant-volume combustion facility, b) Cross-section and dimensions.

The combustion chamber is fueled by direct liquid isooctane injection, with a stoichiometric air/fuel dilution of D_{st} = 15.0. The injection system consists of a 3.6 L vessel filled with isooctane, pressurized by 10 MPa nitrogen, and connected to two GDI injectors (Bosch HDEV 5.2) flush-mounted to the chamber upper wall (see Fig. 1b). The two injectors' total fuel mass flowrate, obtained from the previous measurement [13], is 20 g/s. The overall equivalence ratio in the combustion chamber, denoted OER, is derived from the mass of fuel injected during the cycle, m_f, and from the density of hot compressed air, ρ_{air}:

$$OER = D_{st} \frac{m_f}{\rho_{air} V_{cc}} \tag{1}$$

During firing tests, the spontaneous emission of the flame is recorded by a high-speed color camera (Phantom V310), while the fuel plume is observed by Mie scattering using a high-power halogen lamp (see Fig. 2b). In the visualization window, the fuel plume is roughly 26° wide with a 12° tilt angle (see Fig. 2a). In the orthogonal direction, the plume spans over 42°.

The spray plume penetrates up to 110 mm in atmospheric conditions, so part of the fuel is likely to reach the bottom of the chamber. However, during firing tests the wall-wetting effect is certainly limited by the elevated chamber pressure (0.3 MPa) and hot chamber wall (100–130 °C).

Ignition is performed at the chamber's rear wall, in the visualization area (see Fig. 2b), with a standard non-resistive sparkplug (1 mm gap) 2.5 mm off the wall. A top-plug automobile ignitor placed directly on the sparkplug is used to generate the spark (100 mJ deposit during approximately 2 ms).

The axial thrust of the device, F_x, is measured by a piezoelectric dynamometer (Kistler 9255C, bandwidth 2.2 kHz) that was carefully scaled in-situ. The efforts exerted

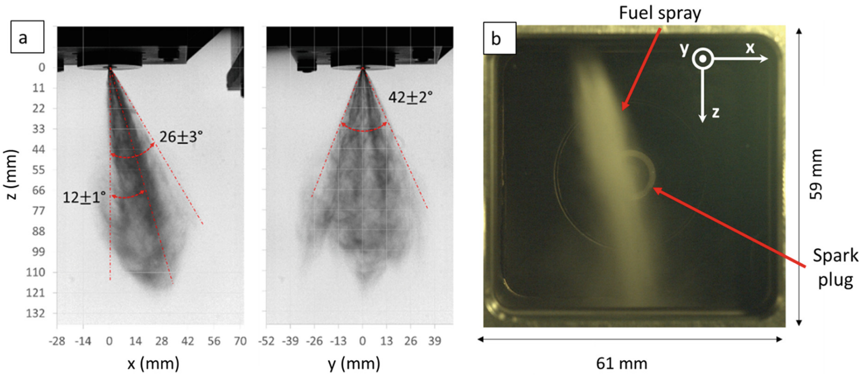

Fig. 2. a) Backlight imaging of a single spray in quiescent air, b) Mie scattering of the two sprays in real flow conditions.

by the flexible hoses that feed air towards the intake plenum have been carefully quantified: their contribution (–3.8 ± 0.25 daN/MPa) is fluctuating cyclically, and remains small compared to the magnitude of thrust obtained in this study. As the working fluid always exerts a thrust on the device, even when inert air flows through the nozzle, removing the thrust contribution of inert cycles recorded before a reacting test is necessary. Thus, in this study, the axial thrust measured during a combustion test is corrected as follows:

$$F_x(t) = F_x(t)|_{combustion} - F_x(t)|_{inert,ensemble-average} \quad (2)$$

A 0D analysis developed, deployed, and validated on another device [13] is used to extract further information, such as the residual burnt gas dilution or the initial temperature, from the pressure traces measured in the chamber.

In summary, this facility offers a fully instrumented, cyclic CVC chamber, with a versatile exhaust assembly featuring variable plenum volume and nozzle diameter. It allows physical analyses of such a PGC device's combustion and propulsion behavior in its operation range, based on time-resolved pressure and thrust measurements, making it possible to derive the pressure gain and specific impulse. In the following, the facility will be implemented using three plenum volumes (0.32, 0.62 and 0.97 L), two nozzle diameters (10 and 20 mm), and its operating conditions will be controlled in terms of air pressure (0.25–4.0 MPa), overall equivalence ratio (0.5–1.5), and cycle frequency (16–50 Hz).

3 Results and Discussion

3.1 Effect of a Nozzled Plenum on the Unsteady Combustor Dynamics

The presence of a nozzle downstream of the combustor is expected to have multiple effects on its operation: it may choke the exhaust flow and subsequently increase the amount of residual burned gas (RBG) in the combustion chamber. In this section, three exhaust nozzle configurations are explored: a 10 mm diameter nozzle, a 20 mm diameter nozzle, and without a nozzle. In this section, the facility is operated at 0.3 MPa, stoichiometry, with a cycle frequency of 16 Hz (hence a 62.5 ms period) to favor air-fuel mixing and ensure a 100% ignition rate. For simplicity, cyclic measurements are plotted versus time t.

Reference Case with an Open Plenum. Without a nozzle, the flow is choked in most phases due to the elevated initial pressure (0.3 MPa); therefore, the boundary conditions are very repeatable, namely the intake plenum pressure P_{in} and the opened exhaust plenum pressure P_{ex}. The intake plenum exhibits a strong but stable pressure fluctuation of ±0.028 MPa (See Fig. 3A). The ignition timing is set to 44.9 ms, which is 12.7 ms after the end of injection. It is adjusted so that most of the combustion pressure peaks occur near the opening of the exhaust valves. The overall equivalence ratio computed with the 0D model is 1.0, and the associated dilution of 1.6%. These values are obtained on the assumption of perfect and continuous gas mixing, especially during the scavenging phase. The dilution is computed based on the CO_2 mass fraction ratio between that at the end of combustion and that at the ignition timing of the following cycle. On the flame pictures (see Fig. 3C) corresponding to the events of a firing cycle (see Fig. 3B), we observe a few rich and sooty areas in the flame, indicated by yellow spots. This implies that the equivalence ratio is locally fuel-lean or stoichiometric, and the mixture is relatively homogeneous. The maximum combustion pressure is of 1.01 ± 0.06 MPa in average and the combustion duration is of $t_{10\text{–}90} = 2.8 \pm 0.3$ ms (from 10% to 90% of the pressure increase). This duration represents well the free propagation of the flame, starting from an ignition kernel to the wall. Both peak pressure and combustion duration are similar to those found previously by the same device operating with a port-fuel injection [5].

Comparison to the Case of A Plenum with Nozzle. In the following, the three conditions investigated refer to the open plenum (without a nozzle), 10 mm and 20 mm diameter exhaust nozzles. The last two configurations are set up with an exhaust plenum of 0.62 L equivalent to the combustion chamber volume (see Fig. 4).

Operating the device with an exhaust nozzle certainly influences the composition of the fresh charge in the combustion chamber. For clarity, pressure traces are normalized by the stagnation pressure recorded in the 65 L reservoir feeding the device with hot air, P_{res}. The average maximum pressure ratio decreases from 3.3 in the open plenum case to 2.8 with a 20 mm nozzle, and 2.3 with a 10 mm nozzle. Meanwhile, the combustion duration $t_{10\text{–}90}$ increases from 2.8 ± 0.3 ms in the open plenum, to 4.0 ± 0.3 ms with a 20 mm nozzle, and 4.9 ± 0.3 ms with a 10 mm nozzle. In the case of the 10 mm nozzle, the nozzle choking prevents the complete scavenging of the plenum, since P_{ex} no longer reaches ambient pressure between two exhaust phases, t = 25–50 ms (see Fig. 4); in turn, this phenomenon also prevents the complete scavenging of the combustion chamber.

Therefore, it is likely that the open plenum corresponds to a well-scavenged, fresh air/fuel charge, whereas the 20 mm and 10 mm nozzles generate an increasing dilution of the fresh gases by RBG, thus decreasing the combustion peak ratio and increasing the combustion duration, as already evidenced in former CVC applications [13]. The

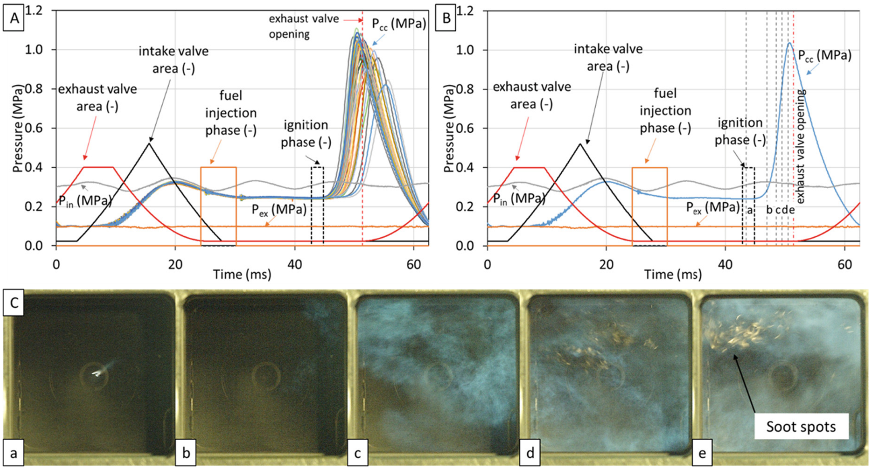

Fig. 3. A) Instantaneous P_{cc} of consecutive cycles, ensemble-averaged P_{in} and P_{ex} from a 3 s sequence without a nozzle. B) Instantaneous pressure traces during a single cycle from that sequence. C) Flame imaging during the combustion phase of that cycle.

air mass flowrate confirms this trend through the facility, which is lower for the 10 mm nozzle (21 g/s versus 58 g/s for the open plenum), and by the RBG dilution computed with the 0D analysis that is higher for the 10 mm nozzle (11.5% versus 1.6% for the open plenum). Consequently, the 20 mm nozzle is selected in the following study to allow for moderate RBG dilution, as the device will be operated at a cycle frequency higher than 16 Hz.

In summary, a nozzled exhaust plenum profoundly affects the behavior of the combustion chamber. The absence of a nozzle favors the complete scavenging of the combustion chamber, whereas the presence of a nozzle allows RBG to dilute the fresh air/fuel charge. Thus, as the nozzle diameter decreases, the combustion pressure is lower, and the combustion time is longer. The exhaust plenum undergoes incomplete scavenging, and its pressure no longer returns to ambient, which may be beneficial to damp the pressure fluctuations upstream of a turbine. Finally, the management of the plenum pressure is a key issue not only for integration purposes but also for the chemical control of the combustion process.

Effect of the Plenum Volume on the Exhaust Dynamics. In this section, three configurations of plenum volume V_{ex} are implemented, namely 0.32 L, 0.62 L and 0.97 L, all using the same 20 mm diameter exhaust nozzle selected previously. As the cycle duration is no longer constant, the signals are plotted as a function of the phase angle θ that ranges 0–180° during each cycle.

For this study, the facility is operated at stoichiometric OER with the same cycle frequency (25 Hz), the same stagnation pressure (0.3 MPa) and temperature (180 °C), the same phasing for injection (θ = 105°) and ignition (θ = 140°). The tests corresponding to the three volumes V_{ex} (see Fig. 5) have a significant success rate of 98% on average. Thrust is delivered over a period corresponding to the opening duration of the exhaust

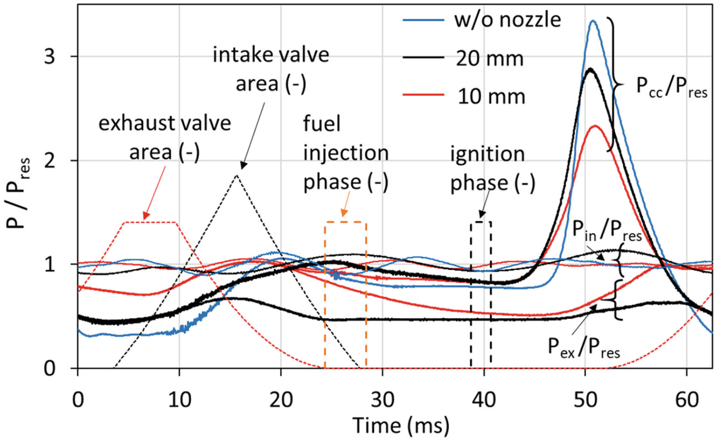

Fig. 4. Normalized instantaneous pressure traces with a 10 mm nozzle (red curves), 20 mm nozzle (black curves) and without a nozzle (blue curves). Plenum volume 0.62 L.

valve; the intake and exhaust sections are respectively denoted by S_{intake} and $S_{exhaust}$. As V_{ex} increases, thrust magnitude increases noticeably. The evolution of thrust over time seems to follow a pseudo-periodic, damped oscillation of apparent frequency 37 Hz, that occurs at exhaust valve opening and vanishes during the constant-volume phase. This oscillation may result from the mechanical excitation of the device structure by the unsteady thrust impulse generated periodically by the nozzle.

Obviously, the plenum volume V_{ex} plays a role in damping the pressure fluctuations generated by the exhaust valve opening: Fig. 5 shows that the fluctuation in P_{ex} decreases with increasing plenum volume. More generally, this effect has been recorded for cycle frequency in the range 25–50 Hz (see Fig. 7b); the time-average magnitude of P_{ex} increases with increasing plenum volume. As a result, the plenum volume drives the instantaneous dynamics of the exhaust pressure and its time-averaged value, which in turn drives the time-averaged thrust.

In summary, the increase in plenum volume yields an increase in the magnitude of the thrust pulse produced during the exhaust valve opening for a given nozzle diameter. For the three plenums implemented in this study, the plenum volume seems to have a marginal effect on the combustion chamber; however, it still drives the dynamics of the exhaust pressure and, subsequently, the thrust of the device.

3.2 Effect of the Main Operating Parameters on the Time-Averaged Combustor Performance

In the following, the effect of cycle frequency, equivalence ratio, and stagnation pressure are investigated and their effect on the performance of the PGC device. The experimental conditions are set to obtain as many secondary cycles as possible, i.e. cycles that take place after a successfully burned cycle because these cycles represent the cyclic operation of a CVC chamber.

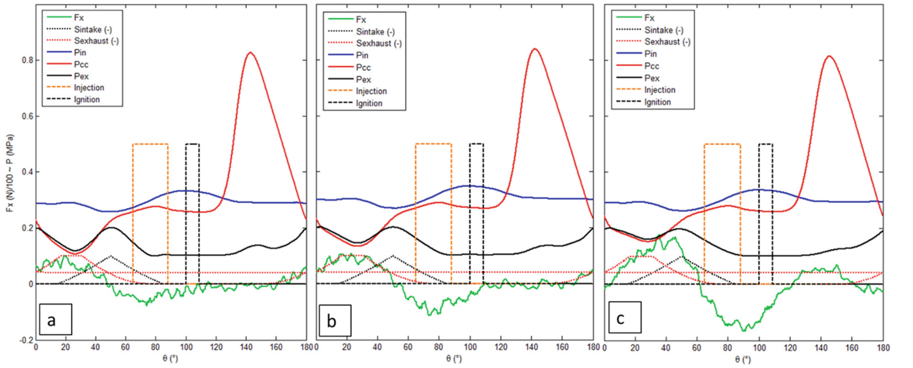

Fig. 5. Ensemble-average of stoichiometric secondary cycles at 25 Hz and 0.3 MPa with a 20 mm nozzle and several plenum volumes: a) 0.32 L, b) 0.62 L and c) 0.97 L.

Effect of Inlet Pressure and Equivalence Ratio. The conditions presented so far involved the same reacting mixture, namely stoichiometric air/isooctane at stagnation conditions 180 °C and 0.3 MPa; in other words, the previous results have been obtained with a constant amount of fuel per cycle. In contrast, this section is dedicated to the respective effects of air supply pressure and equivalence ratio on the average combustor outputs.

The effect of mixture properties is investigated firstly in terms of the air/fuel equivalence ratio (see Fig. 6a), considering the 0.62 L plenum equivalent to the combustion chamber. As opposed to the previous tests, the amount of fuel per cycle is varied accordingly. As usual in such CVC chambers, the maximum pressure ($P_{cc\ max}$) is optimum for near-stoichiometric OER, which corresponds to the minimum value of the combustion time ($t_{10–90}$). As the OER increases, both maximum exhaust pressure ($P_{ex\ max}$) and the time-averaged thrust ($F_{x\ avg}$) increase and reach a plateau for OER = 1.2–1.5. Thus, there is a shift between the optimum OER for combustion (that is 1.1 for $P_{cc\ max}$) and the optimum OER for thrust generation, which may be due to the presence of extra air brought by the scavenging phase. Indeed, the OER has been computed for the chamber volume, whereas the scavenged air contained by the exhaust plenum also contributes to the heat release and thrust generation.

Secondly, the effect of air stagnation pressure P_{res} is observed in the range 0.25–0.40 MPa (see Fig. 6b), as it is known to strongly affect both CVC processes and nozzle flow dynamics. Regarding the combustion phase, the increase in P_{res} yields an increase in $P_{cc\ max}$ and a decrease in $t_{10–90}$. Thus, there is a benefit in operating the combustion chamber at high pressure because it brings a shorter combustion time, which is favorable for operating at high cycle frequency. Moreover, as P_{res} increases, both the exhaust plenum pressure $P_{ex\ max}$ and the time-averaged thrust $F_{x\ avg}$ increase subsequently.

In summary, the combustion process is mainly sensitive to equivalence ratio, as combustion pressure and time are optimal near stoichiometry, and stagnation pressure to a lesser extent. This recalls the usual behavior of premixed flames, in which fundamental flame speed strongly depends on equivalence ratio and temperature, but less on pressure. Thereby, the faster the combustion propagates, the lower the heat loss, and the higher the pressure peak. Regarding propulsion, the air stagnation pressure has a quasi-linear effect on both the time-averaged thrust and the maximum plenum pressure, which is a comparable feature between our unsteady CVC device and classical steady choked nozzles.

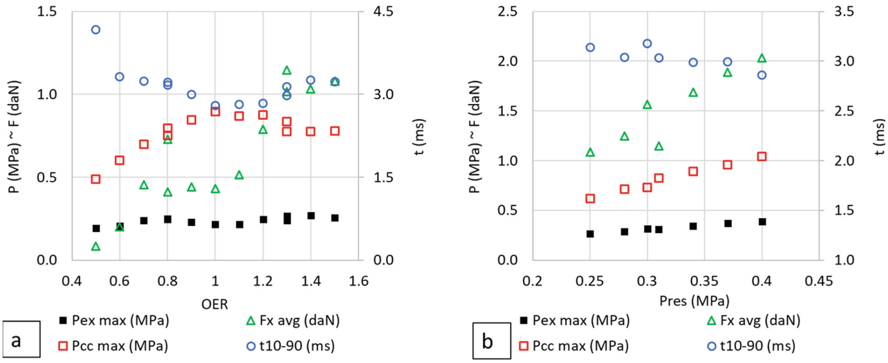

Fig. 6. Combustion and propulsion properties for secondary cycles: a) versus equivalence ratio at 0.3 MPa, 25 Hz and plenum 0.62 L, b) versus air stagnation pressure at stoichiometry, 30 Hz and plenum 0.97 L.

Effect of Cycle Frequency on the Pressure Gain. Overall, the analysis conducted so far evidenced the main parameters regarding the operational performance of the device, regarding either the combustor – that drives the heat release–, or the choked exhaust plenum – that converts it in thrust. Among the operational parameters of the facility, it is clear that the repetition rate of combustion cycles is the main lever to produce thrust. However, one can expect that a higher cycle frequency limits the time allocated to the scavenging phase, which leads to a higher dilution by RBG in the fresh charge. This effect makes cycle frequency a critical parameter regarding the dynamics of CVC systems.

In the following, the intrinsic efficiency of the combustion chamber (resp. of the exhaust plenum) is quantified via the so-called "pressure gain" as usually done in PGC devices. The pressure gain of the combustion chamber is defined as:

$$P_{cc,gain}(\%) = 100 \bullet \left(\frac{P_{cc,avg}}{P_{res}} - 1 \right) \quad (3)$$

The pressure gain related to the combustion chamber is similarly affected by the cycle frequency, whatever the plenum volume (see Fig. 7a). It firstly decreases between 25 and 35 Hz, under the effect of increasing dilution by RBG, as observed earlier (see Fig. 5a–c). Then, the pressure gain increases with increasing frequency. As the cycle duration decreases, P_{cc} gradually reaches equilibrium with P_{ex} during the scavenging phase, and thus its evolution is choked by the throat. This behavior results in converging values of the pressure gain for the combustor and the plenum above 35 Hz (see Fig. 7b). Above this frequency, the cycle duration becomes too short for the fresh charge to burn completely in the combustion chamber. As a result, one can state that increasing the cycle frequency increases the maximum pressure in the exhaust plenum, thus increasing the stagnation pressure upstream of the nozzle, which in turn should contribute to generating more thrust.

The absolute value of the pressure gain, which reaches 31% in the present study at 50 Hz, is quite close to that obtained in another device featuring a PGC turbomachine demonstrator [9], whereby the pressure gain amounts to 28% for a cycle frequency of 13.7 Hz, although thermodynamic conditions differ from the present study.

Finally, in the present experimental device and operating conditions, the pressure gain parameter seems independent of the plenum volume as soon as the cycle frequency exceeds 40 Hz. Therefore, above this threshold of cycle frequency, the operation of our PGC device reaches a regime where the combustor and the plenum act overall as a gas generator with adjustable stagnation pressure. This is a valuable outcome for the PGC system likely to be coupled to a turbine downstream of the gas generator. In the present facility, the choked nozzle represents well the effect of the turbine. As such, a single turbine could be fed by several gas generators featuring a PGC operation. Moreover, the volume of the exhaust plenum was not observed to have a critical influence so that it may be reduced for integration purposes in turbomachines.

In summary, the pressure gain computed in the plenum is a parameter of interest to characterize the efficiency of our PGC device, which reaches a maximum value of 31% in this study. It is more relevant than the pressure gain computed in the chamber, especially at high frequency when the combustion time competes with the cycle duration.

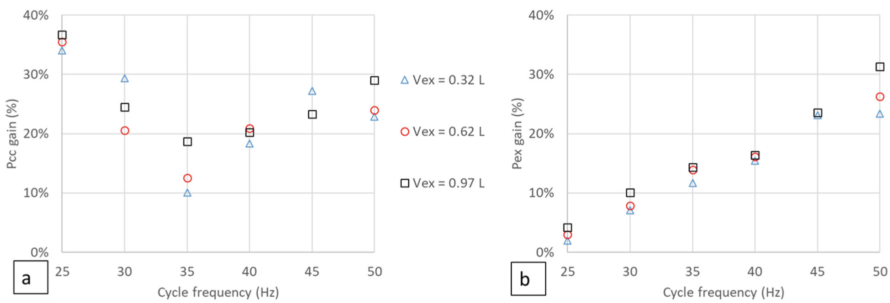

Fig. 7. Effect of cycle frequency on the pressure gain recorded: a) in the combustion chamber, b) in the exhaust plenum. Stoichiometric combustion cycles, 0.30 MPa, 20 mm throat.

Effect of Cycle Frequency on Propulsion Performance. The time-averaged value of thrust $F_{x\ avg}$ is computed in the same operating conditions, as it is a resulting output of the overall system performance. The specific impulse of the device I_{sp} is also derived from thrust, considering the actual fuel flowrate $\dot{m}_f$ and the standard gravity g_0:

$$I_{sp} = \frac{F_{xavg}}{\dot{m}_f \bullet g_0} \tag{4}$$

The time-averaged thrust $F_{x\,avg}$ gradually increases (see Fig. 8a) as the cycle frequency increases, because more cycles are performed during a given time lapse. Noticeably, thrust exhibits the same behavior for the three plenum volumes V_{ex} used in this study; hence these volumes are large enough to allow for successful coupling with the combustion chamber.

To assess the gain in efficiency brought by the pressure-gain technology, the specific impulse resulting from our CVC device is compared to the specific impulse that would be obtained if the same plenum and nozzle were fed by a Constant-Pressure Combustion (CPC) chamber, i.e. the same process as would be implemented in a simple turbojet operating with the same compression ratio (3:1). For this purpose, the thermodynamic properties (composition, temperature, specific heat ratio) of the burned gas resulting from the CPC of air and isooctane are computed with the same initial conditions (pressure, temperature, equivalence ratio) as in the CVC facility, based on usual assumptions: isobaric combustion, chemical equilibrium and adiabaticity. Then, the thrust of the CPC process is obtained by expanding this pressurized flow of burned gas through the same nozzle as in the CVC facility (nozzle pressure ratio and geometry). This method is essential to assess the difference in efficiency between the CVC and CPC processes, despite minor drawbacks. Firstly, current turbomachines cannot sustain the elevated temperatures (up to 2000 °C) obtained in this near-stoichiometric CPC computation, which clearly makes the comparison theoretical. Secondly, our CVC facility is subjected to wall heat losses, whereas the CPC computation is adiabatic, which is rather realistic owing to the thermal management of optimized turbomachine chambers; this comparison might therefore be detrimental to the CVC process due to experimental heat losses.

As a result, the CVC process offers an improvement in specific impulse compared to the CPC process as the pressure gain reaches approximately 25% (see Fig. 8b), above a cycle frequency of 45 Hz. Indeed, in such conditions, the specific impulse of the CVC cycle exceeds that of the CPC cycle by 4%, 5% and 23% for the plenum volumes 0.32 L, 0.62 L and 0.97 L, respectively. The largest plenum volume (0.97 L) may favor the gain in performance by allowing better scavenging of the combustion chamber, while reducing the influence of the exhaust plenum on the combustion chamber (backpressure and dilution by RBG). As suggested by Fig. 8b, cycle frequency plays a critical role in the increase in pressure gain that, in turn, drives the propulsion performance of the PGC device. However, a physical limit may be encountered when increasing the cycle frequency: the time necessary for combustion (several ms, see Fig. 6), as well as for other phases of fluid transfer, is likely to compete with the cycle duration.

In summary, the cycle frequency directly affects the thrust delivered by the PGC device. Compared to a CPC chamber operating in the same conditions with the same nozzle, our CVC facility yields an increase in specific impulse (up to 23%) that seems to be driven by the pressure gain. This is all the more noticeable as the CPC computation is adiabatic, while the CVC data proceed from real experiments with heat losses.

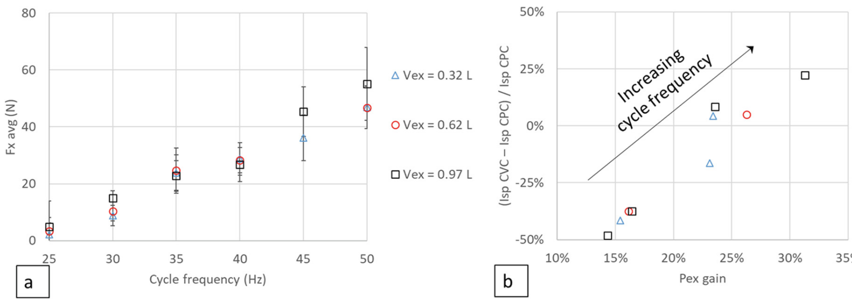

Fig. 8. Effect of cycle frequency: a) on time-averaged thrust, b) on the improvement of specific impulse by the PGC device. Stoichiometric combustion cycles, 0.30 MPa, 20 mm throat.

4 Conclusion

This article reports the experimental study of an air-breathing pressure-gain combustion (PGC) facility, featuring a constant-volume combustor (CVC) coupled to an adjustable exhaust plenum. The facility was operated with compressed air (0.25–0.40 MPa, 180 °C) and direct-fueled isooctane. The operation of this facility showed the interactions between the CVC chamber and the exhaust plenum, based on the physical outputs of the device, such as the pressure gain and the axial thrust.

As the nozzle diameter decreases, the amount of residual burned gas in the combustion chamber increases, which affects the heat release process: the diluted combustion regime exhibits a longer combustion time and lower combustion pressure. The effect of the air/fuel equivalence ratio, which was set in the range 0.5–1.5, showed the usual optima of combustion pressure and duration at stoichiometric conditions. Investigating the cycle frequency in the range 25–50 Hz revealed its key effects on the system dynamics: as the cycle frequency increases up to 35 Hz, the residual burned gas dilution increases, which in turn decreases the pressure gain in the combustion chamber. At cycle frequency above 35 Hz, this effect is alleviated as the flow exiting from the combustor gets choked by the nozzle throat, so that the pressure gain is the same in the chamber and in the plenum.

It is noticeable that – whatever the plenum volume – the pressure in the exhaust plenum increases almost linearly with increasing cycle frequency, and so does the time-averaged thrust and the specific impulse. For comparison purposes, the specific impulse of a constant-pressure combustion (CPC) chamber coupled to the same nozzle is computed with the same compression ratio. Although the present CVC facility is not adiabatic, its specific impulse noticeably exceeds the ideal CPC process by up to 23%.

Finally, the pressure gain in our CVC facility reaches around 31% at 50 Hz, which means a 31% increase in the stagnation pressure of the gas generator. The pressure gain in the exhaust plenum remains a critical parameter for such PGC applications, as it drives the inlet pressure of a turbine located downstream. Thus, designing PGC-based turbomachines will require optimizing the plenum feeding by single or multiple CVC chambers.

References

1. Kailasanath, K.: Review of propulsion applications of detonation waves. AIAA J. **38**(9), 1698–1708 (2000). https://doi.org/10.2514/2.1156
2. Reichel, T.G., Schäpel, J.S., Bobusch, B.C., Klein, R., King, R., Paschereit, C.O.: Shockless explosion combustion: experimental investigation of a new approximate constant volume combustion process. J. Eng. Gas Turbines Power **139**(2), 021504 (2016). https://doi.org/10.1115/1.4034214
3. Kaiser, S., Seitz, A., Donnerhack, S., Lundbladh, A.: Composite cycle engine concept with hectopressure ratio. J. Prop. Power **32**(6), 1413–1421 (2016). https://doi.org/10.2514/1.B35976
4. Tarnawski, P., Ostapski, W.: Pulse-powered turbine engine concept implementing rotating valve timing system: numerical CFD analysis. J. Aerosp. Eng. **32**(3), 04019017 (2019). https://doi.org/10.1061/(ASCE)AS.1943-5525.0001001
5. Boust, B., Michalski, Q., Bellenoue, M.: Experimental investigation of ignition and combustion processes in a constant-volume combustion chamber for air-breathing propulsion. In: AIAA–Joint Propulsion Conference (2016). https://doi.org/10.2514/6.2016-4699
6. Labarrere, L., Poinsot, T., Dauptain, A., Duchaine, F., Bellenoue, M., Boust, B.: Experimental and numerical study of cyclic variations in a constant volume combustion chamber. Combust. Flame **172**, 49–61 (2016). https://doi.org/10.1016/j.combustflame.2016.06.027
7. Exilard, G.: Large Eddy Simulation of Constant Volume Combustion in a Ground-Breaking New Aeronautical Engine. Paris Saclay University, Paris (2018)
8. Michalski, Q., Boust, B., Bellenoue, M.: Experimental investigation of ignition stability in a cyclic constant-volume combustion chamber featuring relevant conditions for air-breathing propulsion. Flow Turbul. Combust. **102**(2), 279–298 (2019). https://doi.org/10.1007/s10494-019-00015-1
9. Salminen, H.J., Ciccateri, F., Ijäs, T., Ulmala, O., Mikulski, M.: Experimental demonstration of a novel deflagration-based pressure gain combustion technology. In: AIAA–Joint Propulsion Conference (2020). https://doi.org/10.2514/6.2020-3871
10. Watson, N., Janota, M.S.: Turbocharging the Internal Combustion Engine. Macmillan Education, London (1982)
11. Michalski, Q., Boust, B., Bellenoue, M.: Toward a cyclic self-ignited constant-volume combustion for air-breathing propulsion applications. In: AIAA–Joint Propulsion Conference (2018). https://doi.org/10.2514/6.2018-4478
12. Kaemming, T.A., Paxson, D.E.: Determining the pressure gain of pressure gain combustion. In: AIAA–Joint Propulsion Conference (2018). https://doi.org/10.2514/6.2018-4567
13. Michalski, Q., Boust, B., Bellenoue, M.: Influence of operating conditions and residual burned gas properties on cyclic operation of constant-volume combustion. In: King R. (ed.), Active Flow and Combustion Control 2018, vol. 127, pp. 215–233. Springer (2019). https://doi.org/10.1007/978-3-319-98177-2_14

Control of Auto-ignitive Wave Propagation Modes from Hot Spots by Mixture Tailoring in Shockless Explosion Combustion

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Abstract. Shockless Explosion Combustion is a novel combustion concept that achieves pressure gain combustion by quasi-homogeneous auto-ignition of the fuel/air mixture. Shockless Explosion Combustion is, like other combustion concepts based on auto-ignition, prone to premature ignition and detonation formation in the presence of reactivity gradients, so called hot spots. Two measures to inhibit detonation formation and to achieve quasi-homogeneous auto-ignition, dilution and fuel blending, are investigated by means of zero-dimensional simulations of generic hot spots. Experimental ignition delay times measured in a high pressure shock tube are used to select suitable chemical-kinetic models for the numerical investigation and the calculation of temperature sensitivities of ignition delay times. The main focus of this investigation are the two non-dimensional regime parameters ξ and ε, as they enable characterization of the mode of auto-ignitive wave propagation from hot spots. ξ is the ratio between the speed of sound and the auto-ignitive wave propagation velocity and ε describes the ratio between the time a pressure wave travels through the hot spot and the excitation time. Dilution of the combustion mixture with steam and CO_2 aims at extending excitation times and therefore decreasing the parameter ε. Fuel blending of Dimethyl ether with hydrogen or methane aims at reducing the temperature sensitivity of ignition delay time and low values of ξ. It is demonstrated that both measures are effective at mitigating detonation development while maintaining quasi-homogeneous auto-ignition in presence of hot spots.

Keywords: Ignition delay time · Excitation time · Knock · Auto-ignition · Detonation peninsula · Dilution · Fuel blending

1 Introduction

The novel combustion concept Shockless Explosion Combustion (SEC) is a way to implement pressure gain combustion in a gas turbine [1]. It promises a substantial increase in efficiency over a conventional gas turbine cycle [2,3], while it

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circumvents the disadvantages associated with using detonation waves to achieve pressure gain combustion like high pressure peaks or deflagration-to-detonation and exergy losses [1].

In SEC the pressure rise is achieved by quasi-homogeneous auto-ignition of the fuel-air mixture. The ensuing pressure wave generated by the volumetric heat release is reflected at the end of the combustion chamber as a suction wave. It is used to refill the combustion tube with a fresh fuel-air mixture to initiate the next combustion cycle. The quasi-homogeneous auto-ignition that is required for the process is achieved by matching the residence time of the fuel-air mixture in the combustion chamber with its ignition delay time through fuel stratification. Realizing quasi-homogeneous auto-ignition in a real combustion environment demands on-the-fly control of fuel stratification and is still a topic of on-going research [4]. Nevertheless, it is experimentally proven that the homogeneity of ignition correlates with the pressure increase in SEC [5,6].

Combustion concepts that are based on auto-ignition are prone to detonation formation and inhomogenoues ignition. Premature ignition in a local spot with increased reactivity can lead to the development of undesired detonation waves. These local spots with increased reactivity are here referred to as hot spots and can be caused by a temperature or concentration gradient. This is not only a challenge for SEC, but also for different auto-ignition based combustion concepts such as HCCI (homogeneous charge compression ignition) [7]. Detonation development from hot spots can be explained with the SWACER (Shock Wave Amplification by Coherent Energy Release) mechanism [8]. Premature ignition leads to localized heat release. This local heat release causes a pressure rise, which propagates as an acoustic pressure wave. If this pressure wave is in phase with heat release resulting from the auto-ignition of subsequent discrete mixture volumes along the reactivity gradient, the heat release can reinforce the pressure wave and a detonation wave may form.

Zeldovich et al. [9] demonstrated the importance of the temperature gradient of the hot spot for detonation formation. Different modes of auto-ignitive wave propagation can be initiated depending on the value of the temperature gradient [10]. Premature ignition along the reactivity gradient of the hot spot generates an auto-ignitive wave. In the following a hot spot with a temperature gradient is considered as in the analysis in [11]. The velocity of the ensuing auto-ignitive wave u_{ai} that results from the gradient in ignition delay time $\partial\tau_i/\partial r$ can be expressed by the temperature gradient of the hot spot $\frac{\partial T}{\partial r}$ and the temperature sensitivity of ignition delay time $\frac{\partial \tau_i}{\partial T}$ [11],

$$u_{ai} = \left(\frac{\partial \tau_i}{\partial r}\right)^{-1} = \left(\frac{\partial \tau_i}{\partial T}\frac{\partial T}{\partial r}\right)^{-1}. \tag{1}$$

When the auto-ignitive wave velocity is close to the speed of sound, the pressure wave is reinforced by the heat release and a detonation wave may form. However, when the auto-ignitive wave velocity exceeds the speed of sound characterizing the pressure wave propagation, reinforcement of the pressure wave by the heat release is not possible and the auto-ignitive wave will propagate without being affected by pressure waves as a supersonic auto-ignitive wave. In the limiting case of infinite auto-ignitive wave velocity the gas auto-ignites homogeneously as a thermal explosion. When the auto-ignitive wave velocity is below the speed of sound, wave propagation occurs with two different propagation mechanisms depending on the velocity: subsonic auto-ignitive propagation, which is driven by the reactivity gradient in the hot spot and flame propagation, which is driven by diffusive processes.

The aim to classify the wave propagation led to the development of non-dimensional parameters ξ and ε [11]. The non-dimensional parameter ξ normalizes the speed of sound of the gas a to the velocity of auto-ignitive wave,

$$\xi = \frac{a}{u_{ai}}, \tag{2}$$

and expresses the influence of the auto-ignitive wave velocity on the propagation mode based on the work of Zeldovich [10] which is discussed above. In theory, the heat release of the auto-ignition can reinforce the pressure wave when ξ equals one, i.e. the auto-ignitive wave propagates with a velocity at the speed of sound, and detonations may occur. In practice, lower and upper bounds in ξ are defined for detonation formation depending on the conditions and fuel/oxidizer mixture, as the initial temperature gradient of the hot spot may change during the induction period [11]. This is attributed to heat conduction, mass diffusion and gas expansion [11]. For small values of ξ the regime of supersonic auto-ignitive wave propagation is observed, while subsonic auto-ignitive wave propagation appears at large values of ξ. A second non-dimensional parameter ε is proposed, to account for the rapidness of heat release rate, which is expressed by the excitation time [11]. It describes the ratio of the transit time of an acoustic wave though the hot spot relative to the excitation time of the gas τ_e, which is the characteristic time scale of the heat release,

$$\varepsilon = \frac{r_{hs}/a}{\tau_e}, \tag{3}$$

where r_{hs} describes the radius of the hot spot. Small values of ε indicate that heat release is much slower than acoustic waves traveling through the hot spot. Therefore, reinforcement of the pressure wave becomes less likely.

To classify modes of wave propagation from a hot spot a regime diagram as $\xi - \varepsilon$ diagram has been proposed [11]. The area in regime diagram where detonation formation is observed is usually referred to as detonation peninsula.

Furthermore, a criterion is proposed to discern whether detonation formation is possible [12–14]. If the excitation time τ_e is much longer than the difference in ignition delay time between the hot spot and the surrounding gas $\Delta\tau_i$, the surrounding gas ignites before the formation a of detonation wave is possible. Only for negative $\Delta\tau_i$ premature ignition appears in the hot spot that can possibly lead to the formation of a detonation wave. Hence, in the case of premature ignition the following condition

$$\left|\frac{\Delta\tau_i}{\tau_e}\right| < 1 \tag{4}$$

is fulfilled when the surrounding gas ignites before a detonation wave can form. The criterion in Eq. (4) has also been used to classify experimentally observed detonation transition [15].

In the following it is demonstrated, that the condition in Eq. (4) can be reformulated in terms of the non-dimensional parameters ξ and ε. $\Delta\tau_i$ can be expressed by the mean ignition delay time gradient $\overline{\frac{\partial\tau_i}{\partial r}}$ and the radius r_{hs} of the hot spot,

$$\Delta\tau_i = -r_{hs}\overline{\frac{\partial\tau_i}{\partial r}} = -r_{hs}\bar{u}_{ai}^{-1} \tag{5}$$

and can thus be related to the mean auto-ignitive wave velocity $\bar{u}_{ai}$. In other words, the difference in ignition delay time $\Delta\tau_i$ equals the time that the auto-ignitive wave that originates at the maximum reactivity in the hot spot needs to reach the surrounding gas. As the temperature sensitivity of ignition delay time may vary with temperature, also the ignition delay time gradient and auto-ignition velocity may vary within the hot spot. Therefore, the mean values $\overline{\frac{\partial\tau_i}{\partial r}}, \bar{u}_{ai}$ are chosen such that relation (5) holds. The ratio in criterion (4) can be rearranged using Eq. (5) for the case of premature ignition in the hot spot to

$$\left|\frac{\Delta\tau_i}{\tau_e}\right| = \frac{r_{hs}\bar{u}_{ai}^{-1}}{\tau_e}\frac{a}{a} = \frac{a}{\bar{u}_{ai}}\frac{r_{hs}/a}{\tau_e} = \xi\varepsilon, \text{ for } \overline{\frac{\partial\tau_i}{\partial r}} > 0. \tag{6}$$

Thus, when premature ignition appears in the hot spot the formation of a detonation wave is suppressed due to the auto-ignition of the surrounding when the following condition holds,

$$\xi\varepsilon < 1. \tag{7}$$

While it is shown above that the product of ξ and ε can be used interchangeably to the ratio $\frac{\Delta\tau_i}{\tau_e}$ to discern suppression of detonation development for the case of auto-ignition of the surrounding gas, it has also been used in the literature to distinguish between auto-ignitive wave propagation and deflagration [16,17]. It is proposed that values of $\xi\varepsilon$ over 1500 are associated with deflagration [16]. However, the border between both propagation modes is not very sharp [16].

Temperature or concentration inhomogeneities that may cause premature ignition are always present in technical systems, which also pose a challenge for SEC. Both detonations, as well as subsonic auto-ignitive wave propagation are to be avoided in SEC, as it is not designed for the former and the latter results in burned gas expansion with insufficient pressure gain. SEC requires supersonic auto-ignitive wave propagation or thermal explosion to a achieve (quasi-)homogenous ignition even in the presence of hot spots, i.e. low values of ξ and/or ε.

The parameters that influence the wave propagation mode are highly dependent on the physicochemical properties of the fuel-air mixtures and the thermodynamic conditions. Especially, the ignition and heat release characteristics of a mixture, namely the temperature sensitivity of ignition delay time and the excitation time, play an important role for the mode of auto-ignitive wave propagation. This enables tailoring of the mixture with focus on these properties. In this work two approaches are investigated: the extension of excitation time by dilution with CO_2 and steam [14,18], which is targeted at decreasing ε; and decreasing temperature sensitivity of ignition delay time by fuel blending [19,20], which is targeted at decreasing ξ.

Dimethyl ether (DME) is used as a fuel, respectively fuel component, in both investigations. The reason is that it is suited for auto-ignition based concepts due to its relatively high reactivity [21]. DME's negative temperature coefficient (NTC) behavior, i.e. an increase in ignition delay time with increasing temperature within a certain temperature range, makes it suitable as a fuel blend component. Due to the application of SEC in gas turbines, usually similar conditions as in conventional gas turbines are of interest [19]. Rähse et al. [2] demonstrated, that a gas turbine with SEC achieves a significantly increased efficiency for pressures between 24 and 50 bar and temperatures between 823 to 1039 K. For the investigations in this study a thermodynamic condition of 35 atm and 887 K, is chosen which resembles the condition at the inlet of a gas turbine combustor. It is determined by compression from ambient conditions with a pressure ratio of 35 and a compression efficiency of 90%.

The overall goal of this study is to assess the impact of dilution and fuel blending on the non-dimensional detonation parameters in the presence of hot spots.

2 Experimental and Numerical Methods

In order to determine the temperature sensitivity of ignition delay time and choose suited chemical kinetic models to investigate the effects of the proposed mixture tailoring, ignition delay times are measured behind reflected shock waves in a high-pressure shock tube. Detailed information about the facility and the measurement procedure can be found in [20,22,23].

Zero-dimensional homogeneous reactor simulations are performed for both, the choice of the chemical-kinetic model and the determination of the relevant gas properties for the calculation of ξ and ε as explained below. The reactor models are implemented in *Python* with the software package *Cantera* [24]. Excitation time is defined as the time that elapses between 5% of the maximum heat release rate and the maximum heat release rate. This definition is very common and used in e.g. [11,18,25]. Furthermore, it is chosen because it is also used in the simulations in [25–27], which the obtained results will be compared to.

Generic hot spots of a defined radius and fixed temperature gradient are used to investigate the effect for the two investigated measures, i.e. dilution and fuel blending. Equations (2) and (3) are then used to calculate the respective ξ and ε parameters, utilizing excitation times and temperature sensitivity of ignition delay time determined by reactor simulations.