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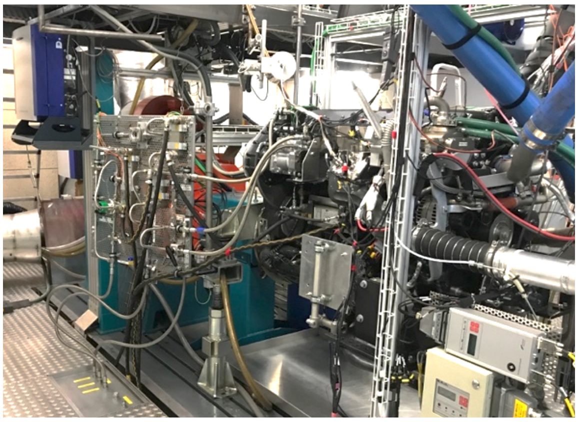
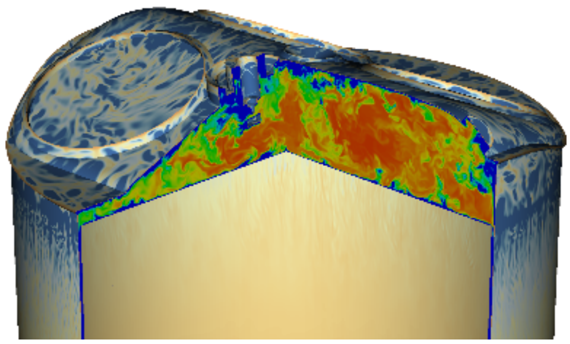
Conference on Combustion Research in Switzerland 2021

Programme & Abstracts

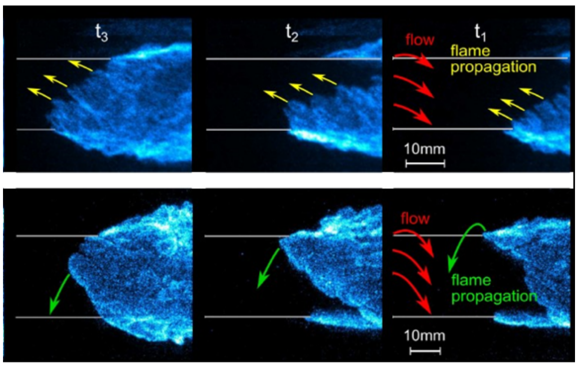
Date:	**Friday, 17th September 2021**
Location:	ETH Zürich, Zentrum HG E3
Time:	9:15 a.m. to 5:00 p.m.



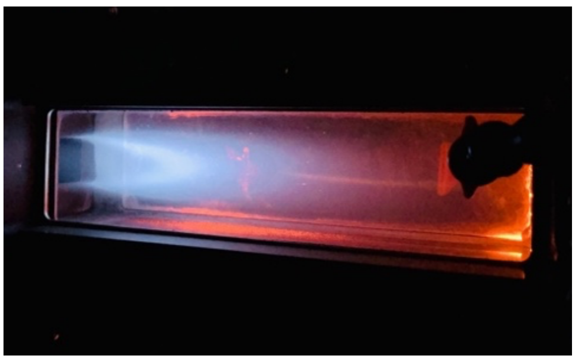
6-cylinder Diesel-Engine on a test rig with DME injection and EGR blower
Hardy, FPT; Soltic, Empa



DNS of full scale pent-roof engine: temperature distribution on cut planes, wall heat flux on surfaces
Giannakopoulos, Frouzakis, Keskinen, Bolla, Wright and Boulouchos, LAV ETHZ



Two distinct flame propagation pathways in a gas turbine burner: (a) 50° (b) 65° Swirler
Ebi, Energy System Integration, PSI



Combustion of Hydrogen in the hot vitiated flow of a laboratory sequential combustor
Solana Pérez, Shcherbanev, Noiray, CAPS ETHZ

Conference on Combustion Research in Switzerland 2021

Welcome

Chemical energy carriers (fuels) play a unique role in the energy system because they have a very high energy density and can be stored for long periods of time. They can be sourced from many different pathways and tailored for a broad range of applications.

However, to achieve the objectives of international climate policy, the use of fossil fuels must be drastically reduced. More sustainable fuels are produced from biomass, waste materials or by using renewable electricity. A unique advantage of combustion as a thermochemical energy conversion is its high tolerance towards fuel composition and properties.

Extensive knowledge is available about the combustion of fossil fuels in internal combustion engines or gas turbines, which are systems that already achieve high efficiencies with low pollutant emissions. This knowledge must now be adapted and expanded for the use of more sustainable fuels. Maximum efficiency, minimum emissions, and load flexibility remain overarching objectives, complemented with application specific requirements in sectors like transport or power generation. Increasing expectations on fuel flexibility come on top of this.

Swiss combustion researchers from industry and the universities of applied sciences and the ETH domain actively address these challenges. Their competence is internationally recogniced. At the 2021 edition of our biennial Conference on Combustion Research in Switzerland, you will hear results from their current research projects. Please check the preliminary conference program for a list of invited presentations.

The primary goal of the conference is to foster the exchange of information between industry and academia, especially for junior scientists. We hope that the event will once again be a valuable networking opportunity. The conference is organized as a hybrid event on site at the ETH Zurich or online via livestream.

Contact:
Anna Michailidis
Secretariat Prof. Nicolas Noiray
CAPS - Combustion and Acoustics for Power & Propulsion Systems Lab.
Sonneggstrasse 3, 8092 Zurich

E-Mail: mianna@ethz.ch
Tel.: +41 44 632 08 71

Organizing committee:
Prof. Dr. Nicolas Noiray,
Head of the laboratory of Combustion and Acoustics for Power and Propulsion Systems CAPS; ETH Zurich
Prof.em. Dr. Konstantinos Boulouchos; ETH Zurich
Dr.-Ing. Peter Jansohn,
Energy System Integration; Paul Scherrer Institute (PSI)
Dr.-Ing. Carina Alles,
Head of the research domains Industrial Processes, Combustion, Heat Pumps; Swiss Federal Office of Energy
Dipl.-Ing. Stephan Renz,
Head of the research programme on Combustion Based Energy Systems; Swiss Federal Office of Energy

Programme

08:30 Registration starts ▪ Networking

09:15 **Welcome address and presentation of CAPS Combustion and Acoustics for Power & Propulsion Systems Laboratory at ETHZ**
Nicolas Noiray, CAPS ETH Zurich

09:35 **Keynote: Thermochemical conversion of renewable fuels for climate change mitigation AND security of energy supply**
Konstantinos Boulouchos, LAV ETH Zurich

10:05 **Contribution of DNS to in-depth understanding of combustion processes with different fuels**
Christos Frouzakis, CAPS ETH Zurich

10:30 Coffee break

Session 1, Internal Combustion Engines

11:00 **Investigation of the suitability of DME as an alternative fuel in heavy duty vehicles**
Gilles Hardy, FPT Motorenforschung AG, Arbon, Patrik Soltic, EMPA

11:25 **Flexible engines: optimized operation with alternative fuels and various aftertreatment configurations**
Christophe Barro, Vir2sense GmbH, Baar

11:50 **Fundamental investigation of lube oil pre-ignition phenomena in gas engines**
Pascal Süess, ITFE FHNW, Brugg-Windisch

12:15 **Advanced modelling of wall heat transfer in Otto engines validated through DNS and nonintrusive experiments**
Yuri Wright, LAV ETH Zurich

12:45 Lunch break

Session 2, Gas Turbine

14:15 **Boundary layer flashback at gas turbines conditions with hydrogen addition**
Alex Novoselov (CAPS, ETH Zurich), Dominik Ebi (Paul Scherrer Institute)

14:40 **Plasma-assisted combustion in sequential combustors**
Sergey Shcherbanev (CAPS, ETH Zurich)

15:05 **Thermoacoustic instabilities in annular combustors**
Abel Faure Beaulieu (CAPS ETH Zurich)

15:30 Coffee break

Session 3, Gas Turbine & Internal Combustion Engines

15:50 **Center body burner for sequential combustion: superior performance at lower emissions**
Andrea Ciani, Ansaldo Energia Switzerland, Baden

16:15 **Towards the Development of an Engine Performance Digital Twin**
Markus Wenig WIN GD & Markus Kerellaj ITFE FHNW

16:40 **Closing remarks**
Stephan Renz, Swiss Federal Office of Energy

Abstracts

Contribution of DNS to in-depth understanding of combustion processes with different fuels

Christos E. Frouzakis
Combustion and Aeroacoustics for Power & Propulsion Systems (CAPS)
ETH Zurich

By resolving all relevant spatiotemporal scales, direct numerical simulations (DNS) provide a complete description of the variations in the flow, temperature and composition fields in a combustion system. The insights that can be obtained by post-processing the generated data can complement theoretical and experimental investigations towards in-depth understanding of the complex interactions of the multiple physico-chemical processes in the reacting mixture.

Following a brief presentation of the high-order low Mach number reactive flow solver that can efficiently take advantage of large-scale high-performance computing systems and a showcase of some of its applications in canonical and laboratory-scale setups, the presentation will focus on the propagation speed of premixed flames into different fuel-air mixtures. Wherever possible, the DNS results will be compared with theoretical expressions that are obtained in the asymptotic limit where the flame is thin in comparison to the representative hydrodynamic length scale (hydrodynamic model). We will also discuss thermodiffusively-unstable flames of hydrogen and syngas.

References

G. Giannakopoulos, C. Frouzakis, S. Mohan, A. Tomboulides, M. Matalon, Consumption and Displacement Speeds of Stretched Premixed Flames - Theory and Simulations, Combustion and Flame, 208, 164-181, 2019

M. Jafargholi, G. K. Giannakopoulos, C. E. Frouzakis, K. Boulouchos, Laminar syngas-air premixed flames in a closed rectangular domain: DNS of flame propagation and flame/wall interactions, Combustion and Flame, 188, 453-468, 2018

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C. Altantzis, C. E. Frouzakis, A. G. Tomboulides, K. Boulouchos, Direct numerical simulation of circular expanding premixed flames in a lean quiescent hydrogen-air mixture: Phenomenology and detailed flame front analysis, Combustion and Flame, 162(2), 331-344, 2015

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C. E. Frouzakis, N. Fogla, A. G. Tomboulides, C. Altantzis, M. Matalon, Numerical study of unstable hydrogen/air flames: Shape and propagation speed, Proceedings of the Combustion Institute,35, 1087-1095, 2015

Investigation of the suitability of DME as an alternative fuel in heavy duty Vehicles

Gilles Hardy, Daniel Klein, FPT Motorenforschung AG
Patrik Soltic, Thomas Hilfiker, Empa
Tommaso Lucchini, Andrea Schirru, Politecnico di Milano

For long-haul heavy-duty transport, ICE (Internal Combustion Engine) will continue to play a dominant role until 2050 and probably beyond.
Diesel fuel with its high energy density, even made of biogenic or synthetic source, will not remain the prime and cost-efficient solution under always more stringent emission limits for greenhouse gas and pollutants.
Our theoretical assessment of all relevant alternative fuels from renewable source resulted in DME (Dimethyl-ether) being the most promising fuel. DME shows one of the best compromises regarding energy density, emission reduction potential and production cost. The aim of the project led by FPT was to demonstrate such potential by running on a testbed a typical engine for long-haul applications (FPT Cursor11: 11 L Diesel engine with 338 kW / 2300 Nm) which has undergone some specific modifications to run on DME.
To make relevant comparisons, the same engine has been measured with diesel fuel before replacing only the DME related parts like the high pressure pump and or the injectors. The rest of the base engine remained untouched.
CFD simulations were carried out to pre-optimize the combustion chamber and later validate a consolidated numerical methodology based on experimental data for future optimization activities.

1.https://www.aboutdme.org/aboutdme/files/ccLibraryFiles/Filename/000000002392/BioDME_Volvo_brochure.pdf

2.“DME Handbook” edited and published by Japan DME Forum. ISBN 978-4-9903839-0-9 C3050

3.https://oberonfuels.com/2017/01/12/oberon-fuels-mack-trucks-york-city-department-sanitation-customer-demonstration-dimethyl-ether-dme-powered-mack-truck/

Flexible engines: optimized operation with alternative fuels and various aftertreatment configurations

Christophe Barro
Vir2sense GmbH

The reduction of greenhouse gases has become one of the key challenges in transportation and mobility. While electrification appears as a viable solution in some subsectors (or at least a relocation of the challenge into other sectors i.e. power generation), combustion engines are more difficult to replace in others (e.g. marine, aircraft). In these subsectors, the best opportunities to reduce greenhouse gas emissions are the introduction of fuels with lower CO2 footprint, a reduction in fuel consumption due to efficiency increase, or ideally the combination of both. The combustion characteristics of such fuels are different and require engine settings' modifications to profit most from these characteristics. In addition, not only the fuel, but also the engine hardware configuration can change from one application to another. For this reason, a tool to optimize the engine efficiency depending on fuel used and hardware configuration has been developed.
In a first approach[1)], a model platform has been developed. The combustion and emission formation process has been modelled and included into a GT Power model of a 6-cylinder heavy-duty engine. The model includes an SCR (selective catalytic reduction) for NOx reduction and a DPF (particulate filter), which requires energy for regeneration depending on the soot oxidation activity of each fuel which was determined through detailed analysis within this project. This model platform enables the comparison of engine efficiency when operating the engine with different fuels, including e.g. benefits from a fuel with lower tendency to form soot. The fuels tested include Hydrogenated Vegetable Oil (HVO), Gas-to-Liquid fuel (GTL) and polyoximethylene dimethylether (OME3-6), which were tested neat and as blends with Diesel or among each other.
The different fuel characteristics result in a potential to optimize diesel internal combustion engines including aftertreatment systems (Diesel particulate filter and NOx SCR catalyst) for operation with fuels of different composition. For the fuels investigated, the following maximum and minimum well-to-wheel CO2 reduction potential values were found among different loads and different SCR volume (well-to-tank in brackets):
• Diesel with 20% HVO: 19.2% / 17.7% (18%)
• HVO: 90.2% / 89.6% (90%)
• Diesel with 7% OME 6.1% / 3.8% (4%)
• 77% HVO with 18% OME and 5% stabilizer: 88.2% / 87.9% (88%)
In particular fuel blends with low percentage of renewables benefit most from the fuel specific adaptations of engine settings.
In a second example[2),3)] a modified approach has been applied online on a 6-cylinder 1 MW marine engine equipped with an SCR system, which was run in a test cycle combining steady state and transient operation. In this strategy, the engine settings have been adapted according to the real-time SCR NOx reduction capability, based among others on internal SCR temperature, estimated by an SCR digital twin. The engine settings are adapted using an online optimizer, which was fed with modelled engine characteristics. In addition to that, a physically-assisted virtual NOx sensor (Vir2sense NOx PVS[4)]) was used to adapt the engine model and correct for different environmental conditions and component ageing etc. During the cycle, the Intelligent SCR system was able to reduce the NOx tailpipe emissions by more than 60% compared to a standard map-based control system set to 90% NOx reduction in the catalyst, while simultaneously lowering fuel consumption by roughly 1.7% and ammonia slip by more than 40%. The system was also tested with different SCR catalysts to showcase the adaptability of the system to different setups. Using a different, smaller catalyst, the engine showed 0.5% lower fuel consumption, 40% lower tailpipe NOx emissions and similar ammonia slip compared to the base setup. When using a less reactive catalyst (33% less Vanadium), the engine demonstrated 1.5% lower fuel consumption, combined with more than 30% less

NOx and 10% lower ammonia slip. For the latter two configurations, the only adaptation was the inclusion of the new catalyst design characteristics in the control system setup. Such a system can be used to achieve very low NOx emissions with limited ammonia slip combined with low fuel consumption in any installation without the need for extensive engine tuning.

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Fundamental investigation of lube oil pre-ignition phenomena in gas engines

Pascal Süess, Patrick Cartier, Silas Wüthrich and Kai Herrmann
FHNW – University of Applied Sciences and Arts Northwestern Switzerland, Windisch

Internal combustion engines have progressed to efficient and reliable machines. Even though the electrification of individual mobility increases, they will probably remain the dominant propulsion source for heavy-duty or marine freight transportation. In view of emission legislation, combustion processes need to be improved and carbon-reduced or alternative (renewable) fuels considered. In the marine sector, gas/dual-fuel engines feature efficiency comparable to a diesel engine with reduced CO_2 and considerably lower particulate as well as NO_X emissions. In the underlying (low temperature) combustion concept, ignition of a lean premixed gas/air charge by a pilot fuel or reactive jet takes place. With increasing efficiencies, a reliable operating range becomes limited due to "knocking" or "misfiring" effects. Moreover, unwanted pre-ignition can appear since the premixed charge under high pressure and temperature conditions is susceptible to early ignition phenomena, probably based on self-ignition of lube oil in hot zones. Those effects can cause steep pressure gradients and high peak pressures, respectively temperatures that can even damage the engine.

Fundamental investigation of pre-ignition based on standard quantities obtained from conventional engine test benches is difficult since necessary information on (turbulent) flow field, evaporation and mixing processes, phase transitions and subsequent reactions (uncontrolled inflammation) can usually not be determined. Thus, application at the optically accessible engine test facility[1] "Flex-OeCoS" [1] with a possibility of selective lube oil addition allows in-depth examination of the underlying mechanism of the phenomena. Since common fuel injectors are not suitable for this application because of their hydraulic working principle using high injection pressures, special injectors had to be evaluated. They should allow for controlled lube oil addition and still withstand engine relevant conditions in terms of pressures and temperatures. A self-developed so-called "PZDI" injector (PieZo-Droplet-Injector [2]) for defined single lube oil droplet addition as well as a modified piezo direct-actuated common-rail injector for the introduction of smallest lube oil amounts were applied.

In this talk, latest results of experimental investigations to gain detailed insight into pre-ignition phenomena are presented. The influence of a variety of affecting parameters has been investigated – such as gas/air charge composition, process gas temperatures and pressures, injection rate/duration, and flow field. Conclusions shall give extended insight into pre-ignition processes of dual-fuel combustion [3], and acquired reference data is used to validate and further develop corresponding simulation models.

Acknowledgments

This work has been conducted by the research projects "PROGrESs" (SFOE, SI/501942-01) as well as "Modeling of Pre-ignition in Gas Engines" (FVV/CORNET) and financial support is gratefully acknowledged.

References

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Boundary layer flashback at gas turbine conditions with hydrogen addition

A. G. Novoselov[1], **D. Ebi**[2], **P. Jansohn**[2], **N. Noiray**[1]
[1] CAPS Laboratory, Department of Mechanical and Process Engineering, ETH Zürich, Zürich
[2] Energy and Environment Division, Paul Scherrer Institute, Villigen

The addition of hydrogen fuel to stationary gas turbines presently running on natural gas is an appealing path forward for the reduction of carbon emissions because it can be achieved without dramatic changes to the current power generation infrastructure. Unfortunately, the addition of hydrogen can significantly modify the flame dynamics. One byproduct of such addition is flame flashback, a potentially destructive event wherein the flame exits the combustion section and propagates through the mixing section. Despite the relevancy of boundary layer flashback in practical devices, this phenomenon is generally studied only at low Reynolds numbers, atmospheric conditions, and in non-swirling flows, none of which are representative of conditions in real gas turbines.

In the present work, several open questions regarding boundary layer flashback are addressed through a study of an axial swirl burner at conditions approaching those in practical combustors. Measurements are taken at pressures up to 7.5 bar, preheat temperatures up to 300°C, and inlet velocities up to 40 m/s and are studied in tandem with hydrogen content variations up to 100%. These measurements indicate a significant increase in the flashback propensity with increasing hydrogen concentration. Two distinct flame rotation modes are identified during flashback with the transition occurring as a function of the swirl number. Critically, the flashback limit is shown to occur at a constant extinction strain rate regardless of hydrogen quantity.

These measurements motivate the development of a simple model for boundary layer flashback limits based on critically strained flames. According to the model, the flashback limit occurs at the equivalence ratio where the extinction limit flamespeed matches the mean axial flow velocity one thermal distance from the wall. The model performs extremely well when compared to non-swirling turbulent boundary layer flashback data. It is then extended to study the effect of additional parameters including pressure and hydrogen content on the flashback limit indicating excellent qualitative agreement with the limited available data.

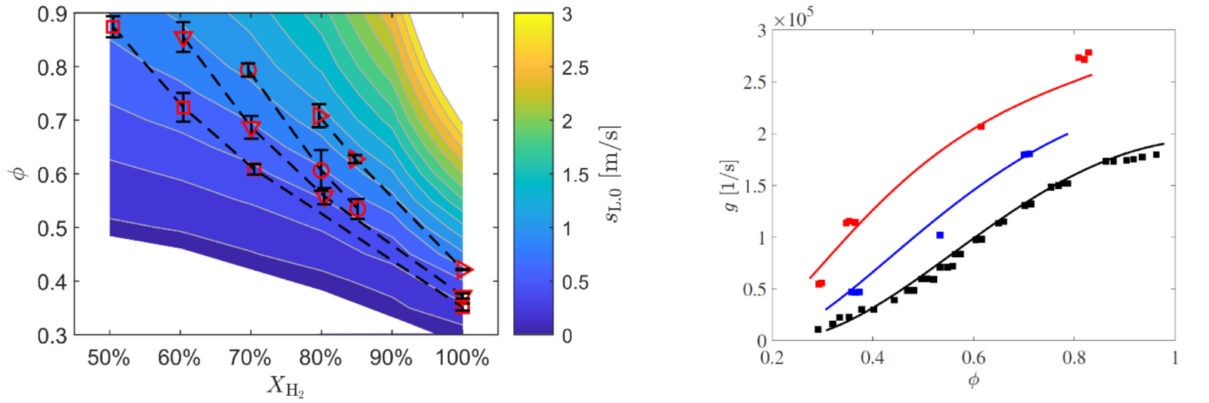

Figure 1: On the left, the flashback limits at p=2.5 bar and Tpre=200 °C [1]. On the right, experimentally measured boundary layer flashback limit data of Eichler [2] (squares) compared to the model developed in this work (lines). The flashback limits cover three discrete preheat temperatures of 20 °C (black), 200 °C (blue), and 400 °C (red).

Acknowledgments: This project is supported financially by the Swiss Federal Office of Energy (SFOE) under the research project Flash-GT.

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Plasma-assisted combustion in sequential combustors

<u>S. Shcherbanev</u>, B. Dharmaputra, Q. Malé, T. Krzymuski, M. Impagnatiello, N. Noiray
CAPS Laboratory, Department of Mechanical and Process Engineering, ETH Zürich, Zürich

Sequential architecture of the combustion chamber of the heavy duty ground based gas turbines allows the power production with renewable sources while increasing the operational flexibility and maintaining low emissions. The key idea of sequential combustors is to arrange two or more flames in series. The first lean premixed pilot flame serves as a generator of hot vitiated flow containing the combustion products and remaining oxygen. The second stage flame is autoignited in the hot products of the pilot flame. The sequential combustion architecture used in Ansaldo GT36 gas turbines and described in [1] includes an air dilution section located upstream of the sequential fuel injection. This arrangement enables very high fuel flexibility, thanks to the sequential combustion of a homogeneous air-fuel mixture.
Thermoacoustic instabilities entail significant technical difficulties in organizing sequential flames. Such type of instabilities originates from the constructive feedback between chamber acoustics and heat release rate fluctuations of the flames. It leads to the increased danger of the gas turbine operation because of the induced vibrations and risk of the flame extinction and/or flashback during a high power operation.
The control of thermoacoustic instabilities can be carried out either by passive or active control methods. Passive methods implies the use of different types of dumpers inside the combustion chamber. Whereas active control is performed adaptively by means of energy delivery to the system. An important criterion for active control is that the energy supplied to the system must be much smaller than the energy released by the system. Non-equilibrium plasma is an efficient tool for the active control of the flames in sequential combustors.
The kinetics processes of the plasma-assisted combustion [2] is the fundamental basis for understanding the processes of ignition of combustible mixtures and flame stabilization with low temperature plasma. In this talk, the kinetics of the non-thermal plasma will be discussed for the discharges in air and in hot vitiated environment. Three types of the discharges: glow, spark and thermal spark and their efficiencies on ignition are considered. The results of the plasma-assisted active control of the flames in sequential combustor is presented. One of the distinctive features of the active control with non-equilibrium plasma is that the power of the controlled discharge is very small compared to the thermal power of the flames in sequential combustor (<0.5%). The experimental tests were performed within the atmospheric pressure sequential combustor presented in figure 1.

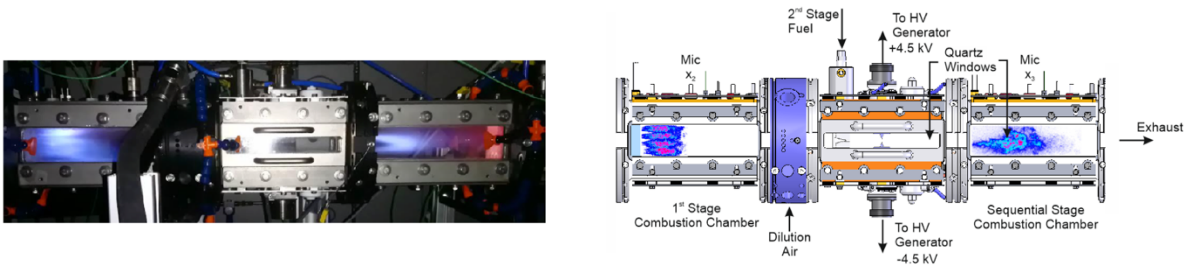

Figure 1: Atmospheric pressure sequential combustor.

Acknowledgments: This project is supported financially by the European Research Council under the ERC Consolidator Grant (No: 820091) TORCH (2019-2024).

References:
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Thermoacoustic instabilities in annular combustion chambers

A. Faure-Beaulieu[1], **T. Indlekofer**[2], **J. R. Dawson**[2], **N. Noiray**[1]
[1] CAPS Laboratory, Department of Mechanical and Process Engineering, ETH Zürich, Zürich
[2] Department of Energy and Process Engineering, NTNU, Trondheim

Thermoacoustic instabilities result from a constructive feedback loop between a flame and its own combustion noise reflected back. They frequently happen in combustion systems with low acoustic dissipation and can lead to high amplitude acoustic oscillations that cause mechanical fatigue and failure. Additionally, they are extremely sensitive to various factors like the geometry of the combustor, the fuel composition, the temperature, the acoustic properties of the walls, and therefore they are difficult to predict. This is why they can slow down the development of many high-power combustion systems like rocket engines, gas turbines or aircraft jet engines, especially in the actual context where new architectures and new fuels are needed. Since full-scale tests are expensive, we need better theoretical understanding and modelling of these instabilities to tackle them at early design stages. In this talk, we focus on the specific case of annular combustion chambers, frequently adopted in gas turbines, and even more in aircraft jet engines, because of their light weight and their simplicity of manufacturing compared to can-annular combustors.

In annular chambers, thermoacoustic instabilities frequently involve azimuthal acoustic modes, which are degenerate because of the rotational symmetry of the chamber: this specificity causes a very wide range of thermoacoustic dynamics that are non-trivial and are not observed in simpler systems like single-can combustors. The instantaneous state of an azimuthal mode can be described as a standing wave, a spinning wave, or a sum of both. Experiments on a lab-scale annular combustor reveal that thermoacoustic modes can stabilize in one of these states, or undergo transitions between different states without stabilizing, depending on the operating conditions. We propose a low-order model based on a 1D wave equation, which reproduces most of these intriguing experimental dynamics and provides physical insight for several observed phenomena [1-3]. The conclusions obtained from our studies can be valuable to develop strategies for detection and protection against instabilities in commercial engines, which can be equipped with only a limited amount of acoustic pressure probes. It can also be used for growth rate identification to guide the design of acoustic dampers.

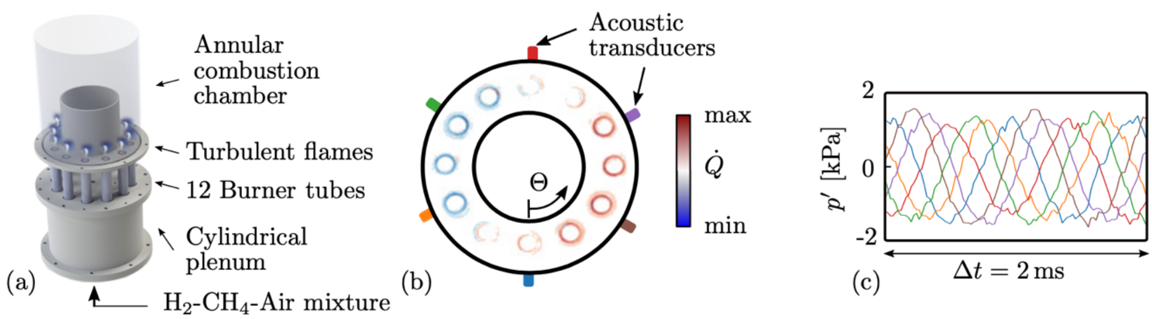

Figure 1: (a) Model gas turbine combustor. (b) Phase-averaged flame chemiluminescence. (c) Acoustic pressure recorded with 6 transducers. During the selected interval, the thermoacoustic limit-cycle is a quasi-purely spinning eigenmode.

Acknowledgments: This project is supported financially by the European Union's Horizon 2020 program under the research project Annulight (Grant 765998).

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Center Body Burner for sequential combustion: superior performance at lower emissions

A. Ciani, J. P. Wood, M. Maurer, B. Bunkute, D. Pennell, S. Riazantsev, G. Früchtel
Ansaldo Energia Switzerland, Baden

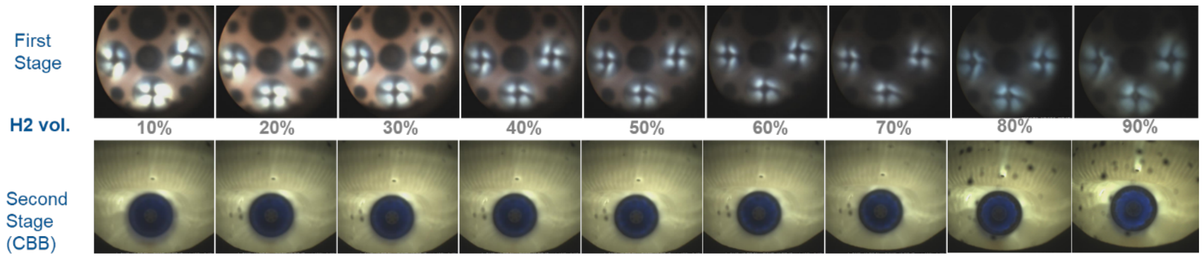
Modern gas turbines call for an ultra-high firing temperature and fuel flexibility while keeping emissions at very low levels. Sequential combustion has demonstrated its advantages toward such ambitious targets.

A sequential combustion system, as deployed in the GT26 and GT36 engines, consists of two burners in series, the first one optimized to provide the optimum boundary conditions for the second one, the sequential burner. This is the key component for the achievement of the required combustor performance dictated by F- and H-class engines, including versatile and robust operation with hydrogen-based fuels.

This talk describes the key development considerations used to establish a new sequential burner surpassing state-of-the-art hardware in terms of emission reduction, fuel flexibility and load flexibility.

A novel multi-point injector geometry was deployed based on combustion and fluid dynamic considerations to maximize fuel / air mixing at minimum pressure loss. Water channel experiments complemented by CFD describe the evolution of the fuel / air mixture fraction through the mixing section and combustion chamber, to enable operation with major NOx reduction. Furthermore, Laser Doppler Anemometry and Laser Induced Fluorescence were used to best characterize the interaction between hot-air and fuel and the fuel / air mixing in the most critical regions of the system. To complete the overview of the key development steps, manufacturing considerations based on additive manufacturing are also presented.

The outcome of 1D, CFD and fluid dynamic experimental findings were validated through full-scale, full-pressure combustion tests. These demonstrate the Center Body Burner is enabling operation at lower emissions, both at part-load and full-load conditions. Furthermore, the validation of the burner was also extended to hydrogen-based fuels with a variety of hydrogen / natural gas blends (see figure below).



Operation concept for highly reactive fuels (hydrogen): the first stage flame temperature is tuned for optimum boundary conditions of the second stage (Center Body Burner), maintaining maximum combustor exit temperature for best engine performance at low NOx emissions. Images from full-scale high-pressure testing.

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Towards the Development of an Engine Performance Digital Twin

Markus Wenig, Markus Kerellaj
WinGD, ITFE/FHNW

The research topic of Digital Twins has significantly grown in popularity over the last five years[1]. Due to its recency a common theory has not emerged yet, multiple definitions exist, and even its application is not fully clear[2]. At the moment, Digital Twins are mostly used for health monitoring and predictive maintenance. In this context, this presentation focuses on the development of an operational Digital Twin for large two-stroke marine engines. In doing so, it emphasizes collaborative R&D activities between industry and academia and illustrates the benefits of such collaboration by means of selected application cases. Today's challenges of Digital Twin development are addressed and, in this regard, the particularity of the slow-running marine combustion engines shall be highlighted. Conclusively, an outlook on the future potential deployment and direction of development is given contributing another case study to the theory of Digital Twins.

Literatur
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