Forced pulsed flow regime for developing and possibly operating innovative, high-performance, low-emission burners

Symposium on Thermoacoustics in Combustion: Industry meets Academia (SoTiC 2025)
Sept. 09 – 11, 2025
Trondheim, Norway,
Paper No: 38
©The Author(s) 2025

Fabrice Giuliani[1], Andrea Hofer[1], Nina Paulitsch[2], Alexander Sigg[3], Johannes Hofer[3], Markus Dielacher[3], Lukas Andracher[4]

Abstract

The phenomenon of thermoacoustics was first observed in the 19th century as a curiosity (“the singing flame”), and then found its first application in a propulsion system in the early 20th century (the Schmidt tube). After remaining marginal in the face of the development of other technologies, thermoacoustics was studied again in the mid-twentieth century due to problems arising in rocket engines. It was then studied increasingly at the end of the twentieth century due to similar problems arising in high-power, high-compression-ratio gas turbines. Our research team has over 25 years' experience in this field, and this article focuses on the siren device we developed for experimental thermoacoustics research.

The basic idea is to use the siren as an exciter to generate a thermoacoustic phenomenon in a thermal system. This application relates to the field of acoustics, where pressure fluctuations are an infinitesimal fraction of the ambient pressure, and to the analysis of resonant phenomena, where the dynamic reaction amplitude of the thermal system is enormous compared to the excitation amplitude. Compared with other systems, such as loudspeakers, the siren has the advantage of operating robustly and durably under industrial conditions. Developed in the context of experiments on gas turbine burners, we have perfected a siren system that decouples frequency from modulation amplitude. The first part of this paper explains how the siren works and gives an insight on the methods developed for its applications. Two opposing case studies are then presented. The first application addresses the question of whether an innovative gas turbine burner is stable. The second application involves using the siren to fine-tune and improve combustion performance through adaptive pulse combustion.

More precisely, the first application connects to the Recursive Sequential Combustion (RSC), that combines the recirculation of burned gases into the combustion zone with the principle of sequential combustion, using the annular shape of the combustor to capture a continuously recirculating quantity of burned gases. The incentive is to produce robust lean combustion, more robust than conventional lean burners due to the higher heat conservation. The challenging aspect of this technology is the shape of the combustor, where the burners are arranged behind each other in a loop, with the inlets and outlets at the sides. Therefore, ensuring stable combustion is paramount.

The second application connects to the BLUETIFUEL project, which focusses on improved combustion of non-carbon fuels, and more particularly the safe, low-NOx combustion of hydrogen. The other non-carbon fuels studied here are ammonia and hydrogen sulfide, for energy or sulfur processing applications (e.g., sulfuric acid production or off-gas cleaning). Compared to conventional premixed burners, BLUETIFUEL technology incorporates two innovations. The first is improved premixing for fast-reacting mixtures, combining fuel placement with rapid mixing to create an aerodynamically-stabilised flame in the low-swirl category. The second innovation is thermoacoustic forcing at ad hoc frequencies using a siren.

Keywords

Siren, Recursive Sequential Combustion, pulse combustion, forced flow dynamics, hydrogen combustion, fast premixing, low emissions, NO_x reduction, mathematics to shape.

Introduction

Although it has become challenging to speak positively about combustion, we must acknowledge its role as a pillar of the modern world's energy system. It is present in virtually every sector and generates four-fifths of the primary energy demand. Combined with an agile global economy and growing population, hydrocarbon consumption is expected to rise until at least 2030 [1]. The problem is that, despite the services it provides, conventional combustion consumes our fossil capital without moderation. The massive release of greenhouse gas emissions seriously disrupts our environment and endangers the human project [2].

Among the technical solutions that will enable us to gain time - in other words, to make better use of the fossil fuel capital we have left - and/or to compensate for this capital by using new fuels, there are the possibilities of improving conventional combustion systems on the one hand, and producing new combustion systems using new fuels such as hydrogen on the other.

This paper discusses two applications in which controlling combustion stability is essential. Both applications involve developing high-performance burners. The first is a highly promising low-emission combustion system called sequential recursive combustion (RSC) that delivers lean, robust combustion. In principle, it is compatible with the full range of available fuels. In this case, it is essential that the combustion remains stable. The second application involves the complete, low-emission combustion of non-carbon fuels. While hydrogen burns well due to its high reactivity, this is not always the case for other fuels, such as hydrogen sulphide or ammonia, which are less reactive. In contrast to the first case, here we desire combustion instability. The idea is to induce thermoacoustic coupling in a hydrogen pilot flame to support and improve the performance of the main flame, which may be fuelled by a less reactive fuel.

What these two studies have in common is the equipment used, in particular a siren developed by Combustion Bay One e.U. (CBOne) as part of its research in thermoacoustics. The article describes this equipment, and the methods employed. Two applications are presented, both of which produced satisfactory results. The aim is to introduce these technologies in the short term to alleviate the climate emergency as quickly as possible.

1. Desired & undesired thermoacoustics: the development context of CBOne's Siren

1.1. Context of development

Continuous flow machines such as gas turbines, or any industrial thermal process involving a continuous flame, are understood as operating under steady-state conditions at defined stations with constant pressure. Enthalpy calculations and energy balances are established under stationary conditions, and changes can be considered to be to be quasistatic. However, it is known that under certain conditions, at a given operating point or during a transient, the process can become unstable and generate what is known as combustion instability.

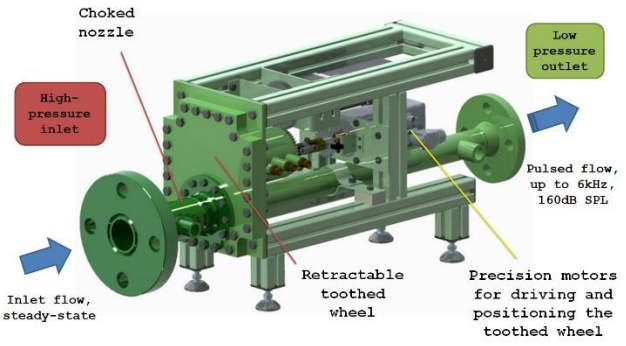


Figure 1: CBOne' siren E. Designed to operate under gas turbine conditions, it can drive thermoacoustic phenomena in combustors up to 40 bar.

The thermoacoustic phenomenon, also known as combustion instability, occurs when there is a natural transition from a stationary combustion regime to a resonant regime, in which the noise of the flame and the vibrations it generates reach considerable proportions. A combustion instability in a high-power, high-pressure system can cause severe structural damage in a short amount of time. For example, Ref. [3] shows a premixing module tested for the aeronautical industry that was destroyed during a brief testing period. The main elements of such a coupling are the unsteady heat release, which exchanges energy with the acoustics of the environment, i.e. the unsteady pressure in the flame. This can influence the fluidics and lead to unsteady transport phenomena such as vortex detachment, that impacts the unsteady heat release. And so on.

These undesired effects appear when testing a combustion chamber or thermal system. Although the current level of modelling allows the detailed simulation of combustion instability phenomena, predicting them in new systems prior to testing is not trivial. Detailed simulations begin once the conditions conducive to instability are known. It is possible to predict which lengths, volumes, and abrupt transitions are likely to encourage resonances in particular frequency bands. However, estimating their likelihood or degree of severity is still difficult. This is the reason why experimentation is required, and tools such as the siren are necessary. They identify the dangerous situations based on an empirical approach, by forcing the flow resonance. This statement is limited by the fact that the siren disturbs the acoustic system simply by being present. However, experience and practice make it possible to address this issue and identify the characteristics specific to the burner by dissociating the source terms.

In the case of pulsating combustion, where this coupling is exploited, thermoresonators have evolved over time. Initially, they were developed for their playful aspect; De Rijke wanted to build an organ based on this principle. Then, they were developed academically through the work of Rayleigh, leading to applications in propulsion, such as the Schmidt tube and the V1, and heating, such as the work of Reynst. However, pulsed combustion remains anecdotal compared to conventional systems. The noise it generates and its lack of adaptability are the two main reasons for limited interest in it.

Nevertheless, the literature demonstrates that pulsed combustion can significantly increase combustion efficiency by up to 5% (Zinn [13]), for example, and offer advantages such as total combustion and low NOx emissions. Since noise and vibrations take place in the hot core, these can be damped or muffled if weight and congestion are not a problem. According to the same source, the most important benefits of pulse combustion are complete fuel combustion due to the strong turbulence governing the flame, that can be seen as a shaker. Zinn comments that "pulsation usually increase the rates of mass, momentum and heat transfer" and reports about fuel savings in the 5 percents range, due to the fact that strong pulsations transform continuous

constant pressure combustion into a periodic, batch combustion process including a low pressure phase that feeds in the reactants followed by an intense combustion phase at a slightly higher pressure than ambient, resulting in a higher heat extraction without involving moving parts. The benefit of using pulse combustion is therefore double: the combustion is complete on the one side, and there is a potential for efficiency improvement of several percent on the other.

If industry were to exploit the benefits of pulse combustion at large scales, the potential fuel savings would be enormous.

1.2. CBOne's Siren E

The siren model "E" (Combustion Bay One e.U., Graz, Austria, see Figure 2) is a flexible device that generates pulsations up to 6 kHz. Our siren technology can vary the amplitude of the pulsation independently of the frequency. It is the latest development of several models used since Giuliani's PhD. The first upgrade was a precision frequency automation (2008), followed by the decoupling frequency-amplitude (2011). Later models followed with the Kölner Dom procedure (2016), the high frequency range 6 kHz relying on a slot-nozzle, and the multi-modal excitation (2020). After that, the model "E" for energy was developed to comply with the flow conditions of a modern large gas turbine under elevated operating pressure ratio (e.g. OPR above 30). The technology is detailed in [14].

Its basic principle is based on the cyclic shear of a critical jet by means of a rotating tooth wheel. The pressure step necessary to generate the critical jet can go up to 40 bar, making pulsations in the 150 dB SPL possible. The amplitude is varied independently from the frequency by reducing or augmenting the sheared surface of the jet. The figure highlights this technical detail, where an excentric chassis is used to control this effect.

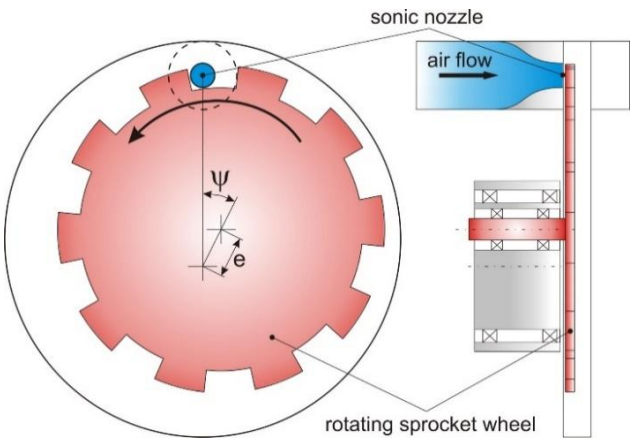


Figure 2: CBOne's siren technology can set the pulsation amplitude independently from the frequency. The principle of retractable rotating wheel in comparison to the nozzle location using an off-axis chassis is shown, enabling amplitude variation. The larger the periodic coverage of the nozzle section, the stronger the pulsation.

1.3. Adaptive pulse combustion

While the major research effort in the field of thermoacoustics is focused on avoiding combustion instabilities to guarantee safe operation, the proposal is to exploit the positive aspect of the same phenomenon. In that case, the thermoacoustic coupling is actuated on demand in a flexible manner to improve combustion. This is called adaptive pulse combustion.

The CBOne team has been involved in thermoacoustics research for around 25 years, with two main aims: to understand combustion instabilities and to achieve flexible and adaptive control of pulsating combustion. One continuous work stream is the siren presented in this paper. This research has also led to the development of peripheral instruments and methods, including a combined optical-acoustic probe [4].

Our incentive is that if the learning curve of constant pressure combustion meets the limits of what is technically feasible (e.g. always higher operating pressure ratio), the field of pulse combustion offers potential fuel savings one cannot ignore. Therefore, we propose augmenting a steady, safe industrial burner into a flexible, on-demand tunable pulse combustor based on the approach shown in Figure 3.

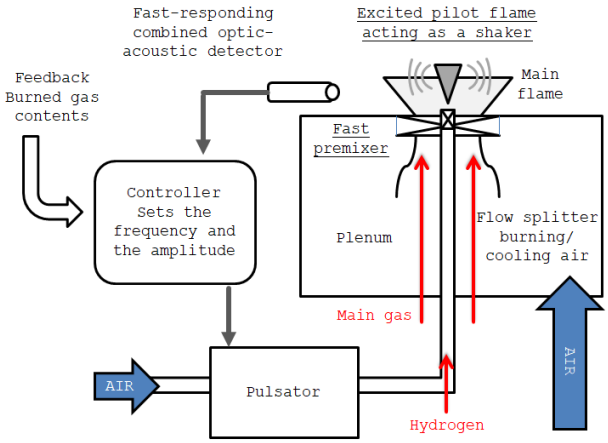


Figure 3: set-up for enhanced combustion performance using adaptive forced pulsation.

The empirical characterization of the „good and bad" frequencies of the combustor is done using the "Kölner Dom" procedure shown in Figure 4. The siren performs frequency sweeps on the flame, possibly repeated with different excitation amplitudes. The frequencies of interest detected during the sweeps are then studied one by one, with a sensitivity analysis of the amplitude. At the same time, the combustion performance is monitored. One of these excitation frequencies could be advantageous, e.g. in terms of flame robustness near the lean blow-out limit, and/or in terms of complete combustion, low NOx, low CO, low soot…

Attention was paid to the fact that the burner has no natural self-excited combustion instability. It is designed to sustain a thermoacoustic instability only when excited, so that the augmented burner performance happens "with on-demand thermoacoustics" only.

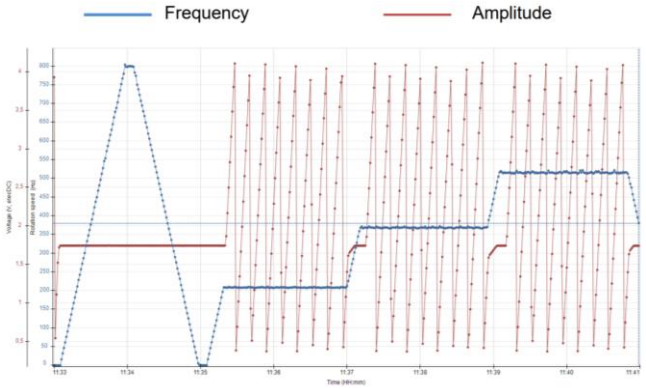


Figure 4: The Kölner Dom procedure.

Figure 5 shows a detail of the previous procedure, highlighting the match between the flame's sound and its flickering at a given frequency. A thermoacoustic coupling happens at these frequencies.

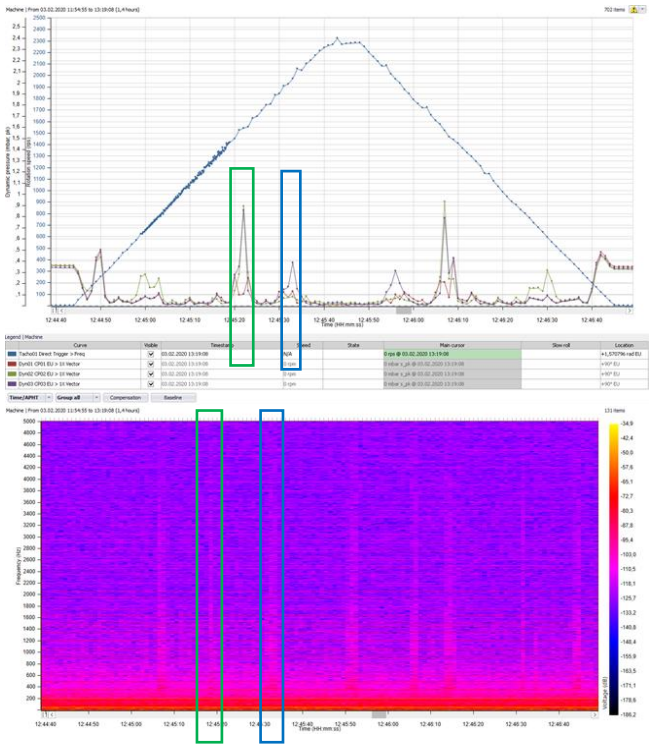


Figure 5: Experimental determination of the excitation frequency of the siren. Top: the graph plots a frequency sweep up and down, as well as phase-locked fast pressure measurements. Bottom is the spectrogram of a photodiode signal observing the flame. A match in frequency means a thermoacoustic coupling. These frequencies can be investigated in the next step.

One could therefore imagine a siren permanently installed on a ground-based thermal system.

For both applications shown in the following, the siren was used at low power.

2. First application: combustion stability in a recursive sequential combustor

The most promising combustion solution in terms of emissions is lean premixed combustion [5]. However, while this technology is well suited to stationary gas turbines, the low margin against lean blowout and the fact that this type of combustion is prone to provoke combustion instabilities pose an unacceptable risk in aeronautics. Therefore, aero-engines rely for example on staged burner solutions, where a pilot flame operating close to the equivalence ratio guarantees the presence of a flame, or on architectures that allow a rapid transition from a rich to a lean flame using a Rich-Quench-Lean combustor. The most promising lean technology for aviation is lean direct injection, which operates at a higher operating pressure ratio so that the higher compressed air temperature makes combustion robust [6].

Over the last two decades, alternative solutions have been developed to find alternative ways of maintaining elevated temperatures in the hot core at conservative operating ratios. For example, flame-flame interaction can be improved by tilting and tiling the burners, as in the Short Helical Combustor [7]. More radical solutions consist in discharging the burnt gases from a first combustion stage into a second combustion stage, this is called sequential combustion [8].

Recursive sequential combustion combines the features and advantages of the last two examples by trapping a volume of gas that has been burnt in the annular combustor. The burners are arranged in a loop and partially discharge their burnt gases into the next one. The flow dynamics are organised by the pressure cascade from the compressor diffuser to the turbine inlet vanes, or more precisely by the injection dynamics and the momentum flux ratio between the inlets and outlets of the recursive sequential combustor.

The expected benefits are robust, lean, low NOx, low soot and low CO combustion when using conventional fuels, and a better NOx performance when using hydrogen. Other benefits could be a better flame propagation at ignition along the combustor annulus, a broader lean operation and a more compact combustor design due to the orientation of the flames along the circumference of the combustor rather than in the direction of the engine flow.

While the possible combustor geometries to achieve and exploit this RSC benefit are shown in the following, we discuss one configuration called discrete sector in detail. A question that often arises is about the stability of the process, i.e. whether the modes associated with the annular boundary cause combustion instability. This aspect is currently under investigation, using forced flow modulation by means of a siren. We show below that so far this is not the case, which is promising for the development and deployment of RSC technology.

2.1. Recursive sequential combustion

CBOne works since 2020 on this concept, first stand-alone in the frame of the MOeBIUS project (Momentum-Enhanced Blend of Reactants and Recirculated burned gases), then with partners in the frame of the crystAIr project (Artificial intelligence and sensing driven burners) in the fields of materials and digital techniques (Joanneum Research GmbH) and the company Piezocryst GmbH (fast pressure sensors). Lately, a program investigating the compatibility of the RSC with replacement fuels has been started with the Technical University of Graz in the frame of the MOeBIUS.H project.

Figure 6 shows the RSC principle. The effect of circulating about 20% by mass of the burnt gases is to preheat the reactants (reaction enabler) while dissolving the oxygen content (reaction brake). The process requires a time lag in which the fuel, fresh air and burnt gases can interact before they start to burn. The reburning effect occurs with conventional fuels where the fresh fuel interacts with the burnt gases, resulting in the reduction of the NO content by CH radicals issued from the conventional fuel into N_2 and H_2O [5]. The most obvious feature of the RSC is the novel orientation of the flames. The idea of a more compact combustor can be seen below with a geometry called constant section RSC, where a multitude of flames are placed behind each other like the braids of a rope, forming a ring of fire.

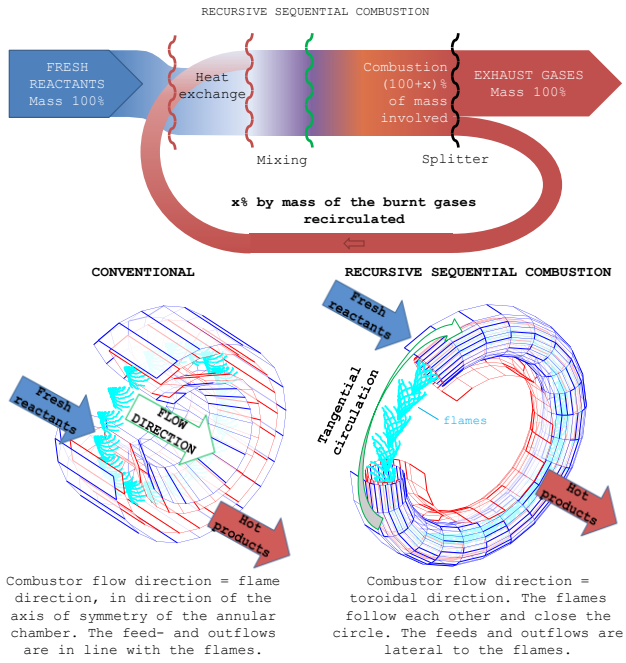


Figure 6: The principle of recursive sequential combustion .

Figure 7: Ultimately, the constant section RSC is the combustor shape we want to develop for aeronautics. Our previous publications have reported on the sizing and flow plausibility of the concept, including CFD studies. While the shape of the reactor can be produced conventionally, we have also verified the feasibility of using additive technology to produce these shapes.

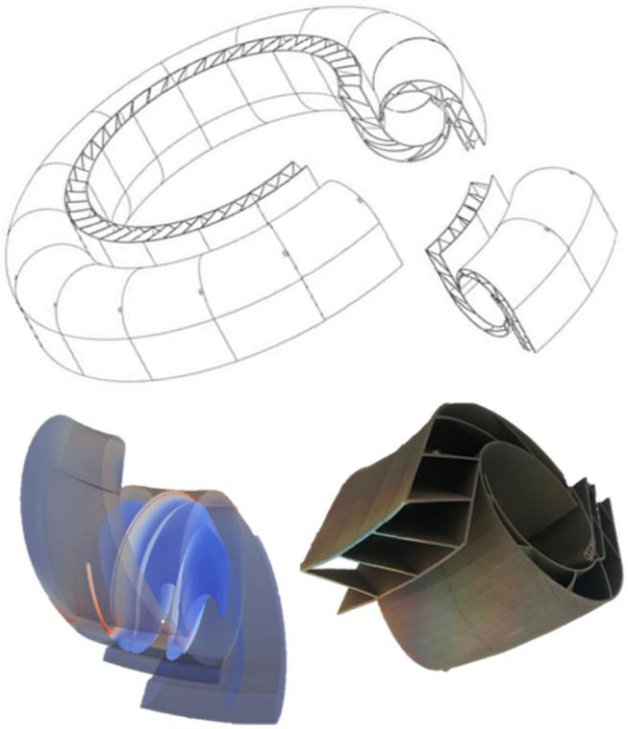


Figure 7: A vision of the aeronautic RSC, called constant section concept. Bottom: flame flow pattern evolving in the flame tube computed with CFD, and feasibility study using additive manufacturing of Inconel 718.

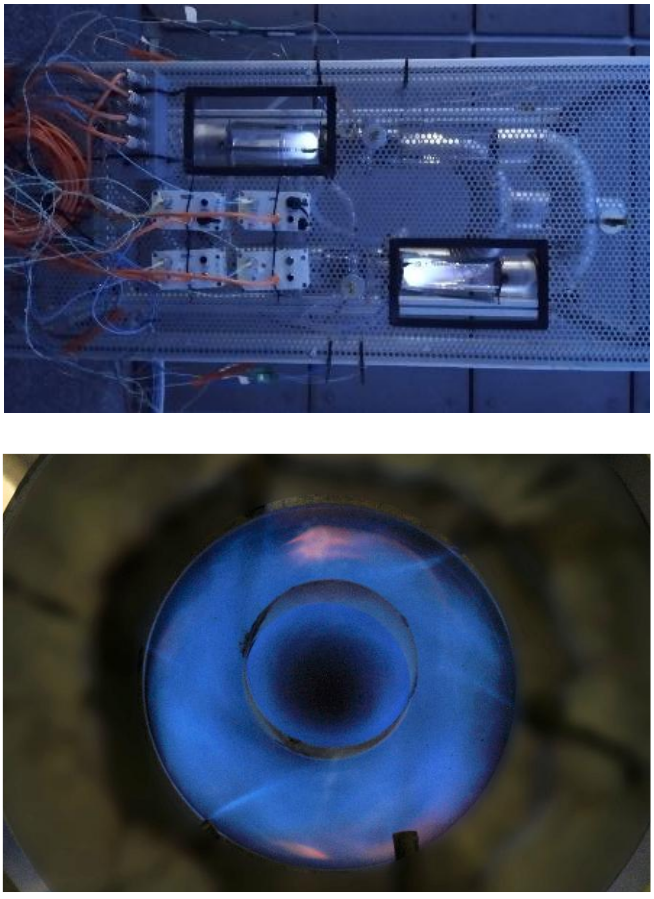


Figure 8: RSC atmospheric demonstrators. Top: the discrete sector RSC demonstrator with two burners in a loop. The burned gas collector is situated behind. Bottom: Ring of fire in a constant section configuration.

Figure 8 shows the atmospheric test set-ups of both RSC architectures. These demonstrators are used at the moment mostly with propane and butane.

The discrete sector concept (DSRSC) has two burners in a loop. The total thermal power ranges from 4 kW at start-up to 20 kW at full load. Most experiments are done at 10 kW. The current limitation is the temperature on the instruments, we therefore do not exceed 500°C on the burner temperature yet. Early tests were done with good success using hydrogen on a single discrete burner, where the hydrogen could premix with air and burn without flash-back.

The joint study MOeBIUS.H with the Technical University of Graz focuses on the combustion of new fuels, such as hydrogen, in this constant cross-section geometry. The demonstrator used for that purpose is shown in Figure 8, where the fuel is butane. The flow dynamics meet the flow designed in Figure 7. Assessments on the operability and on the combustion performance are a work in progress.

2.2. The discrete sector concept, for demonstration purposes

In the following we discuss mostly about the discrete sector concept, that allows to separate the flames and eases the interaction between burnt gas and fresh reactants. Experiments were conducted mostly with propane, with a few single burner tests with hydrogen.

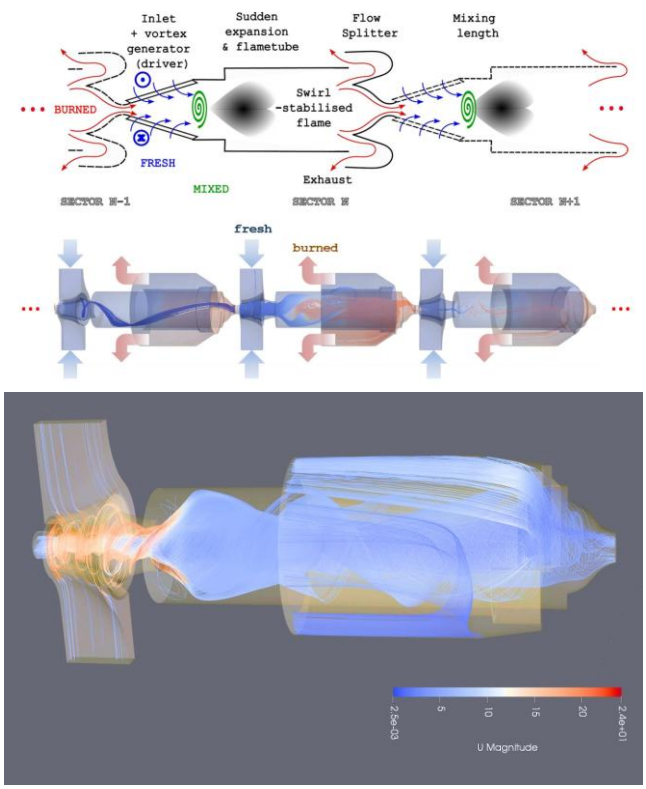


Figure 9: The discrete sector concept. Top: arrangement of the sector, imagine a closed loop of N sectors. Middle: intake and burnt gases management. Bottom: a detail of the flow dynamics. The circulation drive is generated by the vortex generator at the fresh air intake. The fuel injection takes place in the vortex generator.

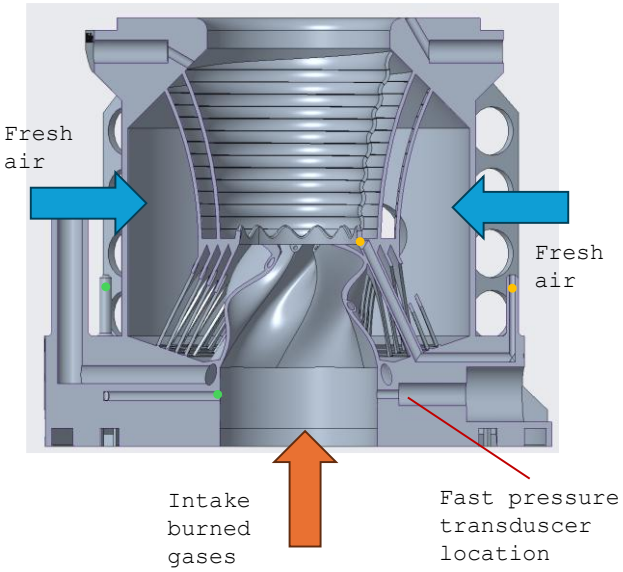


Figure 10: Cut view of the burner of vortex type with a large intake, additively manufactured.

Figure 9 details the discrete sector concept. All essential subfunctions for the flow conditioning are represented.

Figure 10 shows a detail of a single burner. It draws burned gases from below along its center line. The aspiration dynamics are due the fresh air flowing in the vortex generator, creating a depression. This is where the fuel is injected.

Figure 11 : Concerning fuel placement, the first decision was to inject the fuel over a low number of points at high speed, expecting an effective premixing during its rapid passage through the generator vortex. This was a poor technical decision, also confirmed by CFD: the mixing was not effective as intuitively thought. It resulted in a partially premixed flame leading to production of soot and CO.

There was therefore one design iteration, keeping the aerodynamics mostly unchanged but acting on the fuel placement. We therefore reverted to a more distributed multi-point injection, resulting in a much better premixing flame and complete combustion.

2.3. Flame stability analysis

Figure 12: The siren model “E” discussed previously (Figure 2) excites or the flow in the loop via the feed air of one of the two burners when built in RSC mode, or it feeds the axial air when the burner is studied alone. Prior to that test, it was verified on one single burner that no particular combustion instability would be produced on a single burner, combusting in the open, when pulsating the tangential or axial air inlets.

With a distance of 0.8 m between the burners and a total distance of 1.6 m, and an average temperature of 800 K in the burned gases at a low-power test point where the flame is particularly loud, we expected to see a fundamental mode appear at around 350 Hz and observe its subharmonics. However, nothing of the sort has happened yet.





Figure 11: A design detail of the hot gas intake, the fuel injection (see the holes on the tip of the sketches), with a dramatic impact on the combustion quality. No more diffusion flame is visible with the multipoint injection.

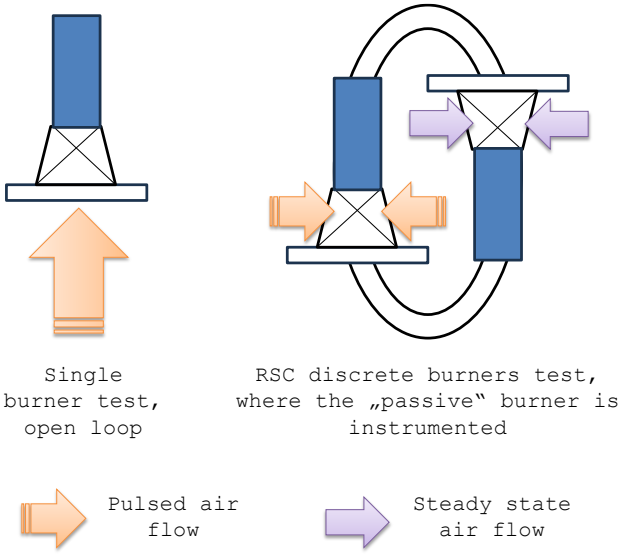


Figure 12: Combustion stability tests. Left: first configuration with an isolated burner combusting in the open, where the axial air flow is pulsed by the siren. Right: RSC configuration with two discrete burners, where the tangential air feed of one burner is pulsed by the siren.

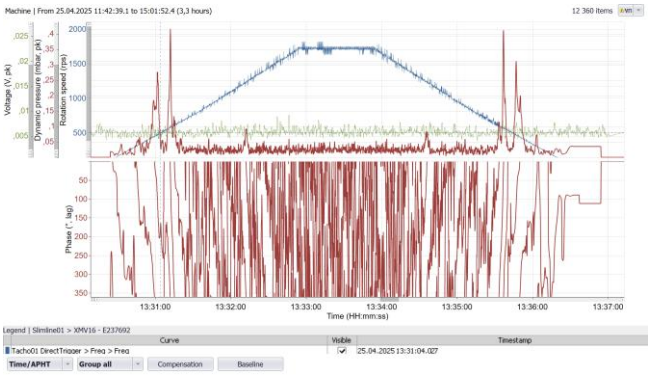


Figure 13: Typical stability test. The blue curve shows the frequency sweep of pulsed air injected into the burners. The red curve shows the acoustic response and marks two peaks in the 450 and 550 Hz region. The green curve corresponds to the photodiode signal, that reports no such flame dynamic.

Figure 13: a combustion instability should be marked by a peak appearing on both the acoustic and the optic sensor that monitor one of the two flames. So far, no such instability could be provoked. Which is good.

A similar stability test will soon be organized on the constant section configuration from Figure 8, by actuating only one angular sector of the annular chamber.

3. Second application: Enhanced combustion performance of an advanced hydrogen burner using thermoacoustic tuning

BLUETIFUEL stands for “Blue flames for low-emission combustion using non-carbon eco-fuels”. This project is part of the thermal exploitation of fuels that could gradually replace conventional fuels, with a view to decarbonising the energy and process sectors and part of the transport sector (aviation). Further applications lie in carbon free metallurgical furnaces (e.g. ladle furnaces). More specifically, this project is looking at hydrogen, ammonia and hydrogen sulfide (e.g. the by-product needed to produce sulphuric acid, with ammonia and sulphuric acid being two major industrial products of the modern economy).

Although conventional combustion processes for these products are well advanced, there is still room for improvement. Hydrogen, for example, presents problems of thermal NO_x production when burned as a jet flame (diffusion flame) and also causes problems of flashback or combustion instability when burned as a lean premixed flame to avoid NO_x emissions. The other two fuels are more difficult to burn due to their lower calorific value and, in the case of ammonia, produce large amounts of fuel NO_x.

BLUETIFUEL proposes to improve the combustion of these ecofuels by applying two levers. The first lever uses staged combustion and produces a swirl stabilized premixed flame where the pilot stage is supplied with hydrogen. The pilot flame provides the energy input, in turn supporting complete combustion of the other two fuels injected by the main stage. To ensure optimal premixing of these fuels with air, a rapid premixing geometry ensures ideal fuel

placement by exploiting the local turbulence and shaping the flow of what becomes a swirl-stabilised flame.

The second lever relates to combustion stability. Recent techniques for the adaptive control of flame dynamics, developed to combat combustion instabilities, can also be used to force a thermoacoustic coupling that has a positive effect on the performance without compromising engine safety. This is achieved with the help of our siren, tuned to excite resonant flame frequencies that result in an improved mixing prior to combustion (the pulsation in the flow generates a better fuel vapor diffusion), and a better performance in terms lower NO_x production (the pulsed, wrinkled flame occupies less volume, the transit time through the flame is shorter and generates less thermal NOx).

The results on using these levers to improve combustion performance of tests carried out in the kW and early MW ranges are summarized in the following.

3.1. Fast premixer design using additive manufacturing and mathematics to shape

One incentive of the BLUETIFUEL study is to generate a swirl-stabilised flame of premixed hydrogen-air, that minimizes the chances to anchor the flame at the premixer's tip and therefore avoid flashback.

This design approach is more in accordance with conventional gas turbine burner design [10]-[11], than with novel surface distributed microflames such as in the Micromix concept [12], in order to better fit with the acoustic drive described below.

CBOne has gained experience over the last decade in additive manufacturing (AM) design of burners. Modern 3D printing technologies allow to create complex component geometries that would have been unfeasible just a few years ago. The benefits of this technology include rapid prototyping, a monolithic approach as opposed to multiple parts, system integration of additional features such as gas injection or ignition, and advanced thermal management of the monolithic component, which better dissipates heat than a composite part.

Figure 14 shows the premixer geometry. One of the most interesting features of AM is the freedom of design. This allows the design of a thermal machine part to match the flow as closely as possible, making it ideal for fluid mechanics applications.

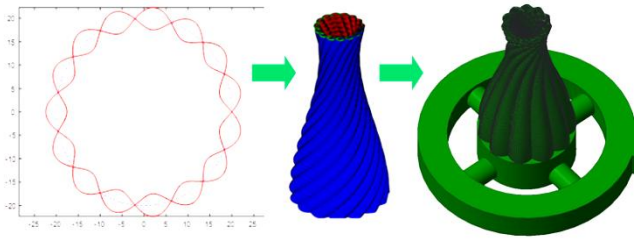


Figure 14: Shaping the fast premixer with help of a parametric curve, extruded and twisted to generate the best possible interaction between the reactants on the shortest possible path.

One current limitation of AM is the wall surface quality, that does not meet standards required for injection fuel nozzles. These need to be machined separately.

Knowing that, we took advantage of the fact that hydrogen needs rather large passages to try a new approach, with the aim of distributing evenly the fuel at the tip of a fast premixer, while giving the fuel a strong swirling motion. Figure 14 shows the parametric curve we used to define a surface, so that the fuel can flow within the cells drawn on the periphery. So that we do not discuss a flow through a pipe arranged in the thickness of the wall anymore, but we arrange a lenticular passage between two walls. This tentative was a success.

This thinking bringing equations and geometrical shapes together allows flow transformations calculated on a corner of a table to be implemented in a direct manner, using analytical approaches that are sometimes faster than numerical methods for counting areas or volumes. We call this approach "Mathematics to Shape".

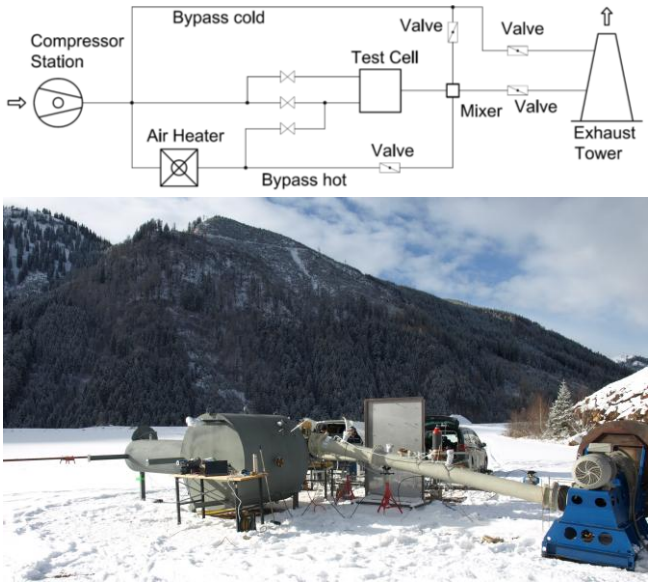


Figure 15: Test set-up in the MW range realized at the Erzberg premises. Top: the main machinery components, where the Test Cell corresponds to Figure 3.

3.2. BLUETIFUEL Set-up

The BLUETIFUEL set-up was shown in Figure 3. It combines fast premixing of the fuels with adaptive forcing, via an excited pilot flame. Since lean premixed hydrogen is very responsive to thermoacoustics, this effect is used.

The premixing geometry discussed before is used at least in the pilot stage, which is fed – partly or totally – by the pulsed air coming from the siren. At specific frequencies, a thermoacoustic coupling takes place resulting in a strong deformation and a strong dynamic of the flame. In turn, the pilot flame is a strong shaker at the heart of the main flame, bringing in the benefits of a strong pulsation. Therefore, the burner must be shaped so that it does not self-oscillate without siren control, a feature of the fast premixer.



Figure 16: The MW BLUETIFUEL burner as seen from the end of the 3 m long, 2 m diameter combustor. The burner outer diameter is 400 mm. The burner is an AM part made of Inconel 718.

3.3. Summary of results in the kW range

The following observations could were made on the demonstrator in the kW range: the fast premixer met the objectives in terms of rapid mixing, steady-state and pulse operation were possible under safe conditions, significant decrease in NO_x at given frequencies for all the three fuels were observed when using the siren, plus a few improvements in terms of equipment and methods. Interestingly also the fuel NO_x emission during the NH_3-combustion experiments could be significantly lowered.

3.4. Tests with hydrogen in the MW range

For safety reasons and due to the lack of research facilities dedicated to industrial-scale hydrogen research in our region, finding a place to conduct the tests was challenging. We had the chance to find a site near an open-pit iron mine in the Styrian region that would welcome us (Figure 15). The whole set-up reproducing the sketch of Figure 3 is shown in the same picture. During these tests, we burned only hydrogen.

The burner used (Figure 16 to Figure 18) is a tailored version of the kW-range module showed in Figure 14, scaled to reach MW thermal power. The part overall dimensions are roughly 250 mm in diameter times 350 mm in length. The AM burner material is Inconel 718.

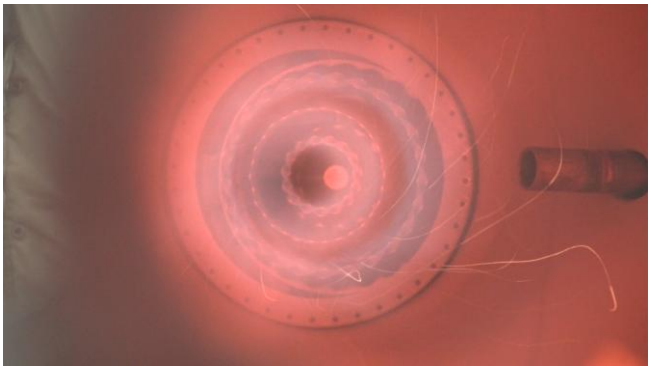


Figure 17: Operating burner in the MW range as seen from the end of the combustor.

The test was successful regarding the following aspects: a well-controlled, a soft ignition was achieved from the side into the pilot in the center. Then, the pilot flame softly ignites the main stage. All controls and procedures that were prepared for ramping up the flame performed very well. Controlled extinction was coupled with a nitrogen flush to ensure a smooth flame stop without flashback through the fuel lines. Under steady-state condition, while operating at 1 MW, global equivalence ratio 0.45 – supposedly local equivalence ratio 0.65 if subtracting the dilution air from the reaction zone, the burner showed less than 15ppm NO_x. If the testing time was too short to find effective frequencies of thermoacoustic control, at least the excitation sweeps performed by the siren did not provoke a combustion instability.

Figure 17: The fuel used is hydrogen. The two stages are active. The reddish color relates to the glowing metal parts in the rear and by the side. The traces of impurities in that shot underline the swirl dynamics. A faint blue color is visible, indicating premixing.

Figure 18: Despite temperatures of about 1200°C to 1400°C in the direct proximity of the burner, it was completely intact when the facility was dismounted. No molten part, no discoloration, no erosion, nothing showing a contact with the flame. The MW burner is therefore good for service, pulsated or steady state.

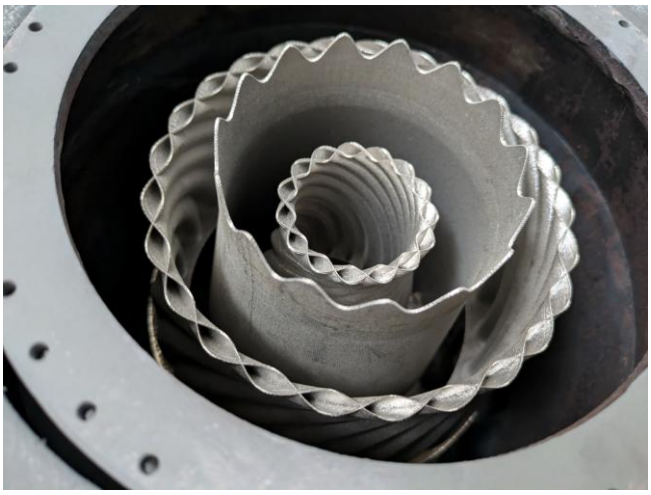


Figure 18: Same burner, intact after 6 hours of operation including at least 30 minutes at full load.

Conclusions

This paper proposes methods to seek for combustion instabilities and study their criticality – or mitigate these, as well as it shows how to actuate effectively thermoacoustics when the positive effects of these are desired. In the second option, it is assumed that the energy of excitation needed is much less that the energetic response of the flame, according of the rule of small perturbations bringing steady-state processes out of balance, and initiating instabilities.

The two studies are also two branches of mainstream work of authors. In the future we will report regularly on the progress made on the MOeBIUS and BLUETIFUEL technologies. For the time being, the conclusions follow.

Conclusion Application I

(about ensuring safe and efficient combustion of a combustor for aeronautics where stability and flame position control are paramount)

The recursive sequential combustion is progressing in terms of TRL. In the moment we have demonstrated with good success the two concepts, discrete burner and constant section, at early TRL 4 under atmospheric conditions. The benefits in terms of combustion performance have been established for the discrete combustor approach, and we are currently assessing the constant section combustor.

All experiments about forcing one discrete sector approach tend to believe that the RSC principle is highly damping flow disturbances. The next steps are similar tests on the constant-section mock-up. If the tests are passed, pressure tests will be started. We are confident these will go well, meaning that we will validate in the short term our current assumptions and get ready for the industrialization process (TRL 5 and above).

Conclusions Application II

(about using on demand and in an adaptive manner thermoacoustics to improve the combustion performance)

The premixer design of the BLUETIFUEL study was effective. The tunable pulsation could dramatically reduce the NOx emissions. The siren, instrumentation and regulation equipment used in the project were validated and will be used in new test cases.

The BLUETIFUEL project ended successfully with the validation of the hydrogen burner in the MW range. Having mastered a scaling factor 100 in power between laboratory and industrial demonstration, we are confident that larger scales are achievable for atmospheric burners, as well as this shape technology could also serve in gas turbines or metallurgical applications.

Copyright statement

Combustion Bay One e.U., Patent AT516424B1: Tunable Thermoacoustic Driver for Combustion Control, device and method for operating a flame

Combustion Bay One e.U., Patents AT523924B1, US12013122B2, WO2022067359A1, EP4222361A1. Method and device for recursive sequential combustion

Combustion Bay One e.U., University of Applied Sciences Joanneum GmbH, Patent AT519720B1: Combined Optic-Acoustic Compact Probe and method for monitoring combustion processes and/or an ignition process

P&P Industries AG, Patent Ref. EP4471330 A1. Rapid mixing device for mixing a stream of air with a liquid or gaseous highly reactive fuel and process for producing the same.

Acknowledgements

The research and development of the Recursive Sequential Combustion has received financial support of the FFG (Austrian Research Promotion Agency) and of the BMK (Austrian Federal Ministry for Climate Protection, Environment, Energy, Mobility, Innovation and Technology) in the frame of the following projects:

MOeBIUS (contract 881041), crystAIr (contract 894105) and KI-Pirinha (contract FO999910254). Partner institutions in these projects are the FH Joanneum / Aviation (laboratory and signal processing), the Joanneum Research GmbH / Materials & Digital for the AM aspects and signal processing, and Piezocryst GmbH for the instrumentation.

The Austrian Research Promotion Agency (FFG) is entrusted with the operational handling of funding awards the KLI.EN-Fonds of the Climate and Energy Fund Act (KLI.ENFondsG). FFG manages the contract BLUETIFUEL Nr. 881129 in the name and for the account of the Climate and Energy Fund. The funding is based on the Directive for the Promotion of Economic-Technical Research, Technological Development and Innovation (RTI Directive 2015) of the Federal Minister of Transport, Innovation and Technology (GZ BMVIT-609.986/0011- III/I2/2014) and the Federal Minister of Science, Research and Economy (GZ BMWFW-97.005/0003-C1/9/2014).

We hereby wish to acknowledge all parties involved.

References

[1] International Energy Agency. World Energy Outlook 2024

[2] Paris Agreement to the United Nations Framework Convention on Climate Change, Dec. 12, 2015. 21st Conference of the Parties (COP 21). In United Nations Treaty Collection. UNFCCC, 7 2016

[3] Giuliani, F. Analysis of the behaviour of an aeroengine air-blast injection device with forced entries. Doctoral thesis no.346. École nationale supérieure de l'aéronautique et de l'espace (Toulouse), 2002. https://oatao.univ-toulouse.fr/28999/

[4] Morinière, T. Dynamique du spray et de la combustion dans une chambre de combustion de

modèle de turbine à gaz de moteur à réaction. Thèse de doctorat Energétique et transferts Toulouse 3, 2023. https://theses.fr/api/v1/document/2023TOU30325

[5] Lieuwen, T. C., & Yang, V. (Eds.). (2013). *Gas turbine emissions* (Vol. 38). Cambridge university press.

[6] Hassa, C., Meier, U., Heinze, J., Magens, E., Schroll, M., & Bagchi, I. (2017, June). Investigation of the reacting flow field of a lean burn injector with varying degree of swirl at elevated pressure condition. In *Turbo Expo: Power for Land, Sea, and Air* (Vol. 50855, p. V04BT04A006). American Society of Mechanical Engineers.

[7] Ariatabar, B., Koch, R., Bauer, H. J., & Negulescu, D. A. (2016). Short helical combustor: Concept study of an innovative gas turbine combustor with angular air supply. *Journal of Engineering for Gas Turbines and Power*, *138*(3), 031503.

[8] Pennell, D. A., Bothien, M. R., Ciani, A., Granet, V., Singla, G., Thorpe, S., ... & Yaquinto, M. (2017, June). An introduction to the Ansaldo GT36 constant pressure sequential combustor. In *Turbo Expo: Power for Land, Sea, and Air* (Vol. 50855, p. V04BT04A043). American Society of Mechanical Engineers.

[9] Putnam, A. A. (1971). Combustion-driven oscillations in industry. American *Elsevier, 1971.*

[10] Lefebvre, A. H. (1998). *Gas turbine combustion*. CRC press.

[11] Blätte, L., Goeb, D., Gruhlke, P., Prade, B., Schildmacher, K. U., Streb, H., & Vogtmann, D. (2024, June). SGT5-4000F Hydrogen Capability–High Pressure Combustion Rig Tests Part II. In *Turbo Expo: Power for Land, Sea, and Air* (Vol. 87943, p. V03AT04A023). American Society of Mechanical Engineers.

[12] Aoki, S., Uto, T., Takahashi, N., Okada, K., Kroniger, D., Kamiya, H., ... & Kusterer, K. (2024, June). Development of hydrogen and micromix combustor for small and medium size gas turbine of Kawasaki. In *Turbo Expo: Power for Land, Sea, and Air* (Vol. 87936, p. V002T03A003). American Society of Mechanical Engineers.

[13] Zinn, B. T. (1992, January). Pulse combustion: recent applications and research issues. In *Symposium (International) on Combustion* (Vol. 24, No. 1, pp. 1297-1305). Elsevier.

[14] Giuliani F., Stütz M., Paulitsch N., and Andracher L. Forcing Pulsations by Means of a Siren for Gas Turbine Applications. Int. J. Turbomach. Propuls. Power 2020, 5(2), 9; https://doi.org/10.3390/ijtpp5020009

[1]Combustion Bay One e.U., www.CBOne.at
[2]Graz University of Technology, Institute for Thermal Turbomachinery and Machine Dynamics, www.TUGraz.at
[3]P&P Industries AG, www.pp-industries.at
[4]University of applies technology Joanneum GmbH, www.fh-joanneum.at

Corresponding author:
Fabrice Giuliani, Combustion Bay One e.U.
Schuetzenhofgasse 22,
8010 Graz, Austria
Email: Fabrice.Giuliani@CBOne.at