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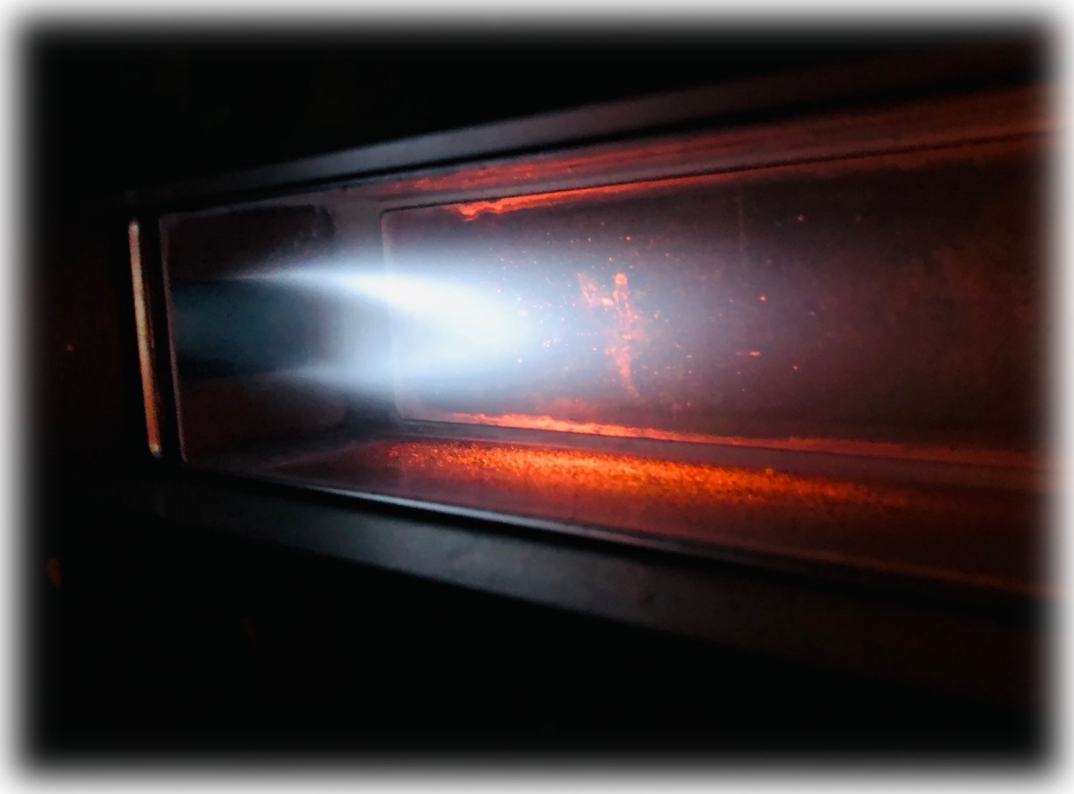
Advanced Reheat Combustion of Hydrogen (ARCH)



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Zusammenfassung

Das ARCH-Projekt wurde im Zusammenhang mit dem dringenden Bedarf an CO2-freien Technologien zur Eindämmung des Klimawandels initiiert. Die weltweiten Bemühungen zur Bewältigung dieses enormen Problems zielen auf den Aufbau nachhaltiger Energienetze ab, die auf verschiedenen technologischen Lösungen basieren. Da der Ausgleich der Schwankungen erneuerbarer Energiequellen in großem Maßstab (GW) und über lange Zeiträume (Monate) mit modernen Batterietechnologien nicht erreicht werden kann und sofortige und wirksame Maßnahmen auf globaler Ebene und in den nächsten 30 Jahren ergriffen werden müssen, ist die rasche Entwicklung tragfähiger Alternativen zur Lösung des Problems der saisonalen Unterbrechungen der erneuerbaren Energien von entscheidender Bedeutung.

Eine Möglichkeit, dieses Problem zu lösen, besteht darin, sich auf große Mengen nachhaltig erzeugter chemischer Brennstoffe zu stützen, die relativ leicht über lange Zeiträume gelagert werden können, sowie auf neue Verbrennungstechnologien, mit denen diese Brennstoffe mit hohem Wirkungsgrad und äußerst geringen Schadstoffemissionen wieder in Strom umgewandelt werden können. Letzteres Ziel könnte mit großen Gasturbinen erreicht werden, die über sequenzielle Verbrennungskonzepte verfügen, die mit grünem Wasserstoff (H_2) betrieben werden, unter der Voraussetzung, dass auch das frühere anspruchsvolle Ziel der großtechnischen Wasserstoffspeicherung in ausreichendem Maße erreicht wird. Tatsächlich gibt es bereits Belege dafür, dass mit Erdgas (NG) betriebene sequentielle Verbrennungssysteme eine sehr hohe betriebliche Flexibilität aufweisen und auch für mit H_2 angereichertes NG hochflexibel ausgelegt werden können. Allerdings ist die Verbrennung von reinem H_2 mit den modernsten auf dem Markt verfügbaren Technologien noch nicht ohne Effizienzverlust und erhöhte NO_x-Emissionen möglich. Daher müssen in den kommenden Jahren weitere Anstrengungen unternommen werden, um die Physik von H_2-Flammen bei hohem Druck besser zu verstehen, damit Systeme entwickelt werden können, die mit 100% H_2 hochleistungsfähig und flexibel betrieben werden können.

Vor diesem Hintergrund zielte das ARCH-Projekt darauf ab, grundlegende Fragen im Zusammenhang mit der Verwendung von H_2-reichen Brennstoffen in sequentiellen Verbrennungssystemen zu klären. Ziel war es, ein detailliertes Verständnis der Flammen in zwei verschiedenen Konzepten der sequentiellen Verbrennung bei Atmosphärendruck zu erlangen: axiale Brennstoffstufung ohne Zwischenluftverdünnung (AFS) und sequentielle Verbrennung bei konstantem Druck mit Zwischenluftverdünnung (CPSC). Der turbulente Verbrennungsprozess unter stationären und transienten Bedingungen wurde experimentell untersucht und numerisch modelliert. Mehrere experimentelle Studien wurden mithilfe eines akademischen Prüfstands durchgeführt, der die Hauptmerkmale der komplexen industriellen AFS- und CPSC-Konfigurationen aufweist. Darüber hinaus wurden Simulationen (LES) mit einem hochtreuen numerischen Löser und Ressourcen durchgeführt.

Dieses vom CAPS-Labor der ETH Zürich geleitete Projekt lieferte Schlüsselergebnisse zu 1) den Mechanismen, die die Verankerung der H2-Flamme in sequentieller Konfiguration unter einer Vielzahl von Betriebsbedingungen regeln, 2) den in der Brennkammer vorherrschenden turbulenten Verbrennungsregimen, 3) der Empfindlichkeit der Flamme auf die Einlassbedingungen des sequentiellen Brenners und 4) der Modellierung und Vorhersage der turbulenten H2-Verbrennung mit numerischen Methoden. Diese Ergebnisse werden zur Entwicklung der Brennkammern von Industriegasturbinen beitragen, insbesondere zu den neuen Technologien von Ansaldo Energia, das sich aktiv an diesem ehrgeizigen Forschungsprojekt beteiligt hat.

Résumé

Le projet ARCH a été lancé dans le contexte du besoin urgent de technologies sans émissions de CO_2 pour atténuer le changement climatique. Les efforts mondiaux engagés pour faire face à cet énorme problème visent à mettre en place des réseaux énergétiques durables basés sur différentes solutions technologiques. Étant donné que la compensation des fluctuations des sources d'énergie renouvelables à grande échelle (GW) et sur de longues périodes (mois) ne peut être atteint avec les technologies de batteries modernes et que des mesures immédiates et efficaces doivent être prises à l'échelle planétaire et dans les trente prochaines années, il est essentiel de développer rapidement des solutions alternatives viables pour résoudre le problème d'intermittence saisonnière des énergies renouvelables.

L'une des façons de résoudre ce problème est de s'appuyer sur de grandes quantités de combustibles chimiques produits de manière durable et pouvant être stockés relativement facilement sur de longues périodes, ainsi que sur de nouvelles technologies de combustion permettant de reconvertir ces combustibles en électricité avec un rendement élevé et des émissions polluantes extrêmement faibles. Ce dernier objectif pourrait être atteint avec de grandes turbines à gaz, dotées de concepts de combustion séquentielle alimentés en hydrogène vert (H_2), à condition que l'objectif précédent de stockage de l'hydrogène à grande échelle soit également atteint de manière adéquate. En effet, il est déjà prouvé que les systèmes de combustion séquentielle fonctionnant au gaz naturel (NG) présentent une très grande flexibilité opérationnelle et peuvent également être conçus pour une grande flexibilité en matière de NG enrichi à l'H_2. Cependant, la combustion de H_2 pur avec les technologies de pointe disponibles sur le marché n'est pas encore possible sans perte d'efficacité et augmentation des émissions de NO_x. Par conséquent, des efforts supplémentaires doivent être faits dans les années à venir pour mieux comprendre la physique des flammes d'H_2 à haute pression afin de développer des systèmes qui peuvent être exploités de manière robuste et flexible avec 100% d'H_2.

Dans ce contexte, le projet ARCH visait à résoudre des questions fondamentales liées à l'utilisation de combustibles riches en H_2 dans les systèmes de combustion séquentielle. L'objectif était d'acquérir une compréhension détaillée des flammes dans deux concepts différents de combustion séquentielle opérés à pression atmosphérique: l'étagement axial du combustible sans dilution d'air intermédiaire (AFS) et la combustion séquentielle à pression constante avec dilution d'air intermédiaire (CPSC). Le processus de combustion turbulent dans des conditions stationnaires et transitoires a été étudié expérimentalement et modélisé numériquement. Plusieurs études expérimentales ont été réalisées à l'aide d'un banc d'essai académique ayant les principales caractéristiques des configurations industrielles complexes AFS et CPSC. De plus, des simulations aux grandes échelles (LES) ont été réalisées à l'aide d'un solveur numérique haute-fidélité et de ressources informatiques haute-performance.

Ce projet mené par le laboratoire CAPS de l'ETH Zürich a fourni des résultats clés sur 1) les mécanismes régissant l'ancrage des flammes de H_2 en configuration séquentielle dans une large gamme de conditions de fonctionnement, 2) les régimes de combustion turbulente qui dominent dans la chambre de combustion, 3) la sensibilité de la flamme sur les conditions d'entrée du brûleur séquentiel, et 4) la modélisation et la prédiction de la combustion turbulente de H_2 avec des méthodes numériques. Ces résultats contribueront au développement des chambres de combustion des turbines à gaz industrielles, et en particulier aux nouvelles technologies d'Ansaldo Energia qui a participé activement à ce projet de recherche ambitieux.

Summary

The ARCH project has been initiated in the context of the urgent need for zero-CO_2-emission technologies to mitigate the climate change. The global efforts engaged to address this huge problem aim at future sustainable energy networks with a mix of technological solutions. Considering that balancing the fluctuations from renewable energy sources at large scale (GWs) and over long time periods (months) cannot be achieved with foreseeable battery technologies and that immediate and effective actions must be taken at the global level within the coming thirty years, it is key to quickly develop alternative workable solutions for the problem of seasonal intermittency of renewable sources.

One of way to address this issue is to rely on large quantities of sustainably produced chemical fuels that can be stored over long time scales relatively easily, and on new combustion technologies for converting these fuels back to electricity at high efficiency and ultra-low pollutant emissions. The latter objective could be attained with large gas turbines, featuring sequential combustion concepts supplied with green hydrogen (H_2), under the condition that the former challenging objective of large-scale hydrogen storage is also adequately reached. Indeed, it is already proven that sequential combustion systems operated with natural gas (NG) exhibit very high operational flexibility and can also be designed for high fuel flexibility with blends of NG and H_2. However, combustion of pure H_2 with state-of-the-art technology available in the market is not yet possible without efficiency loss and NO_x emission increase. Consequently, further efforts must be made in the coming few years to better understand the physics of H_2 flames at elevated pressure in order to develop systems that can be robustly and flexibly operated with 100% H_2.

In this context, the ARCH project aimed at solving fundamental questions associated to the use of H_2-rich fuels in sequential combustion systems. The goal was to obtain a detailed understanding of the flames in two different sequential combustion concepts at atmospheric pressure: the axial fuel staging concept without intermediate air dilution (AFS) and the constant pressure sequential combustion concept with intermediate air dilution (CPSC). The turbulent combustion process in stationary and transient conditions was investigated experimentally and modelled numerically. Several experimental investigations were carried out using an academic test-rig having the main characteristics of complex industrial configurations based on AFS and CPSC. Moreover, large eddy simulations (LES) were performed using a high-fidelity numerical solver and high-performance computing resources.

This project led by the CAPS Lab of ETH Zürich has provided key findings on 1) the mechanisms governing the anchoring of H_2 flames in sequential configuration under a wide range of operating conditions, 2) the turbulent combustion regimes that dominate in the combustion chamber, 3) the sensitivity of the flame on the inlet conditions of the sequential burner, and 4) the modelling and prediction of the turbulent combustion of H_2 with numerical methods. These findings will contribute to the development of industrial gas turbine combustors, and in particular, the new technologies of Ansaldo Energia who actively took part to this challenging research project.

Main findings

- The transient ignition sequence of highly reactive premixed jet in hot vitiated crossflow is initiated at the windward side, at locations leaner than the most reactive conditions. It is followed by a propagation of the flame front around the jet. At steady state, the main mechanism for the flame stabilization is the autoignition along the windward side of the premixed jet.

- The addition of hydrogen to jet-in-crossflow configurations pushes the flame towards the injector where it anchors strongly and creates a more compact and tight flame that reduces the entrainment inside the crossflow. This increases the asymmetry of the flow and the risk of damage to the hardware. The flame topology and dynamics are characterized experimentally in details, which constitute a solid basis for future validation of numerical methods for simulating H_2 combustion.

- The quality of the mixing process upstream from the anchoring location of the sequential flame is of paramount importance to ensure high efficiency and low emissions. It was shown that the sequential flame is highly sensitive to this mixing process and that the upstream conditions can strongly influence the anchoring characteristics and the dominant combustion regimes. New predictive models were validated with experiments.

- Three types of stabilization mechanisms are found in the hydrogen sequential flame as function of the operating conditions of the engine, from which only one is desired for proper operation of the system. It was shown that these mechanisms can be effectively predicted using low-order models both in stationary and transient conditions.

Contents

Abbreviations

AFS	Axial fuel staging
ARCH	Advanced reheat combustion of hydrogen
CAPS	Combustion and acoustics for power and propulsion systems
CERFACS	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique
CFD	Computational fluid dynamics
CPSC	Constant pressure sequential combustion
DA	Dilution air
DLE	Dry low emissions
DLN	Dry low NO_x
GT	Gas turbine
IC	Injector configuration
LES	Large eddy simulations
LIF	Laser induced fluorescence
NG	Natural gas
OEM	Original equipment manufacturers
OES	Optical emission spectroscopy
RJICF	Reactive jet in cross flow
SB	Sequential burner
TDLAS	Tunable diode laser absorption spectroscopy
WLE	Wet low emissions

Variables

J	Momentum ratio
$\dot{q}$	Heat release rate
t	Time
T	Temperature
Y_k	Mass fraction of species k
Z	Mixture fraction
φ	Equivalence ratio
τ_{AI}	Autoignition delay

1 Introduction

1.1 Background information and current situation

Humankind is facing the immense challenge of climate change. The global efforts engaged to address this critical issue aim at future sustainable energy networks characterised by a mix of technological solutions [1]. The strong emission regulations, the introduction of novel fuels, and the requirement of high operational flexibility to adapt to higher shares of renewable sources are boosting the interest and research of novel concepts for combustion systems. In particular, gas turbines for power generation present a powerful combination of characteristics that makes them a strong candidate to tackle the aforementioned problems. Firstly, these systems have great operational flexibility, their fast start-up, loading and de-loading capabilities [2,3] allow them to balance the intermittency associated to high concentration of renewable sources in the energy mix, providing the required inertia and base load for safe operation and reliability of the power grid. Power grid inertia is defined as the energy stored in large rotating power generator components, such as gas turbines, and it is a key component for reliable power grid operation. When a power plant fails, this stored energy is available for several seconds and provides enough response-time for the mechanical systems that control the power plant to detect and react to the failure. In short, inertia in the power grid prevents the drop of grid frequency, i.e. the drop of the balance between energy supply and demand. Historically, inertia in national power grids has been taken for granted due to the abundance of fossil fuels, nuclear and hydro power generators. However, with the higher penetration of renewable energy sources, mainly wind and solar that lack inertia, this is becoming an important issue to be considered in the design of future power grids. Secondly, the levels of carbon dioxide CO_2, nitrogen oxides NO_x, and unburned hydrocarbons emissions associated to gas turbine operation are notably lower than any other combustion-based system, reaching less than 50% of the total CO_2 produced by coal and oil-based systems [4]. Moreover, the overall efficiency associated to gas turbine power plants of several hundred MW in combined cycle can now reach 65% against the much lower efficiencies associated to coal and oil power plants, typically 45% for the latest ultra-supercritical steam technology, and that translates in higher amounts of fuel needed to satisfy the energy demand. Furthermore, as synthetic fuels and hydrogen are foreseen to be a key ingredient in the future energy mix, modern combustion systems are required to cope with high variance of Wobbe index [5] and fuel reactivity, i.e. high fuel flexibility. Gas turbines can be operated with different types of fuel including liquid and gas fuels, bio and synthetic fuels, and hydrogen-rich fuels. Different concepts and types of gas turbine combustors can be found in the market as part of the development of this technology since it was first introduced in the early 1900s, where the most common are silo combustors, can combustors, can-annular combustors, and annular combustors. See [6] for a comprehensive overview of this technology.

Following the latest technological developments, the strong support from government and industry, and the decarbonization targets, the main original equipment manufacturers (OEMs) are developing gas turbine concepts that allow to introduce hydrogen fuel. Originally, most of the currently available technology in gas turbines for power generation has been designed and optimized for natural gas (NG) combustion. This creates important technological challenges for the retrofitting of the current systems for hydrogen-rich fuels due to the important differences in combustion properties compared to natural gas [7-13]. Despite these technological challenges, some gas turbine systems from different OEMs already in operation are capable of using hydrogen as fuel in different concentrations ranging all the way to 100%

of hydrogen. Current technology able to reach values of 100% of hydrogen fuel use diffusion burners or steam injection to reduce emissions (wet low emissions, WLE). However, these systems usually present levels of NO_x emissions much higher than the dry low emissions (DLE) or dry low NO_x (DLN) technology due to the high post-flame temperatures associated to hydrogen combustion. The latter, DLE and DLN systems are currently limited to concentrations of about 50% to 60% of hydrogen, and they rely strongly on fuel staging concepts and advanced mixing technologies. Siemens current portfolio shows about 60% and 30% H_2 capabilities for their midsize and heavy-duty units respectively using DLE concepts [14]. They also claim tests at 80% and 60% H_2 for midsize and heavy duty, while planning to reach 100% H_2 in all models by 2030 using fuel staging technology and modified fuel injectors to improve flashback behavior [15]. At the same time, General Electric has GTs in combined cycle operation and equipped with diffusion burners, burning up to 100% H_2. They have also design micro-mixers that can handle up to 50% H_2, and they have recently introduced the fuel staging concept (axial fuel staging, AFS) to the HA class units [16,17]. Ansaldo Energia has successfully demonstrated testing up to 70% H_2 in the GT36 with sequentially staged combustion and DLE technology [18,19]. A more detailed overview of the available hardware and hydrogen capabilities by OEM can be found in [7]. Nevertheless, the maximum concentrations of hydrogen (70%) burned in this state-of-the-art lean DLN gas turbines lead to net carbon emission reductions of only around 40%. To achieve negligible carbon footprints of gas turbines much higher hydrogen concentrations in the fuel are required. It should be highlighted that burning high percentages of hydrogen (>90%) with low-NO_X technology poses a great technological challenge at industrial level. Current state-of-the-art technology emphasizes on the recurring theme of fuel staging and advanced mixing technologies in various concepts to achieve high levels of hydrogen concentration in the fuel while keeping low emissions and high operational flexibility. The main OEMs are targeting different concepts of the fuel staging technology, and this translates in an increasing amount of experimental and numerical evidence showing its suitability for hydrogen combustion.

Recently Ansaldo Energia introduced its new GT36 gas turbine into the market. Built on the evolution of several generations of proven technology and on the GT26 excellence, the GT36 gas turbine offers high efficiency at full and part load with very low emissions. In particular, it can achieve a minimum load complying with the allowed emission limits as low as 30 %. The GT36 offers an unmatched operational flexibility in its class: its unique sequential combustion technology allows a high turndown [20]. This enlarges the emission-compliant operation window compared to conventional single stage combustor technologies and consequently the options for the power plant operator – thus offering a clear advantage in todays and future power generation markets (see Figure 1). Alstom Power initially developed this constant-pressure-sequential-combustion (CPSC) technology, in a project that started in 2011. Since 2015, it belongs to and is further developed by Ansaldo Energia Switzerland, whose Gas Turbine R&D division is based in Baden (Aargau), and whose test centre in Birr hosts a GT36 test engine that can produce 369 MW in single cycle. In this context, a substantial part of the R&D effort of Ansaldo Energia is dedicated to the development of sequential combustors that can also burn hydrogen-enriched natural gas. This effort falls within the global push for developing carbon-neutral gas from Power-to-Gas technologies. Developing a low-NO_x H2-combustion gas turbine technology is key for the future energy networks [21]. First, gas turbines capable of being fed with hydrogen-rich synthetic gas from methanation is already a need in nowadays market. Second, energy excess from renewables can be stored in the form of hydrogen by electrolysis and injected in the gas pipelines supplying natural gas fired power plants.

In conventional combustors, combustion of pure H_2 is not possible without severe efficiency loss and NO_x increase. In fact, the high reactivity and diffusivity of H_2 lead to a substantial increase of NO_x emissions for high temperature combustion occurring in regions where H_2 has not well mixed with air. Moreover, H_2 combustion in conventional combustors is very challenging due to a much higher propensity to flashback, which can destroy the burner components. In this respect, and in contrast with conventional combustor architectures, the CPSC concept is particularly promising for reliable and low-NOx combustion of hydrogen. This is because the first stage is operated at low flame temperature and only generates negligible amount of NO_x, and the second stage, where the targeted turbine inlet temperature is reached, exhibits short residence time (low post-flame NO_x formation) and robust flame anchoring based on autoignition. Therefore, the combustion of hydrogen rich mixtures with ultra-low NO_x emissions is foreseen to be achievable with a CPSC system. However, there is a clear lack of knowledge about the complex combustion physics, which is expected to take place in H_2-fueled CPSC systems.

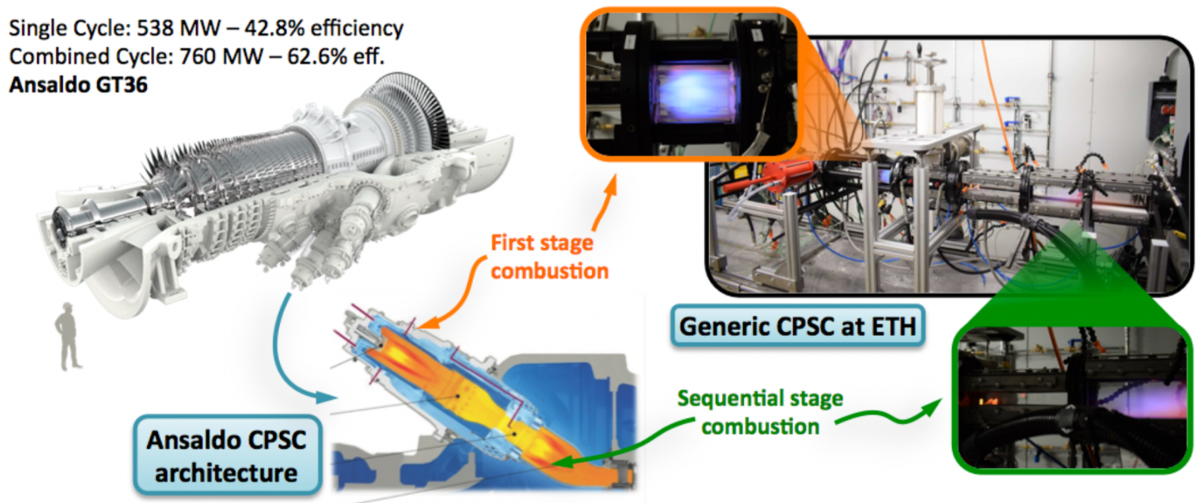

Figure 1. Left: Ansaldo GT36 and its constant pressure sequential combustion (CPSC) system. This heavy-duty gas turbine has very large nominal power and efficiency and has been developed to satisfy the growing demand for increased fuel and operational flexibility. The cornerstone of this versatile gas turbine, that can be used to compensate renewable sources intermittency, is the new sequential combustion technology, which is also very promising for ultra-low NOx combustion of highly-reactive hydrogen-enriched as well as highly-diluted synthetic gas. **Right**: Generic CPSC system used at ETH to conduct the research for the ARCH project.

1.2 Purpose of the project

One challenging task was to understand the **H_2 flame anchoring mechanism in practical sequential combustors under stationary condition**. Indeed, at relevant operating temperature and pressure, it is not possible to predict, with today's theoretical and numerical tools, if the H_2 combustion process will be dominated by flame propagation or by autoignition. Here, it is important to mention that, even in the case of sequential combustors fuelled with natural gas, this question has been the subject of intense research efforts over the last few years in academia and in industry. Substantial progress was made at ETH about the different combustion modes in configurations involving hydrocarbon fuels (NG, CH_4 and C_2H_4) injected in hot vitiated air [22-25] and about the associated thermoacoustic phenomena [26,27]. The experimental research has been performed using the generic CPSC system developed and installed at ETH (see Figure 1). This project aimed at understanding the flame anchoring mechanisms and developing validated predictive tools in the case of injection of H_2-rich mixtures in sequential combustors. Achieving this goal was a key need for the design of these future, flashback-free and ultra-low-NO_x, H_2-fueled sequential combustors.

Another challenge was to **keep the H_2 flame anchoring under control in the sequential combustor under transient conditions**. This is particularly important for operation at particularly low inlet temperature and/or future operation concept with faster temperature changes. Recent investigations at ETH on a generic CPSC system fuelled with NG showed that the combustion process under transient conditions is highly complex [24,25]. Therefore, it was expected that the use of H_2 would also bring challenging questions about the transient behaviour of the reaction zone. In fact, two situations were considered with care: 1) the ignition process of hydrogen-rich fuels in staged configurations, and 2) the transient change of operating conditions in the first and second stages.

Regarding ignition in staged configuration, the temperature of the vitiated air has a very strong influence on the combustion dynamics of the sequential flame. It has been observed at ETH that for sufficiently high temperature, the injection of NG is immediately followed with the appearance of autoignition kernels, which rapidly expand and contribute to the fill up of the sequential chamber with hot products [24,25]. This ignition sequence is not smooth anymore if the burner inlet temperature is too low, and a violent bulk ignition of the chamber may happen with some random delays. Indeed, it is induced by the occurrence of an individual kernel – being an “extreme event” in statistically unfavourable conditions in term of turbulent mixing and thermochemical composition – which can happen seconds after fuel valve opening, and which triggers a global ignition of the chamber that filled up with an ignitable mixture until the formation of that kernel. In that case, the sequential combustor ignition is accompanied with a strong pressure pulse and a flashback, both being threats for the mechanical integrity of the combustor. Such detrimental ignition sequence was also expected with the use of H_2, and it was of utmost importance to investigate the ignition sensitivity with respect to the vitiated air temperature and of the geometry of the burner.

Regarding the transient change of the engine operating conditions, the rate at which the fuel mass flow is changed for a given combustor geometry can have a strong influence on the flame anchoring stability. For combustors featuring a significant area jump downstream of the fuel-air mixing zone, intense hot gas recirculation zones help the flame to stay anchored, even when the vitiated air temperature is decreased to a point where pure flame propagation is the main combustion mode. Modifying the operating condition of the engine could change the dominant combustion regime of the flame, modifying its anchoring location and combustion properties. This could in turn have a detrimental effect on the emission levels and performance of the system.

Furthermore, to increase the combustor efficiency, one may aim at shortening the size of the recirculation zone, which significantly participates to the overall pressure drop of the combustor. In that situation, the same change of the inlet temperature may by accompanied with a substantial flame lift-off and, in the worst-case scenario, to a loss of the flame. In fact, the autoignition time may suddenly become long compared to the combustor residence time and the lack of hot product recirculation would prevent a propagating type of flame to stay anchored at the burner outlet. This is even more important when, on top of decreasing the pressure drop for increasing the GT efficiency by decreasing the size of the recirculation zones, one intends to reduce the residence time in the sequential combustor (higher velocities or shorter chamber) to achieve ultra-low NO_x at high turbine firing temperature. It was therefore very important to investigate how such transient behaviour would manifest itself in the case of sequential combustor fired with H_2-rich mixture.

The goal of this project was to have a detailed understanding of the combustion process in a CPSC and AFS academic model fuelled with hydrogen. We investigated and modelled the turbulent combustion process in sequential combustors that are supplied with mixtures exhibiting high H_2-fraction, under stationary conditions, and using experiments and simulations. Moreover, we scrutinized complex transient combustion phenomena, which are relevant for the future sequential systems, including for instance ignition process and transient operation of the combustor. To achieve this goal, several objectives must be reached, that are described in the following section.

1.3 Objectives

The objectives of this project aimed at investigating the knowledge gaps described in the previous section and associated to hydrogen-rich combustion physics in axially staged combustion systems. The objectives can be summarized as follows:

- Analysis of hydrogen sequential flame combustion under both stationary and transient operation.
- Identification and mapping of the anchoring mechanism and dominant combustion regimes as function of the operating conditions of the engine.
- Development of low-order models to predict the combustion properties of the sequential flame at gas turbine relevant conditions. Validation of this models at stationary and transient operating conditions.
- Effect of key thermodynamic parameters on flame behavior and flashback properties, for example the inlet temperature to the sequential burner and the mixing quality of the flow.

These objectives were investigated both experimentally and numerically. Four different tasks and milestones were addressed that gathered all the mentioned aims and that define the structure of the research carried out within this project. These tasks can be chronologically presented as follows:

1. **Experimental and numerical investigation of highly reactive fuels (pure H_2, H2-enriched, and C_2H_4) combustion at atmospheric conditions in axial fuel staging configuration (AFS concept) in straight channel**. The main objectives were a) the analysis of both transient and stationary phenomena, b) the identification of dominant combustion regimes of the sequential flame, i.e., auto-ignition and/or propagation regimes, and c) the use of various experimental optical diagnostics (high-speed flame imaging, LIF). The AFS concept was addressed first due to its simpler configuration as compared with the CPSC. The investigation of this concept provided relevant information about highly reactive flows burning at reheat conditions in both stationary and transient operation, and that was later of great importance for the setup and understanding of the more complex CPSC configuration. Furthermore, this simple configuration was a good starting point as it allowed for a quicker understanding and

mastering of the required numerical and experimental tools to be used throughout the whole ARCH project.

2. **Numerical simulations of H_2 combustion in simple straight channel under conditions relevant for sequential combustors**. Study of transient and stationary phenomena at atmospheric and high-pressure conditions. This task addressed a) the validation of combustion models and prediction of dominant combustion regimes using low-order models. This was a necessary and important step prior to the start of the more complex CPSC configuration. The development of low-order models helped obtaining analytical data of the flame behaviour and thermodynamic properties as function of the operating points of the engine. This analytical data could then be used as a first order approximation of the expected behaviour of the real flames that were later obtained in the experimental test rig, and it was of great added value for the design and setup of the test matrix and test rig configuration.
3. **Experimental investigation of H_2 combustion in a sequential complex geometry relevant for practical applications (CPSC concept)**. Transient and stationary phenomena at atmospheric conditions. This task addressed a) the investigation of the flame anchoring dynamics and dominant combustion regimes under changing operating conditions, and b) the effect of mixing quality over flame anchoring and flash back behaviour, and c) the validation of the previously obtained low order models for dominant combustion regime prediction. With all the knowledge gathered from the previous experimental and numerical simulations of the AFS concept, together with the low order model analytical data, this more complex task could then be addressed. This task was the culmination of the experimental part of the ARCH project and served as validation of the previous low order models.
4. **Numerical investigation of H_2 combustion in a sequential complex geometry relevant for practical applications (CPSC concept)**. Flame stabilization and combustion regimes were analyzed at atmospheric conditions. This task addressed a) the study of the effect of the mixing process inside the mixing channel of the combustor and the performance of different injector geometries over the flame morphology and anchoring, b) a mapping of the turbine operating conditions based on real turbine operation procedures and its effect over dominant combustion regimes and flame stabilization mechanisms, and c) the study of the so-called “spontaneous propagation” mechanism affecting the sequential flame near crossover temperatures of hydrogen. After obtaining experimental data, numerical simulations of the CPSC could be performed and validated using pure hydrogen as sequential fuel. Numerical simulations allowed to investigate flow phenomena difficult to achieve by experimental means, as the so-called Zeldovich mechanism of spontaneous propagation.

This report is an abstract of the work that has been performed over the course of the ARCH project. The full content of the research project can be found in the doctoral dissertation of Roberto Solana and in the publications listed in chapter 7 of this report. Links to publicly accessible versions of these publications are also provided in this list.

2 Description of facility

Two different sequentially staged combustor configurations were investigated within the scope of this project, the AFS concept and the CPSC concept. At CAPS Laboratory, the experiments were conducted with an academic combustion test rig that operates at atmospheric conditions. Its modular configuration allowed to modify the existing combustor setup relatively easy, making it possible to set up both the AFS and CPSC configurations.

2.1 AFS Concept (Task 1, Fig. 2)

This configuration [16] features a unique combustion chamber where both the first stage flame and the sequential flame are in series. The first stage burns a lean premixed flame that is aerodynamically stabilized by vortex breakdown and provides a hot vitiated flow with excess of oxygen to ensure combustion of the second stage fresh fuel. The second stage features a reactive jet in crossflow (RJICF) configuration where air and fuel are premixed prior to injection into the combustion products. This configuration is characterized by higher temperatures of the vitiated flow at the second stage injection point, as no dilution air is injected between both stages. This results in extremely short autoignition delays that anchor the flame very close to the sequential injectors in a jet-in-crossflow configuration. The sequential jet is composed by a premixed mixture of air, methane, and hydrogen with different blending ratios. The following optical diagnostic techniques were used: high-speed chemiluminescence and OH planar laser induced fluorescence.

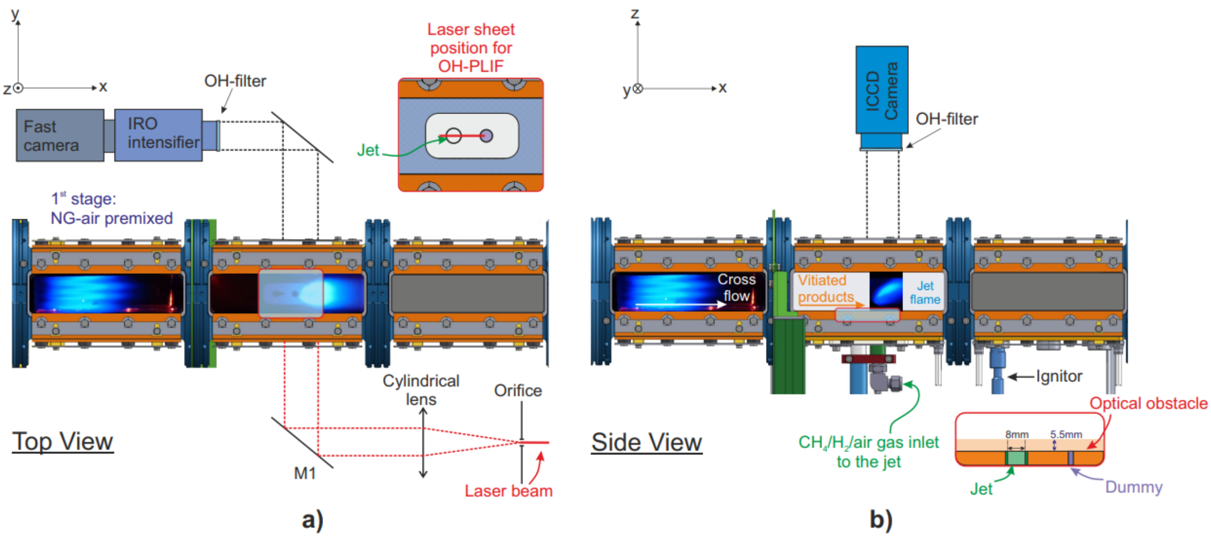

FIGURE 2. Sketch of the sequential combustor test-rig at CAPS Lab featuring the AFS configuration.

2.2 CPSC Concept (Tasks 3 and 4, Fig. 3)

This configuration [18] features two different combustion chambers sequentially located. The first stage burns a lean premixed flame that is aerodynamically stabilized by vortex breakdown and provides a hot vitiated flow with excess of oxygen to ensure combustion of the second stage fresh fuel. The sequential stage is in a different combustor, and sequential air and fuel are not injected together. The products from the first stage are firstly diluted with air in the dilution air mixer, reducing the vitiated flow temperature. The sequential combustor is located downstream and features a jet-in-coflow configuration that delivers the sequential fuel into the diluted hot products from the first stage. The temperature of the vitiated flow in this configuration is relatively lower due to the previous dilution step, leading to longer ignition delays and to a flame anchoring downstream from the injector and inside the sequential combustion chamber. This configuration is an academic model of that deployed in Ansaldo Energia GT36 gas turbines.

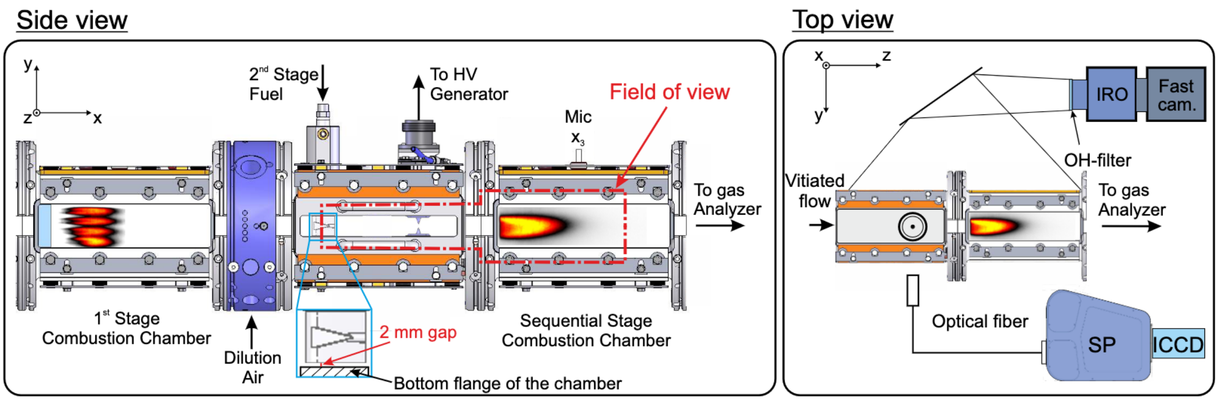

FIGURE 3. Sketch of the sequential combustor test-rig at CAPS Lab featuring the CPSC configuration.

3 Procedures and methodology

The ARCH project includes both numerical and experimental approaches to investigate the sequentially staged configurations presented before (AFS and CPSC). A detailed overview of the numerical and experimental procedures developed in each of the four tasks is given next.

3.1 Task 1: Experimental and numerical investigation of the AFS concept

The experimental part of Task 1 was carried out in the test-rig of CAPS laboratory (see Figure 2). The goal of this task was to analyze the consequences of enriching natural gas with hydrogen fuel in the sequential stage. We focused on the effect on the morphology of a premixed jet flame in vitiated crossflow. To do that, the following experimental approach was taken. The equivalence ratio and thermal power of first stage were kept constant, resulting in very high crossflow temperatures (around 1750 K, measured with OH-PLIF thermometry). Subsequently, the momentum ratio and the equivalence ratio of the premixed jet were varied independently to investigate the individual effects of these two parameters on the morphology of the flame.

The numerical part of Task 1 was carried out using LES with the software AVBP, an explicit cell-vortex code for CFD analysis of unsteady turbulent reacting flows. The goal of this task was to investigate the ignition process of an ethylene lean premixed jet in crossflow configuration under reheat conditions. The initial condition of the numerical simulation features a fully developed non-reactive jet where the ethylene is removed from the mixture. Next, at time t=0, the reactive mixture enters the domain through the jet inlet pipe leading to spontaneous ignition of the mixture and the full stabilization of the jet flame. The full transition from a non-reactive jet to a fully developed jet flame is studied.

3.2 Task 2: Numerical simulations of H_2 flames in simplified geometries

A 0D/1D reactor network was developed using Cantera software with Li and San Diego kinetic mechanisms to study the conditions at which autoignition and flame propagation govern the combustion process in the sequential combustor, see Figure 4. The network model consists of 3 stages: a) first stage flame is simulated using chemical equilibrium at constant pressure and enthalpy of a CH_4/Air or H_2/Air mixture. The required inputs include pressure, gases temperatures, kinetic mechanism, and equivalence ratio. A 0D batch reactor with wall heat losses is introduced to simulate experimental wall losses; b) dilution air is added to the vitiated flow in a perfect mixing process; c) sequential H_2 fuel is added in a partial mixing process as function of a mixture fraction parameter (Z) between the fresh fuel and the vitiated flow, and a 0D adiabatic batch reactor at constant pressure is used to ignite the resulting reactive vitiated flow. The 0D reactors are homogeneous, closed, and have a moving wall to ensure the constant pressure of the system. The autoignition delay is computed from the last batch reactor as the time where the highest temperature gradient is found.

This simplified model simulates each stage of the sequential combustor operated at atmospheric and high pressure, and it is calibrated by introducing heat losses at the first stage to match the temperatures measured experimentally. The target was to use this simplified model to estimate the dominant flame combustion regimes for the sequential configuration as function of the operating conditions, and to use these estimations as an input for the experimental and numerical setups. This model was also used to create the operating conditions that are fed to the numerical simulations (LES) of Task 4. The operating conditions were obtained by balancing the power load between first and second combustors while keeping a constant air ratio between them. Doing so, the system could modify the overall equivalence ratios and input temperatures of both stages.

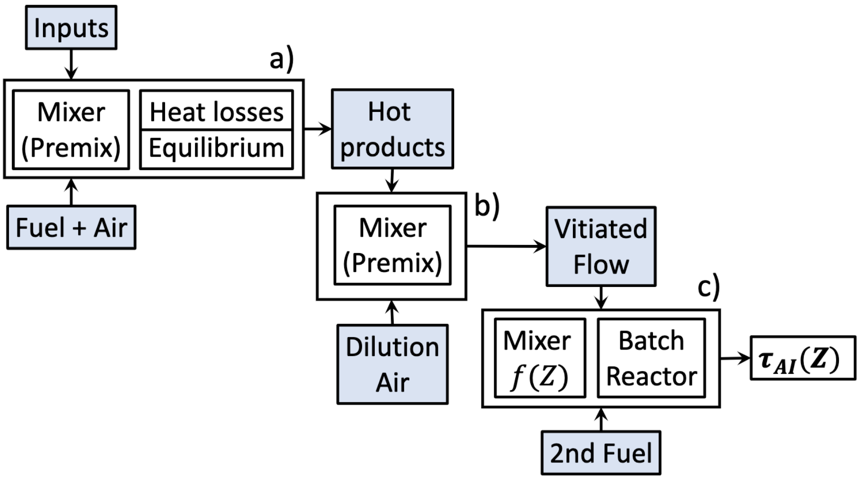

FIGURE 4. Schematic of 0D reactor network model using Cantera modules. a) First stage, b) dilution air, and c) sequential burner modules. Autoignition delays are the output.

3.3 Task 3: Experimental investigation of H_2 flames in the CPSC concept

The experimental investigation of Task 3 was carried out in the test-rig of CAPS laboratory (see Figure 3). The goal of this task was to investigate pure hydrogen flames in sequential configurations, focusing on the dominant combustion regimes under various operating conditions, the anchoring of the flame, the effect of key thermodynamic parameters (temperature and mixing quality) on the combustion process, and to use this experimental data to validate the low-order model developed in task 2. To do that, two cases were analyzed. Firstly, steady operation of the combustor where the operating condition are modified and studied independently. Secondly, transient operation of the combustor where the investigation focuses on the transition of the flame from a propagation dominant mode to an autoignition dominant mode, by modifying the operating point of the engine.

3.4 Task 4: Numerical simulations of pure H_2 flames in the CPSC concept

The numerical part of Task 1 was carried out using LES with the software AVBP. The goal of this task was to investigate the ignition process of an ethylene lean premixed jet in crossflow configuration under reheat conditions. The initial condition of the numerical simulation features a fully developed non-reactive jet where the ethylene is removed from the mixture. Next, at time t=0, the reactive mixture enters the domain through the jet inlet pipe leading to spontaneous ignition of the mixture and the full stabilization of the jet flame. The full transition from a non-reactive jet to a fully developed jet flame was studied.

4 Results and discussion

4.1 Axial Fuel Staging (AFS) concept

The analysis of the axial fuel staging concept was addressed numerically and experimentally in two subsequent studies. The sequential flame in this concept is in the same combustion chamber as the first stage, and it features a jet-in-crossflow configuration where a premixed mixture of fuel and air is injected inside the hot products from the first stage. Autoignition and flame stabilization take place very close to the injection point due to the high temperatures. In this investigation we focused on 2 main topics, a) the transient ignition process of the jet (numerical study), and b) the analysis of stationary jet flames for various concentrations of hydrogen enrichment (experimental study).

The main finding of the numerical study of the AFS concept is that a "heat release outbreak" occurs, in which autoignition patches appear suddenly in scattered locations along the windward side of the jet, at regions of high mixing between jet and crossflow. There, autoignition conditions are met, i.e. very lean most reactive mixture fractions, high temperature and small flow velocities (relatively high residence times). These patches initiate a process of low heat release that diffuses to the surrounding regions increasing their temperature and shifting the most reactive mixture fractions to higher values. Hence, they grow and expand as the autoignition conditions are met in wider areas of the jet surface. These patches collapse into a whole continuous surface that grows not only in the windward side, but also around the jet, wrapping up laterally and finally closing at the recirculation region due to flow advection. However, they do not reach the jet leeward side as autoignition conditions are not met there.

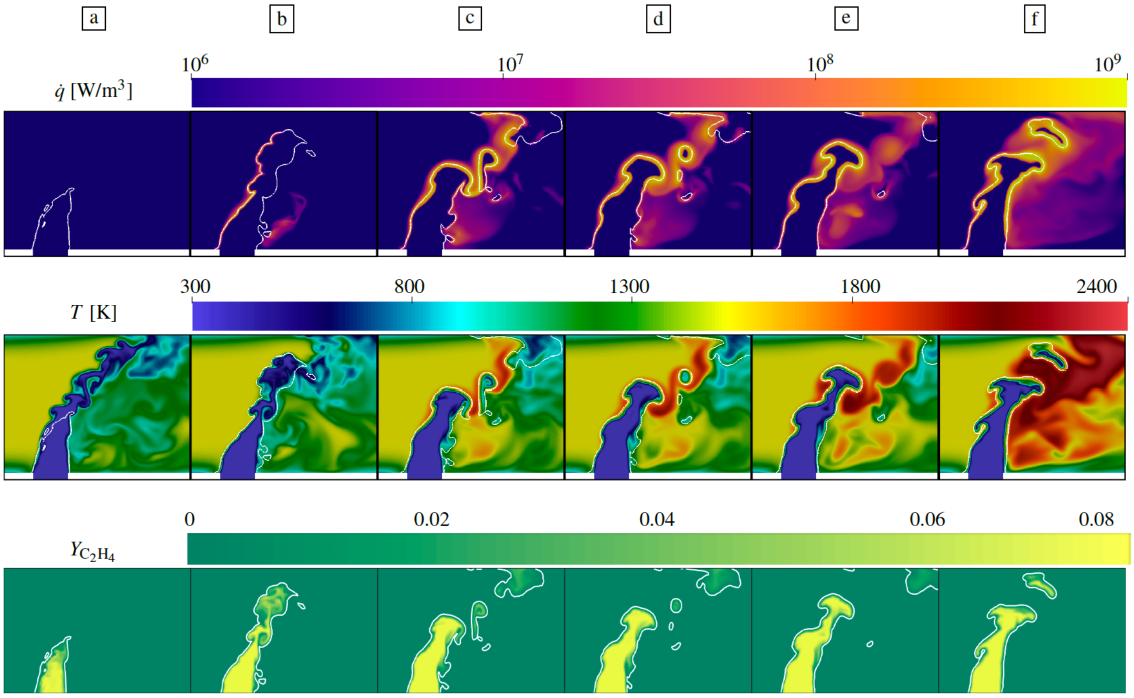

FIGURE 5. Instantaneous 2D maps at center section of the RJICF. From top to bottom: heat release rate, temperature, and ethylene mass fraction. From left to right: time sequence at t=3, 5, 7, 7.3, 7.8, 10 ms. Jet visualized by ethylene mass fraction Y_{C2H4} = 0.002 isocontour (white).

From this point, the heat release along the jet windward side intensifies due to the autoignition-cascade phenomenon. Low heat release at the lower jet zone diffuses downstream in the jet along and across the shear layer shifting the most reactive mixture fractions to higher values which are accompanied by even higher heat release rate values. This chain reaction allows the overall level of heat release rate on the windward side of the jet to exponentially grow until the flame appears by autoignition of richer regions (near and above stoichiometry). The flame first develops in the windward side and then grows, wrapping the jet in a very similar manner as the "heat release outbreak" process did, reaching the jet leeward side and stabilizing there by flame propagation, see the heat release and temperature maps of Figure 5. These findings were corroborated with chemical explosive mode analysis, that in addition shows the reaction kernels to start forming at very lean locations of the jet windward side root and then stabilizing near the most reactive mixture fraction composition. The added value of CEMA was to capture the initial chemically active regions, which are a precursor of peaks of heat release.

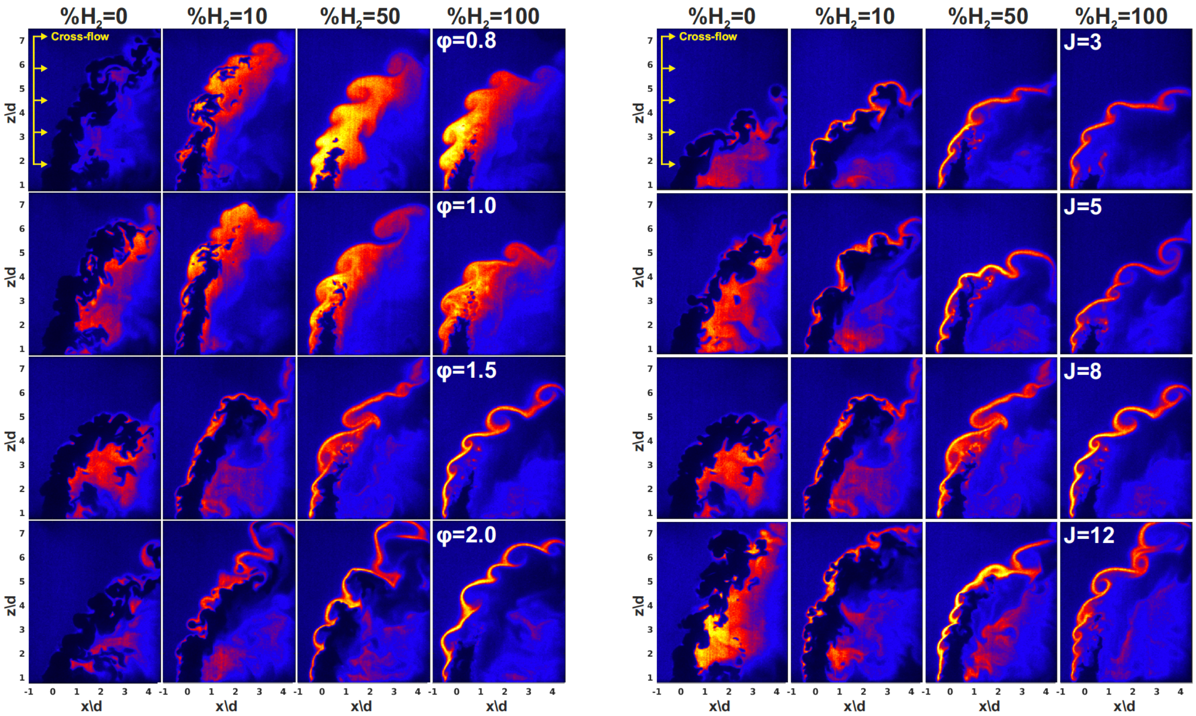

FIGURE 6. Instantaneous OH-PLIF signal for different jet equivalence ratios (0.8, 1.0, 1.5, 2.0) at J=8 (left plot), and jet momentum ratios (3, 5, 8, 12) at φ=1.5 (right plot). Horizontally, hydrogen mass percentage in fuel (0, 10, 50, 100).

From the experimental study of the AFS concept, the OH* chemiluminescence obtained in the experimental tests show a monotonic reduction of jet length, width, and curvature for increasing hydrogen fraction in all the combinations of equivalence ratio φ and momentum ratio J tested. Furthermore, it was observed that sensitivity of the jet morphology to hydrogen addition is higher for leaner mixtures. The time-averaged jet trajectories were fitted and compared to empirical correlations of non-reacting jet trajectories from the literature, showing good agreement. Moreover, a parametric characterization of the jet length was done with the experimental results and an empirical correlation was proposed to estimate it as function of jet-to-crossflow momentum ratio and hydrogen fraction. Instantaneous OH-PLIF images of the symmetry plane of the jet are shown in Figure 6 and used to describe the aerodynamics of the jet. It is shown that in all cases tested, the addition of hydrogen to the fuel mixture induces relaminarization of the jet windward front via its ignition. For H_2=100% the jet windward shear layer is aerodynamically governed by large scale coherent flow structures which develop along the jet. Furthermore, these images show the absence of OH production in the jet windward shear layer for H_2=0% at the current crossflow conditions. At values of H_2=50% robust flame anchoring at jet exit occurs.

Further information and results of the investigation of the AFS concept can be found in the two published articles:

- R. Solana-Pérez, O. Schulz and N. Noiray. "Simulation of the self-ignition of a cold premixed ethylene-air jet in hot vitiated crossflow." In: Flow, Turbulence and Combustion 106 (2021), pp. 1295–1311
https://doi.org/10.1007/s10494-020-00212-3

- R. Solana-Pérez, L. Miniero, S.A. Shcherbanev, M. Bothien and N. Noiray. "Morphology and dynamics of a premixed hydrogen-methane-air jet flame in hot vitiated turbulent crossflow." In: ASME Turbo Expo GT2020-16282 Volume 4B: Combustion, Fuels, and Emissions (2020) pp. V04BT04A066. https://doi.org/10.1115/GT2020-16282

4.2 Constant Pressure Sequential Combustion (CPSC) concept

The analysis of the constant pressure sequential combustion concept was addressed experimentally in two subsequent studies and numerically in a third study. Furthermore, a low-order numerical tool was developed to predict dominant combustion regimes and flame anchoring location. In this configuration, both the main and the sequential stages are in different axially staged combustion chambers. The sequential air is not premixed with the sequential fuel as in the AFS concept, but injected upstream to dilute the hot products from the first stage and reduce the flow temperature before the sequential injection point. This leads to colder flow and longer autoignition times that provide sufficient time for the mixing process between the sequential fuel and the hot vitiated flow before the mixture reaches the sequential flame. This mixing process is of paramount importance to avoid local high temperatures and ensure low emissions and high efficiency of the engine. The investigation of this configuration focused on two main topics, a) the effect of the mixing process quality on the sequential flame anchoring dynamics, and b) the investigation of the dominant combustion regime of the sequential flame under different operating conditions at both steady and transient conditions.

For the study of the effect of the mixing quality, the sequential fuel is injected using different injector geometries. We investigated the transition from a flame anchored in the sequential combustion chamber, to the situation where it stabilizes upstream into the mixing section, when the inlet flow temperature is increased. Of particular interest was the increasing rate of formation of autoignition kernels in this transition process. The underlying combustion regime change was analyzed with 0D reactor simulations, and the limitations and advantages of such a simplified low-order model of the flame location were investigated. The effects and importance of the mixing process between fresh fuel and the hot vitiated co-flow was also examined. Two different injectors were compared under the same operating conditions that create different flow structures along the mixing section. As a result of that, they provide different degrees of mixing between the hydrogen and the hot vitiated flow and allow to demonstrate the impact of mixing quality on the flame morphology.

Figure 7 shows the OH* intensity fields averaged in time and featuring the mixing section and sequential combustion chamber with 2 different injector geometries IC1 (a) and IC2 (b). The figure shows the upstream displacement of the flame front location associated with higher vitiated flow temperatures, transitioning from a flame anchored at the combustion chamber inlet to a flame stabilized inside the mixing channel. This is caused by the decrease of ignition delay times that brings the autoignition location upstream towards the injection point. Differences can be observed between the flames at IC1 and IC2 even though they were tested at the same operating point, especially at case DA16. These differences were solely caused by the different flow structures created at the mixing section by both inlet configurations, i.e. wakes of vortices (IC1) and swirling flow (IC2). 0D reactor network simulations showed that for operating points DA24 and DA20 autoignition occurs far downstream from the combustion chamber inlet, while for DA16 and DA12 it occurs respectively at 80 mm and 20 mm from the fuel injector. Flames in case DA12 are stabilized in the autoignition combustion regime. On the contrary, flames in cases DA24 and DA20 appeared mainly anchored at the combustion chamber inlet, i.e. stabilized by propagation at the recirculation regions created by the backward facing step, similarly to what was shown in [24, 25] for sequential combustion of methane flames. Case DA16 shows differences between IC1 and IC2. While the bulk heat release zone of the former is anchored at the combustor inlet in propagation regime, the latter is stabilized by autoignition inside the mixing channel.

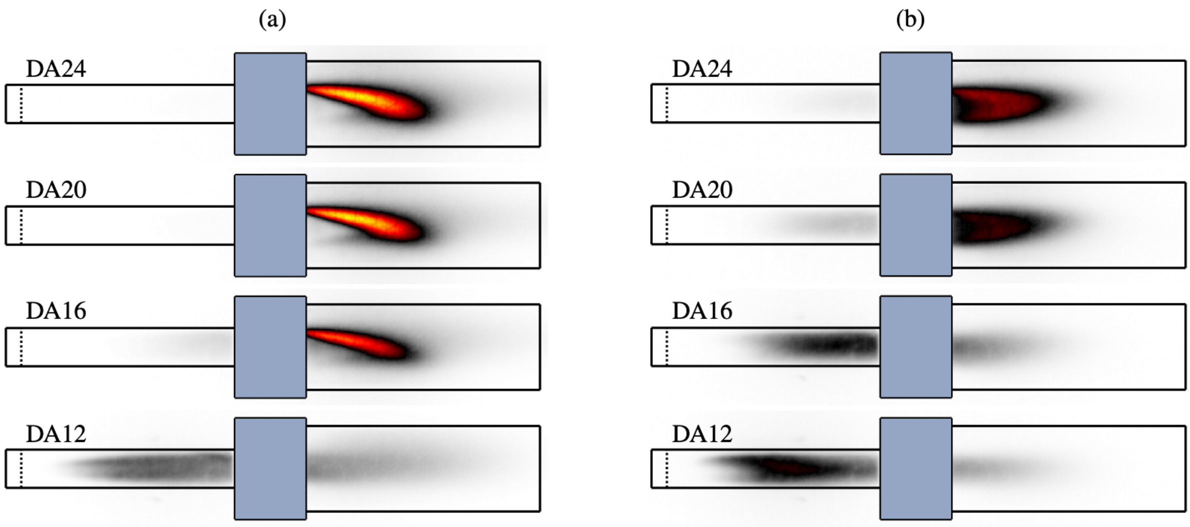

FIGURE 7. OH* Chemiluminescence intensity fields featuring the mixing section and the sequential combustor module. The image shows the time averaged flame morphology for varying dilution air mass flows. a) Results of the Vortex Generator injector IC1, b) results of the S-lobe injector IC2.

Figure 8 shows the NO emissions levels for both injector configurations as function of the operating conditions. It is shown that the NO emissions, that scale exponentially with temperature, are higher in IC1 than IC2. Furthermore, the highest difference (25%) in emission levels occur at operating conditions where the flame is anchored at the sequential combustor, i.e. corresponding to the desired operating point in industrial gas turbines. The cases where the flame stabilizes inside the mixing section show higher emission levels for both configurations. These were very relevant results that highlighted the importance of the mixing process and the flame combustion regime for clean operation of sequential systems.

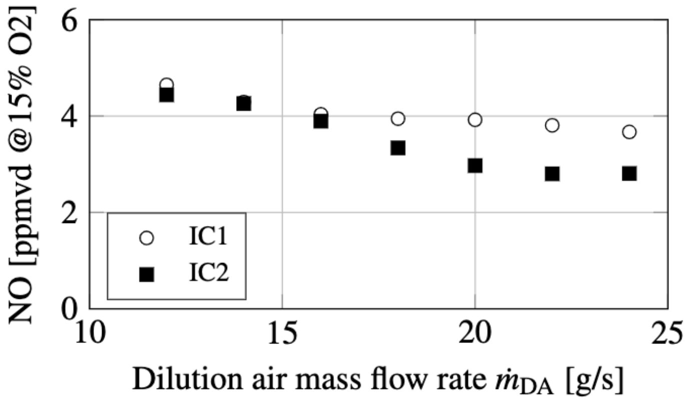

FIGURE 8. NO emissions at each operating condition shown as part per million volume at dry conditions (PPMVD) converted to a basis of 15% O_2

For the investigation of the dominant combustion regime transition of the sequential flame under different operating conditions two approaches were followed, namely steady and transient operation. To study the combustion regime transition during steady operation of the combustor, dilution air mass flow m_{DA} was fixed at several values between 22 g/s and 7 g/s. For transient operation investigations, m_{DA} was suddenly changed between 20 and 7 g/s, which triggered a fast transition of the combustion mode. High-speed hydroxyl radicals OH* chemiluminescence was used to characterize the combustion process, and optical emission spectroscopy (OES) and tunable diode laser absorption spectroscopy (TDLAS) were respectively used to extract mean and time-resolved temperatures of the vitiated gas in the sequential burner (SB). We investigated the transition from a propagation-driven turbulent flame anchored at the inlet of the sequential combustion chamber, to a flame stabilized by autoignition inside the mixing section of the burner when the dilution air mass flow is suddenly reduced. Zero-dimensional (0D) simulations were used to analyze the underlying combustion regime transition. A 0D reactor network was developed and calibrated with the experimental data. This simplified low-order model predicted well the flame location for both steady and transient operation. Moreover, the good agreement between the numerical results and the experimental data demonstrated that time resolved TDLAS successfully enables measurement of small temperature variations in the vitiated flow associated with non-perfect mixing of the different streams in the SB.

Figure 9 compares the experimental averaged flame presence (color map representing OH* averaged intensity) and the autoignition lengths computed from the most reactive autoignition delays of the 0D reactor model (black solid line) for various dilution air mass flow rates. At so-called “cold" conditions (m_{DA} > 18 g/s) the flame only appears anchored at the combustor inlet. The autoignition lengths computed from the 0D reactor (solid line) are far downstream from the actual flame front. This indicates that these flames are anchored by flame-propagation mechanism thanks to the recirculation of hot gas at the inlet of the combustion chamber, similarly to [25,28]. A further decrease of the vitiated flow temperatures does not affect the flame anchoring as it is not dominated by autoignition. At “hot" conditions (m_{DA} < 12 g/s) the flame is always stabilized by autoignition inside the SB mixing section, in agreement with the 0D model. Finally, at “mild" conditions (m_{DA} = 12-18 g/s) coexistence of flame inside the mixing section and at the combustion chamber inlet is observed. At these conditions, the predicted autoignition location is close to the end of the mixing section. At the same time, these temperatures are associated with large gradients of $\tau_{AI,mr}$. This means that small local temperature variations due to non-perfect mixing of the vitiated flow can lead to autoignition length displacements sufficiently large to push the flame front outside the mixing section, promoting a change of the flame stabilization mechanism.

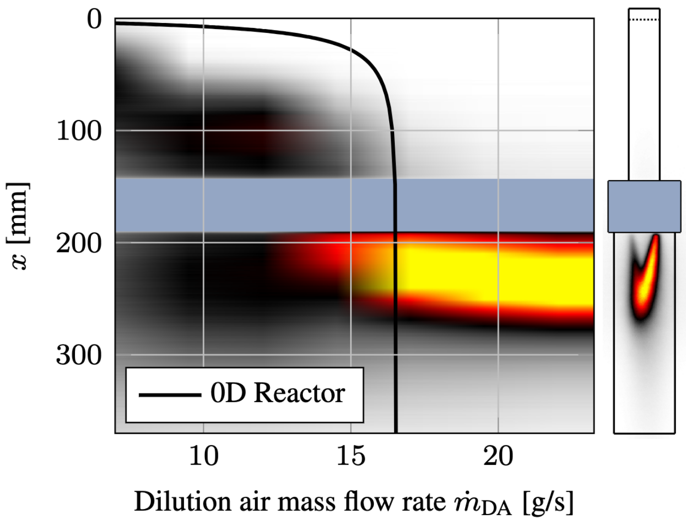

FIGURE 9. Time-averaged OH* intensity integrated in the y-direction along the mixing section (x from 0 to 180 mm) and combustion chamber (from 180 to 370 mm) for various m_{DA}. The solid line represents the autoignition lengths from the calibrated 0D reactor network. Fuel injector at x=0.

The transition from a H_2 flame anchored at the combustion chamber inlet to a flame stabilized inside the SB mixing section during transient operation of the combustor was analyzed in this section using synchronized measurements of OH* chemiluminescence and TDLAS. The TDLAS probe measured the temperature of the vitiated gas resulting from the mixing process between the hot products of the first stage flame and the dilution air stream. The TDLAS temperature signal was introduced as an input in the calibrated 0D reactor network model previously described. The target was to use this simplified low-order model to compute the autoignition delays and the autoignition lengths associated with the measured temperatures of the vitiated flow. Figure 10 shows the results of this analysis centered at the transition event. The red curves represent the estimated flame location computed with the 0D reactor network model that used the TDLAS temperature signal as input to compute autoignition delays at most reactive conditions. The blue curves show the actual flame front location extracted from the OH* chemiluminescence fields. Two different test runs are shown (bottom and top plots) under the same operating conditions for better corroboration. The time shift between both cases is caused by the acquisition setup not being synchronized with the dilution air change. Nevertheless, this has no effect on the results, as they represent the same phenomena just shifted in time. The results of Figure 10 show good agreement. The experimental flame front location (blue) correlates well with the autoignition location computed from 0D model (red). This demonstrated that the TDLAS technique successfully measures instantaneous local variations of the vitiated flow temperature. It also showed the high sensitivity of the autoignition flame to these temperature fluctuations related to the mixing quality, as they largely define the flame stabilization location. It should be noted that the fluctuations measured with TDLAS are associated with local variations of both temperature and gas composition. The vitiated flow was the result of the mixing between the hot products of the first stage and the cold dilution air. However, the mixing quality between these two streams can only be assumed partially premixed, i.e. lower temperatures are associated with higher concentration of dilution air, while higher temperatures are associated with higher concentration of combustion products from the first stage flame. This translates to local variations of temperature and species concentration (oxygen, radicals and other combustion products), that are expected to play a very important role on the definition of the autoignition properties. It is important to stress that the 0D reactor network model takes into account the mixing quality effect, i.e. the mixture composition variations associated with temperature fluctuations of the vitiated flow.

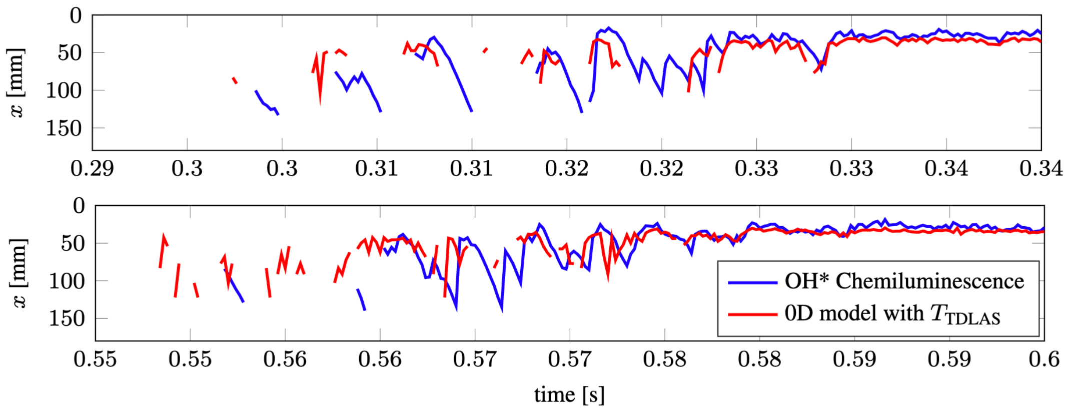

FIGURE 10. Flame front displacement from combustor inlet to mixing section. Blue: Experimental flame front detected from OH* chemiluminescence. Red: Autoignition locations computed from 0D reactor network using the TDLAS measured temperatures. Two test cases are presented (top and bottom).

Finally, the last study of this project addressed numerically the CPSC concept and focused on a) the study of the effect of the mixing process inside the mixing channel of the combustor and the performance of different injector geometries over the flame morphology and anchoring, b) a mapping of the turbine operating conditions based on real turbine operation procedures and its effect over dominant combustion regimes and flame stabilization mechanisms, and c) the study of the so-called “spontaneous propagation” mechanism affecting the sequential flame near crossover temperatures of hydrogen. The reactive LES simulations were conducted using the software AVBP from CERFACS. The results showed several differences in flame topology between different geometries of fuel injectors. A parametric study was performed to optimize the injector shape based on thermodynamic properties of the subsequent flame, and on the mixing quality achieved from each candidate. This led to an optimal shape definition and to the manufacturing of new injectors for future experimental studies that improve the performance of the sequential combustor. Figure 11 shows a mapping of the sequential flame for varying operating conditions of the combustor. For increasing power split (PS), i.e., balancing the amount of fuel from the sequential to the main combustor, one can observe that the flow temperature increases and the flame stabilization mechanism transitions from a propagating flame anchored at the inlet of the combustor, to an autoignition flame that stabilizes inside the mixing section.

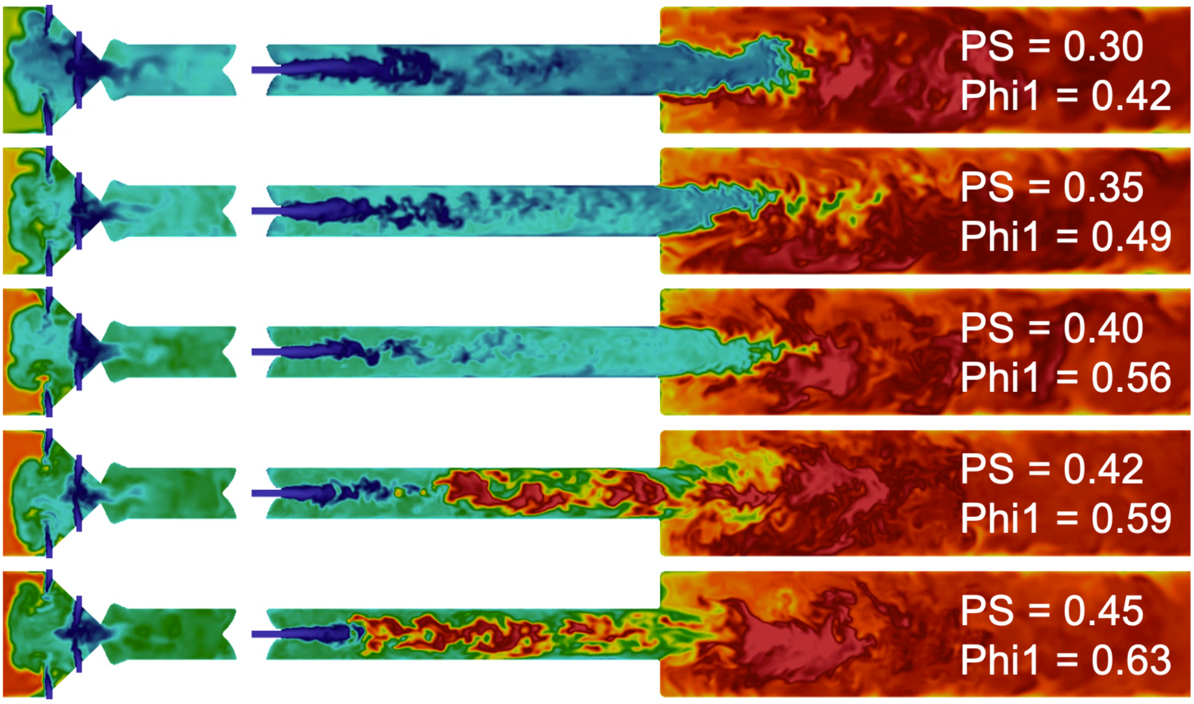

FIGURE 11. Instantaneous temperature fields at the central section of the sequential module. Transition between a flame anchored at the combustor inlet and a flame stabilized inside the mixing section can be observed for increasing Power Split (PS) between first and sequential stage, i.e. for increasing equivalence ratio of the first stage (Phi1).

Further information of the investigation of the CPSC configuration can be found in the two published articles:

- R. Solana-Pérez, S.A. Shcherbanev, A. Ciani and N. Noiray. “Effect of mixing on the anchoring and combustion regimes of pure hydrogen flames in sequential combustors." In: Journal of Engineering for Gas Turbines and Power. GTP-22-1295 (2022) https://doi.org/10.1115/1.4055509
- R. Solana-Pérez, S.A. Shcherbanev, B. Dharmaputra, A. Ciani and N. Noiray. “Combustion regime transition of H2 flames during steady and transient operation of a sequential combustor." In: Proceedings of the Combustion Institute. (2022) https://doi.org/10.1016/j.proci.2022.08.014.

5 Conclusions

The Advanced Reheat Combustion of Hydrogen (ARCH) project has enabled the successful achievement of the following objectives of the research contract: objectives 1 and 2 (Experimental and numerical simulations of sequential H2 combustion in straight channel at atmospheric condition) have been completed in the form of the two scientific papers [29,30]. Objectives 4, 5 and 6 (Experimental and numerical simulations of sequential H2 combustion in complex geometry at atmospheric condition under stationary and transient conditions) have also been successfully completed, in the form of the two journal papers [31,32] and in the last chapter of the Ph.D. thesis of Roberto Solana [33]. Objective 3 (numerical simulation of sequential H2 combustion in straight channel at high pressure) has not been completed and was left for future research on H2 combustion at elevated pressure. Instead, the development of a low order modeling tool based on detailed chemistry, which was not planned initially, has been added to the list of achievements [32].

More specifically, this project aimed at providing physical understanding of the numerous issues and knowledge gaps associated to the introduction of high concentrations of hydrogen fuel in gas turbines. Burning hydrogen in these complex systems is a state-of-the-art challenge that industry is currently facing, and the ARCH project helped in the advance of this technology. This investigation focused on sequentially staged combustion systems, following both experimental and numerical approaches. A summary of the main achievements obtained is given next.

First, we focused on the axial fuel staging (AFS) concept in a straight channel. The sequential flame found in this concept is in the same combustion chamber as the first stage, and it features a jet-in-crossflow configuration in a straight channel where a premixed mixture of fuel and air is injected inside the hot products from the first stage. Autoignition and flame stabilization take place very close to the injection point due to the high temperatures. In this investigation we focused on 2 main topics, a) the transient ignition process of the jet (numerical study), and b) the analysis of stationary jet flames for various concentrations of hydrogen enrichment (experimental study). The findings of this activity showed that, for the transient ignition process of the jet flame, autoignition is the dominant combustion mode that triggers heat release in the windward side of the jet at locations leaner (with less amount of fuel) than the most-reactive conditions. After ignition is triggered in those specific locations the heat release begins a chain reaction that quickly extends the flame around the jet. On the windward side of the jet the flame is stabilized by autoignition, while on the leeward side of the jet the flame anchors strongly by propagation due to the recirculation region in the wake of the jet. On the other hand, the investigation of the steady jet flames for varying concentrations of hydrogen showed that hydrogen enrichment has strong consequences on the jet flame morphology and anchoring properties. It was demonstrated that the addition of hydrogen led to an increase reactivity of the mixture, that translates in more compact flames, strong reductions of the lift-off height and strong anchoring of the flame to the injector, increasing the risk of damage of the test-rig components. We therefore identified the auto-ignition and propagation combustion regimes in such straight channel configuration, analysed the transient ignition and the stationary flame, using various optical diagnostics techniques (experimental) and simulation tools (numerical).

Second, we developed a low-order modelling tool capable of predicting the dominant combustion regime and analytical combustion properties of the flame in complex geometry under reheat conditions. The tool was successfully developed and tested against experimental data, and it provided a first order approximations of the flame expected anchoring location and dominant combustion regimes that are of paramount importance for the design and setup of the experimental investigations. This tool was also extended to high pressure conditions and will be of great importance for future investigations at CAPS laboratory.

Then, we focused on the constant pressure sequential combustion (CPSC) concept in complex geometry with experiments. In this configuration, both the main and the sequential stages are in different axially staged combustion chambers. Furthermore, the sequential air is not premixed with the sequential fuel as in the AFS concept, but injected upstream to dilute the hot products from the first stage and reduce the flow temperature before the sequential injection point. This leads to colder flow and longer autoignition times that provide sufficient time for the mixing process between the sequential fuel and the hot vitiated flow before the mixture reaches the sequential flame. This mixing process is of paramount importance to avoid local high temperatures and ensure low emissions and high efficiency of the engine. We focused on two main topics, a) the effect of the mixing process quality on the sequential flame anchoring dynamics, and b) the investigation of the dominant combustion regime of the sequential flame under different operating conditions at both steady and transient conditions. The results showed that, even at the same operating condition of the engine, the quality of the mixing process of the sequential fuel can influence the dominant combustion regime and the flame anchoring characteristics. This finding was of paramount importance as it demonstrated the high sensitivity of the sequential flame dynamics to this mixing process, and it showed that the mixing performance should be an important design parameter for this kind of engines. Furthermore, the results showed three types of flame stabilization regimes and a full mapping of them was done based on the operating condition of the engine. This experimental data was used to successfully validate the performance of the low order modelling tool.

Finally, we performed numerical simulations of the CPSC concept and focused on a) the study of the effect of the mixing process inside the mixing channel of the combustor and the performance of different injector geometries over the flame morphology and anchoring, b) a mapping of the turbine operating conditions based on real turbine operation procedures and its effect over dominant combustion regimes and flame stabilization mechanisms, and c) the study of the so-called “spontaneous propagation” mechanism affecting the sequential flame near crossover temperatures of hydrogen. The results provided valuable data for the manufacturing of new sequential injectors that improved the mixing process quality. At the same time, a mapping of the flame stabilization mechanism at operating conditions that were not possible to obtain experimentally was successfully achieved. And the transient phenomenon of “spontaneous propagation” was studied, which otherwise could not be obtained experimentally.

6 Outlook and next steps

Based on the results obtained from the ARCH project, there is a clear need to continue this line of research at elevated pressure in order to establish a solid understanding and predicting methods of the physics of H_2 flames in gas turbines. Furthermore, there is a need for developing new control technologies to ensure robust combustion process in gas turbines during rapid transient and combustion instabilities. Recently, it was demonstrated that one can use cold plasma for successfully controlling natural gas flames in sequential combustion systems. Therefore, considering such plasma actuation for H_2 flames also constitutes a very promising research avenue for the development of the next H_2 combustion technologies.

7 Publications

Peer-reviewed articles

- R. Solana-Pérez, O. Schulz and N. Noiray. “Simulation of the self-ignition of a cold premixed ethylene-air jet in hot vitiated crossflow." In: Flow, Turbulence and Combustion 106 (2021), pp. 1295–1311
https://doi.org/10.1007/s10494-020-00212-3
https://www.research-collection.ethz.ch/handle/20.500.11850/440774

- R. Solana-Pérez, L. Miniero, S.A. Shcherbanev, M. Bothien and N. Noiray. “Morphology and dynamics of a premixed hydrogen-methane-air jet flame in hot vitiated turbulent crossflow." In: ASME Turbo Expo GT2020-16282 Volume 4B: Combustion, Fuels, and Emissions (2020) pp. V04BT04A066. https://doi.org/10.1115/GT2020-16282
https://www.research-collection.ethz.ch/handle/20.500.11850/509037

- R. Solana-Pérez, S.A. Shcherbanev, A. Ciani and N. Noiray. “Effect of mixing on the anchoring and combustion regimes of pure hydrogen flames in sequential combustors." In: Journal of Engineering for Gas Turbines and Power. GTP-22-1295 (2022)
https://doi.org/10.1115/1.4055509
https://www.research-collection.ethz.ch/handle/20.500.11850/598107

- R. Solana-Pérez, S.A. Shcherbanev, B. Dharmaputra, A. Ciani and N. Noiray. “Combustion regime transition of H2 flames during steady and transient operation of a sequential combustor." In: Proceedings of the Combustion Institute. (2022)
https://doi.org/10.1016/j.proci.2022.08.014
https://www.research-collection.ethz.ch/handle/20.500.11850/598109

- S.A. Shcherbanev, Q. Malé, B. Dharmaputra, R. Solana-Pérez and N. Noiray. “Effect of plasma-flow coupling on the ignition enhancement with non-equilibrium plasma in a sequential combustor", Journal of Physics D: Applied Physics. (2022)
https://doi.org/10.1088/1361-6463/ac82fa
https://www.research-collection.ethz.ch/handle/20.500.11850/566923

Conference contributions

- R. Solana-Pérez, O. Schulz and N. Noiray. "The ignition process of a premixed reactive jet in hot vitiated crossflow", 17th International Conference on Numerical Combustion (NC19), Aachen, Germany, May 6-8, 2019
https://www.research-collection.ethz.ch/handle/20.500.11850/514832

- R. Solana-Pérez, O. Schulz and N. Noiray. Simulation of the self-ignition of a cold premixed Ethylene-Air jet in hot vitiated crossflow, 11th Mediterranean Combustion Symposium (MCS11), Tenerife, Spain, June 16-20, 2019
https://www.research-collection.ethz.ch/handle/20.500.11850/514833

Ph.D. thesis

R. Solana-Pérez, “Dynamics of hydrogen flames in gas turbine sequential combustors”, ETH Zürich

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