Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

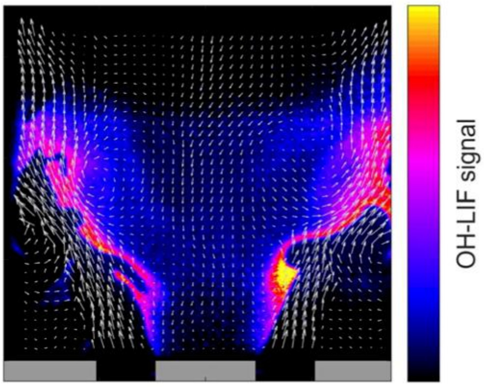
Swiss Confederation

Swiss Federal Office of Energy SFOE

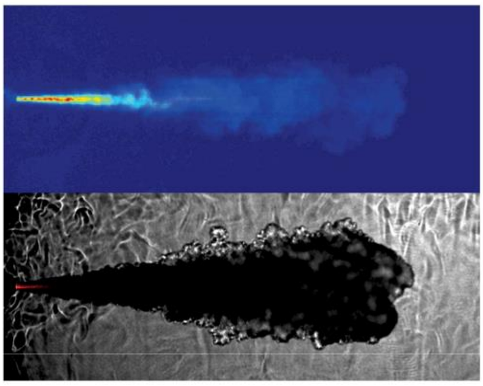
ETH zürich LAV CAPS Lab PAUL SCHERRER INSTITUT PSI

Conference on Combustion Research in Switzerland

Date: **Monday, 24th June 2019**
Location: ETH Zurich, Zentrum campus (ML D 28)
Time: 9:00 a.m. to 5:00 p.m.

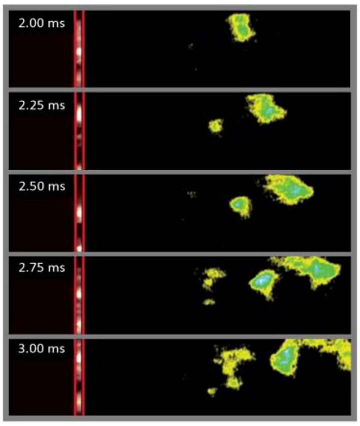


"Simultaneous high-speed PIV/OH-LIF of a turbulent swirl flame experiencing thermo-acoustic instability"
D. Ebi et. al. / Paul Scherrer Institut (PSI)



"Tracer LIF and Schlieren + Mie Scattering of a 300bar Methane Jet"
W. Vera-Tudela / LAV-ETH

"Diesel engine test rig with EGR blower"
G. Hardy / FPT et. P. Soltic / Empa



"Plasma enhanced autoignition"
Xiong et. al., Proc. Comb. Inst. 2019 / CAPS-ETH

Conference on Combustion Research in Switzerland

Date: **Monday, 24th June 2019**
Location: ETH Zurich, Zentrum campus (ML D 28)
Time: 9:00 a.m. - 5:00 p.m.

In the current debate on climate change, the future of combustion-based energy systems like internal **combustion engines** and **gas turbines** is controversial. However, it is a matter of fact that worldwide around 80% of the useful energy like heat, propulsion energy and electricity is produced via combustion processes. Furthermore, because of the high energy density and storability of the fuels, combustion will remain for several decades the technologically, economically and ecologically best solution for many applications in transport and power generation. In order to minimize the effects on climate change, combustion systems must become highly efficient and low in pollutant emissions and use fuels that minimize greenhouse gas emissions as much as possible.

Swiss **combustion researchers** from **industry, the universities of applied sciences** and the **ETH domain** address these challenges with internationally-recognized competence. Current examples include the development of highly efficient and low-emission diesel engines, the study of flexible dual fuel combustion, or the direct numerical simulation of ignition processes in gas engines. An important area of research is the use of novel fuels like OME, DME, butanol or hydrogen in internal combustion engines and gas turbines.

The goal of the biennial conference on **Combustion Research in Switzerland** is to foster the exchange of information on the **latest challenges and current research projects** in industry and academia. The event should also serve as a **networking** opportunity and provide earlycareer scientists a forum to present their research to a diverse audience.

Contact:
ETH Zurich, Institute of Energy Technology
Aerothermochemistry and Combustion Systems Laboratory (LAV)
Sonneggstrasse 3, 8092 Zurich,
Switzerland

E-mail: info@lav.mavt.ethz.ch
Phone: +41 44 632 36 68

Organizing committee:
Prof. Dr. Konstantinos Boulouchos, Head of the Aerothermochemistry and Combustion Systems Laboratory LAV; ETH Zurich
Prof. Dr. Nicolas Noiray, Head of the Laboratory of Combustion and Acoustics for Power and Propulsion Systems CAPS; ETH Zurich
Dr.-Ing. Peter Jansohn, Head of the Combustion Research Laboratory; Paul Scherrer Institut (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 ▪ Coffee ▪ Networking

09:00 Welcome address and introduction

09:10 **The case for renewable synthetic fuels - an energy systems point of view**
Konstantinos Boulouchos, ETH Zurich, Zurich

09:25 **Progress and challenges for burning hydrogen in large gas turbines**
Nicolas Noiray, ETH Zurich, Zurich

09:45 **Renewable synthetic fuels: challenges and opportunities for IC engine combustion**
Yuri Martin Wright, ETH Zurich, Zurich

10:05 Panel discussion with the speakers and conclusion

10:30 Coffee break ▪ Poster ▪ Networking

Session 1

11:00 **Heavy duty diesel engines: towards 50% brake thermal efficiency and low exhaust emissions**
Gilles Hardy, FPT Motorenforschung AG, Arbon

11:25 **Study of a high-pressure methane jet in a quiescent environment via optical diagnostics and CFD**
Walter Vera-Tudela, ETH Zurich, Zurich

11:50 **Characterization of dual-fuel combustion processes**
Kai Herrmann, FHNW, Brugg-Windisch

12:15 Lunch ▪ Poster ▪ Networking

Session 2

13:45 **Thermoacoustic dynamics during operating condition transients**
Giacomo Bonciolini, ETH Zurich, Zurich

14:10 **Flashback behavior of methane/hydrogen mixtures in gas turbine burners**
Peter Jansohn, Paul Scherrer Institute, Villigen

14:35 **Sequential combustion in gas turbines – the key technology for burning high hydrogen contents with low emissions**
Mirko Bothien, Ansaldo Energia Switzerland, Baden

15:00 Coffee break ▪ Poster ▪ Networking

Session 3

15:30 **Extreme scale computing in combustion: contributions to physical understanding, theory and modelling**
Christos Frouzakis, George Giannakopoulos, ETH Zurich, Zurich

15:55 **Functionality and potentials of the novel electro-hydraulical valve train “FlexWork”**
Patrik Soltic, Empa, Dübendorf

16:20 **Research challenges for large marine combustion engines**
Dominik Schneiter, Winterthur Gas & Diesel Ltd., Winterthur

16:45 Closing remarks

List of Abstracts

1. **The case for renewable synthetic fuels - an energy systems point of view**
   K. Boulouchos, ETH Zurich, Zurich

2. **Progress and challenges for burning hydrogen in large gas turbines**
   N. Noiray, G. Bonciolini, ETH Zurich, Zurich

3. **Renewable synthetic fuels: challenges and opportunities for IC engine combustion**
   Y. M. Wright, ETH Zurich, Zurich

4. **Heavy duty diesel engines: towards 50% brake thermal efficiency and low exhaust emissions**
   G. Hardy, FPT Motorenforschung AG, Arbon

5. **Study of a high-pressure methane jet in a quiescent environment via optical diagnostics and computational simulations**
   W. Vera-Tudela, D. Sakellarakis, Y. M. Wright, K. Boulouchos, ETH Zurich, Zurich

6. **Characterization of dual-fuel combustion processes**
   K. Herrmann[1], S. Wüthrich[1], P. Süess[1], P. Cartier[1], C. Schürch[2]
   [1] FHNW, Windisch
   [2] ETH Zurich, Zurich

7. **Thermoacoustic dynamics during operating condition transients**
   G. Bonciolini, N. Noiray, ETH Zurich, Zurich

8. **Flashback behavior of methane/hydrogen mixtures in gas turbine burners**
   D. Ebi, P. Jansohn, Paul Scherrer Institute, Villigen

9. **Sequential combustion in gas turbines – the key technology for burning high hydrogen contents with low emissions**
   M. Bothien, Ansaldo Energia Switzerland, Baden

10. **Extreme scale computing in combustion: contributions to physical understanding, theory and modelling**
    G. Giannakopoulos, C. Frouzakis, K. Boulouchos, ETH Zurich, Zurich

11. **Functionality and potentials of the novel electro-hydraulical valve train “FlexWork”**
    P. Soltic[1], N. Zsiga[1], A. Omanovic[1], W. Schneider[2]
    [1] Empa, Dübendorf
    [2] Wolfgang Schneider Ingenieurbüro, Thun

12. **Research challenges for large marine combustion engines**
    D. Schneiter, Winterthur Gas & Diesel Ltd., Winterthur

The case for renewable synthetic fuels - an energy systems point of view

K. Boulouchos
ETH Zurich, Zurich

The future global energy system must be fully “decarbonized” until around mid of the century in order to respect the CO_2-budget that is prescribed by the need to contain global temperature change within the 2°C-range.

Since both nuclear power generation and carbon capture and storage (CCS) are debated in terms of public acceptance and at their current technology status are not considered as sustainability compatible technologies, the burden of the “decarbonization” strategy will inevitably lie on renewable energy carriers. Given the vast amount of requested primary energy at a global scale, renewable electricity will play the major role in this effort. In particular solar (photovoltaics) and wind (increasingly off-shore) energy must dominantly contribute to this disruptive transformation of the energy system.

Both solar and wind energy exhibit however large fluctuations in space and time. Despite envisaged investment in new transmission electricity grids, the challenge of seasonal storage (or for that matter over long “cold, dark and windstill” periods) remains acute. Given the extremely limited capacity of batteries to provide such storage over long time scales, the route over renewable (electricity generated or solar-chemical) synthetic fuels will be a must. A round-trip “electricity → e-fuels → electricity” process can guarantee a security of supply, albeit at low overall conversion efficiencies of the order of around 30%.

On the other hand, a second process of “sector-coupling” refers to the emerging electrification of end-use energy services. In some of these end-use sectors (heat pumps in buildings, battery electric vehicles in urban environments, public transport etc.) direct electrification is the most efficient path. In some others however (industry heat and chemical processes, long-range transport on the road, on the sea and in the air) the use of renewable synthetic energy carriers is the only feasible decarbonization method.

Recent energy-economics studies in the European context indicate significant cost advantages with renewable e-fuels for the overall decarbonized system in comparison to massive direct electrification. Both H_2 and synthetic hydrocarbons are candidate fuels, with advantages for the latter in long range applications.

Using renewable synthetic hydrocarbons requests a carbon source that will ultimately involve carbon capture and re-use but will open up new opportunities for optimization (and development of new) combustion processes with “zero”-pollutant emissions and increased efficiency (“designer” fuels). In order to realize this potential though, dedicated research efforts have to be sustained over the next years (and even decades) to explore new paths and understand science fundamentals in reaction kinetics, flame speeds, two-phase flow phenomena, turbulence/thermochemistry interactions etc.

We can expect that such research will lead to clear improvements in the performance of both steady and unsteady combustion based converters in the mid-term future.

References

1. European Academies Science Advisory Council (EASAC):
   Decarbonisation of transport: options and challenges / March 2019
   https://easac.eu/fileadmin/PDF_s/reports_statements/Decarbonisation_of_Tansport/EASAC_Decarbonisation_of_Transport_FINAL_March_2019.pdf
2. Nationale Akademien der Wissenschaft (Leopoldina), Deutsche Akademien der Technickwissenschaft (Acatech), Union der Deutschen Akademien der Wissenschaft (Akademienunion): Coupling the different energy sectors – options for the next phase of the energy transition / August 2018
   https://www.acatech.de/Publikation/coupling-the-different-energy-sectors-options-for-the-next-phase-of-the-energy-transition/
3. European Parliament
   Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonize? / November 2018
   http://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf

Progress and challenges for burning hydrogen in large gas turbines

N. Noiray
ETH Zurich, Zurich

Humankind is facing the immense challenge of climate change. The global efforts engaged to address this critical issue aim at future sustainable energy networks characterized by a mix of technological solutions. In this context, natural gas fired power from large gas turbines will serve as a lower-carbon and ultra-low pollutant emissions alternative to phasing-down CO_2 and pollution intensive oil- and coal-fired power plants. Thanks to their high operational flexibility, with fast ramp-up and start-up time, these gas turbines will play a key role in stabilizing the electric networks by balancing the intermittent production from the constantly growing wind and solar capacities. The next step toward sustainable power generation using gas turbines is to develop low-NO_X H_2 combustion technologies that will be key for future energy networks. This R&D goal is already taken up by major industrial players, which have very recently advertised their new products capable of burning up to 50% volume fraction of Hydrogen and aiming at significantly more in the coming few years. The rationale behind is that 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. Depending on the fuel composition and the H_2 content, the reactivity of the mixture can drastically vary, which brings serious obstacles to the development of new versatile combustors. Consequently, there is a dire need for understanding, modelling and controlling the associated combustion regimes to develop these future H_2 combustion technologies.

Renewable synthetic fuels: challenges and opportunities for IC engine combustion

Y. M. Wright
ETH Zurich, Zurich

Internal Combustion (IC) engines presently power the majority of vehicles used for on- and off-road freight and passenger transportation, agricultural and building machinery as well as seaborne vessels. They are widely used also for decentralized power (co-)generation at small and intermediate scales due to their flexibility with respect to fuel composition and rapid load uptake capability. While direct electrification of the light-duty sector constitutes a viable pathway towards decarbonisation of individual mobility, long-haul road and marine freight transportation are projected to depend on IC engines in the foreseeable future. The emergence of renewable synthetic fuels with tailored thermochemical properties however opens up opportunities also for these applications; not only in terms of their CO_2-budget, but also with respect to further engine-out emission reduction and efficiency gains by design of the combustion process according to the specifics of the fuel or vice versa.

A broad variety of chemical compounds can be synthesized starting from e-fuels or from sustainable biomass resources, including gaseous and longer-chain liquid hydrocarbons, alcohols, esters, ethers with widely disparate thermo-physical properties and chemical kinetics. While the former are more relevant to the distribution network, storage/handling considerations and fuel injection processes, the latter affect different in-cylinder processes, such as ignition behaviour, early flame development, combustion duration and stability as well as emission formation. While for many of these processes significant advances are reported for conventional fossil hydrocarbon fuels in the last decades, many open questions remain when employing synthetic fuels, in particular when oxygenated. Implications hereto will be discussed in the context of select premixed and non-premixed combustion concepts, highlighting the necessity for further research and development exploiting the specific features of renewable synthetic fuels: e.g. for hydrogen-methane admixtures, with significantly improved tolerance to high dilution levels and corresponding improvements regarding NOx-efficiency trade-off using ‘conventional’ J-type spark plug configurations, and the expected potentials likewise for H_2-scavenged prechamber configurations, in addition to reduction of unburned CH_4.

Heavy duty diesel engines: towards 50% brake thermal efficiency and low exhaust emissions

G. Hardy
FPT Motorenforschung AG, Arbon

Considering upcoming strict EU regulations on CO_2 after 2030 and next emissions EUVII, still under consideration, the BTE50% project aims to investigate suitable combustion and air handling layout for future heavy duty on-road transport vehicles. The engine contribution to the overall CO_2 target reduction of the total vehicle is around 50%, therefore it is important to review and explore individually key technologies at sub-system level. State of the art 3D CFD simulation combined with 1-D cycle and cycle analysis were extensively used to design, improve and perform diagnostic of the combustion chamber geometry and gas exchange efficiency.

Combustion layout: High peak Cylinder Pressure, chamber piston bowl, high injection pressure, post injection and new nozzle concept were investigated.

Air handling layout: Reduced after treatment system efficiency at low exhaust temperatures and potential N_2O limit regulation as a GHG led to the development with a supplier of a volumetric EGR pump to increase flexibility and control within the engine map.

References
1. SAE2018-01-1689 Heavy-Duty Diesel Engine Spray Combustion Processes: Experiments and Numerical Simulations. Maes, N., Dam, N., Somers, B., Lucchini, T.,D'Errico, G., Hardy, G.

Study of a high-pressure methane jet in a quiescent environment via optical diagnostics and computational simulations

W. Vera-Tudela[1], D. Sakellarakis[1], Y. M. Wright[1], K. Boulouchos[1], U. Doll[2], D. Ebi[2], M. Banholzer[3], M. Pfitzner[3]
[1] ETH Zurich, Zurich
[2] Paul Scherrer Institute, Villigen
[3] Universität der Bundeswehr München, München

Natural gas offers CO_2-emissions advantages of up to 25% compared to liquid hydrocarbons, given that the thermodynamic efficiency of the engine working process is the same. In order to achieve optimal process efficiency according to a diesel cycle with natural gas as a fuel, which implies a mainly non-premixed combustion mode; direct gas injection at very high pressures is necessary. This leads to chocked-flow at the exit of the nozzle and strongly under expanded jets, with the injection fluid behaving as real and not ideal gas. The aim of this work was to investigate the propagation and mixing of high-pressure, under-expanded methane jets in a quiescent environment. To achieve this, experimental studies and complementary simulations were carried out.

The experimental part contains measurements in an optically accessible Constant Volume Cell, which allows the application of different optical techniques to quantify the propagation of the jet through the ambient gases. The injector used was a single-hole axial injector working with methane up to 300 bar of injection pressure. In a first step, the schlieren technique was applied to study the evolution of the jet tip penetration under different injection- and chamber-pressure variations, and consequently the pressure ratio [1]. As a second step, Mie-scattering measurements, along with simulations in collaboration with the UniBwM's Thermodynamic, Heat- and Mass Transfer Group were carried out to explore the possibility of fuel condensation in the presence of strong expansion [2]. In a third step and in collaboration with PSI's Combustion Diagnostics Group, the tracer LIF technique was applied under similar conditions in order to investigate the mass-fraction distribution within the jet. Detailed RANS simulations accompanied the experimental studies. These calculations fully resolve the flow within the injector and employ real gas thermodynamics with Soave-Redlich-Kwong as the equation of state. The implementation of real gas thermodynamics is an absolute requirement for accurate computations of jet movements, penetration and mixing [3].

The experimental results show a strong dependence of the tip penetration and radial profiles on the pressure ratio, while the injection pressure has a small influence on them. Scaling of the jet tip penetration and volumetric growth rate matches expressions proposed in literature. Likewise, the hyperbolic decay of axial evolution and the development of self-similarity in the far-field zone under appropriate normalization for each flow variable is confirmed. The simulation and experimental results are in very good agreement. This serves as the basis for further investigation of the dependencies of global jet metrics, mixing state, jet structure in the near-nozzle and local distribution of flow variables in the far-field area of the jet. A workflow for employing coarser-scale simulations under reactive conditions based on extracting artificial boundary conditions from the detailed simulations have been developed and first predictions of ignition delays and location will be shown.

References

1. "An experimental study on the effects of needle dynamics on the penetration of a high-pressure methane jet", W. Vera-Tudela, P. Kyrtatos, B. Schneider, K. Boulouchos, M. Willmann. Fuel, Vol 253, pp. 79-89, 2019.
2. "Numerical Investigation of the flow Characteristics of Underexpanded Methane Jets", M. Banholzer, W. Vera-Tudela, C. Traxinger, M. Pfitzner, Y. Wright, K. Boulouchos. Physics of Fluids, Vol 31, 056105, 2019.
3. "Numerical investigation of nozzle-geometry variations and back-pressure changes on high-pressure gas injections under application-relevant conditions", M. Banholzer, M. Pfitzner, D. Sakellarakis, Y. Wright, W. Vera-Tudela, K. Boulouchos. SAE World Congress 2018 – Detroit, U.S.A., Nº 2018-01-1138.

Funding

Authors acknowledge that part of this work was performed in the frame of Project Gas-Diesel Brennverfahren from the Forschungsvereinigung Verbrennungskraftmaschinen (FVV).

Characterization of dual-fuel combustion processes

K. Herrmann[1], S. Wüthrich[1], P. Süess[1], P. Cartier[1], C. Schürch[2]
1 FHNW, Windisch
2 ETH Zurich, Zurich

Lean-burn concepts are an attractive solution for the compliance with future emission standards towards reduction of CO_2 emissions, combined with considerably lower particulate as well as NO_X and SO_X emissions – all that with efficiency comparable to diesel combustion. In this regard, lean burn gas/dual-fuel engine market is spread over a wide range of application areas, particularly targeting power generation and maritime industry. However, dual-fuel ignition and combustion processes of pilot spray ignited lean-premixed gas/air charge still poses considerable challenges to ensure reliable operation between misfiring and knocking.

Previous valuable studies have investigated influences on pilot fuel ignition and properties of dual-fuel combustion [1, 2] considering alternative pilot fuels [3]. Moreover, a phenomenological combustion description has been developed [4]. However, the optical experimental apparatus employed was limited in range of operating conditions and lack of turbulence.

A novel "optical engine" test rig[1] ("Flex-OeCoS") enables the investigation of pilot spray ignition and the ensuing transition to a turbulent premixed flame. The experimental test facility features ability to achieve engine relevant compression/combustion pressures and temperatures at variable speeds (flow/turbulence) for an adjustable range of gas/air charge composition. Process conditions are tunable with high procedure variance (e.g. variable valve timing, number of cycles) to approach characteristic conditions for ignition and combustion influencing parameters. The optically accessible combustion chamber offers enormous flexibility to apply optical measurement methods to acquire inflammation and flame kernel growth.

In this talk, we will present and discuss latest results of ignition process and flame propagation in the "Flex-OeCoS" test rig based on operation and boundary conditions. Pilot fuels with different properties have been applied. 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 (turbulence). Conclusions shall give extended insight into the thermo-chemical processes of dual-fuel combustion and the acquired reference data will be used to validate and further develop numerical CRFD methods.

Acknowledgments
This work has been conducted by Swiss Federal Office of Energy projects (SFOE contracts SI/501546-01 and SI/501628-01) partly within the SCCER Mobility program (CTI) and financial support is gratefully acknowledged.

References
1. S. Schlatter, B. Schneider, Y.M. Wright, and K. Boulouchos, "Comparative Study of Ignition Systems for Lean Burn Gas Engines in an Optically Accessible Rapid Compression Expansion Machine", SAE Technical Paper No. 2013-24-0112, 2013.
2. A. Srna, M. Bolla, Y.M. Wright, K. Herrmann, R. Bombach, S.S. Pandurangi, K. Boulouchos, and G. Bruneaux, "Effect of methane on pilot-fuel auto-ignition in dual-fuel engines". Proceedings of the Combustion Institute 37 (2019) 4741–4749.
3. A. Srna, C. Barro, K. Herrmann, F. Möri, R. Hutter, and K. Boulouchos, " POMDME as an Alternative Pilot Fuel for Dual-Fuel Engines: Optical Study in a RCEM and Application in an Automotive Size Dual-Fuel Diesel Engine", SAE Technical Paper 2018-01-1734, 2018.
4. C. Barro, C. Nani, R. Hutter, and K. Boulouchos, "Spray Model Based Phenomenological Combustion Description and Experimental Validation for a Dual Fuel Engine", SAE Technical Paper 2017-24-0098, 2017.

[1] jointly pursued by ITFE-FHNW and LAV ETH Zurich (Prof. K. Boulouchos)

Thermoacoustic dynamics during operating condition transients

G. Bonciolini, N. Noiray
ETH Zurich, Zurich

What do earth climate, traffic jams, stock market, infectious diseases and a gas turbine combustor have in common? They can all exhibit sudden transitions to catastrophic states, for small variation of a parameter of the system.

In the case of combustion systems, this variation might lead to a thermoacoustic instability, a phenomenon for which the flame emits high-amplitude, potentially destructive acoustic waves. In this talk, this very challenging problem in gas turbines development will be presented. In particular, the dynamics of thermoacoustic systems under transient operations will be analyzed. The case of thermoacoustic systems changing their stability according to the value of one operating parameter will be considered. When unstable, the system exhibits self-sustained oscillations at a fixed frequency, while when stable, one can measure damped oscillations at about the same frequency. The feature of changing behavior when one of the governing parameters exceeds a certain value is common to many complex dynamical systems. This type of tipping points results from bifurcations of quasi-steady attractors [1]: for a small change of one of its parameters, the topology of the dynamical system phase portrait markedly changes.

In some cases, the system bifurcates to undesirable and/or dangerous states, which can be extremely detrimental for the integrity of the system. In most cases, the system displays an unwanted behavior for a limited interval of the bifurcation parameter, while it runs problem-free otherwise. This type of situation is the scenario considered in this talk, with stochastic forcing of the deterministic system as an additional ingredient.

In this talk, three recent studies will be presented, all having a similar structure. First, the stationary behavior of the system at study is presented. All the cases will feature thermoacoustic bifurcations: for a certain value of one operating parameter the system will exhibit a transition from stable to unstable operation. Each case will have a particular signature, and different reasons generating the phenomenon. Then, the dynamics of the system under transient operation will be analyzed; the operating parameter will be varied in time to study the trajectory of the system through the bifurcations.

The study of bifurcation under varying conditions is very classic in literature in many different disciplines. On the contrary, in the specific context of thermoacoustic instabilities in combustion chambers, this topic has received only very limited attention [2], even though real machines can be subject to rapid changes of operating conditions, like for instance aeroengines at take-off.

References
1. P. Ashwin, S. Wieczorek, R. Vitolo, and P. Cox, “Tipping points in open systems: bifurcation, noise-induced and rate-dependent examples in the climate system,” Phil. Trans. R. Soc. A, vol. 370, no. 1962, pp. 1166–1184, 2012.
2. W. Culler, X. Chen, J. Samarasinghe, S. Peluso, D. Santavicca, and J. O’Connor, “The effect of variable fuel staging transients on self-excited in- stabilities in a multiple-nozzle combustor,” Combustion and Flame, vol. 194, pp. 472–484, 2018.

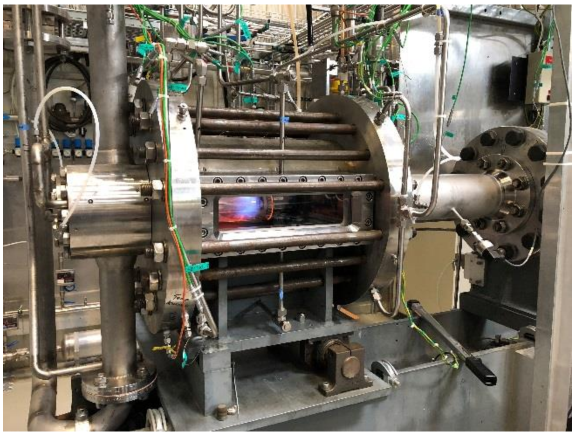
Flashback behavior of methane/hydrogen mixtures in gas turbine burners

D. Ebi, P. Jansohn
Paul Scherrer Institute, Villigen

Renewed interest in operating gas turbines on mixtures of hydrogen and natural gas necessitates an improved fundamental understanding of the mechanisms facilitating flame flashback and better models to predict flashback limits. Previous investigations on boundary layer flashback were mostly limited to low Reynolds numbers and atmospheric pressure. Kalantari and McDonell emphasized in a recent review the need for more studies at gas turbine premixer conditions [1]. In addition, boundary layer flashback has traditionally been investigated in non-swirling jet flames. The effect of swirl, which is present in virtually all gas turbine burners, on flashback mechanisms and propensity is not yet well understood [2-4].

The present study aims at addressing a number of open questions through experiment and modelling by focusing on flashback in an axial swirl burner with a practical swirl number of about 0.6. Mixtures of methane and hydrogen with a systematic variation in hydrogen content up to 100% are investigated. Target conditions for the experimental campaigns range up to 12 bar, 400°C preheat temperature and 40 m/s inlet bulk flow velocity. During flashback, the flame propagates upstream along the cylindrical center body inside the premix section. The wall temperature is controlled via oil heating/cooling to decouple the effect of a change in operating condition (e.g., pressure) on the flashback limit from the change in heat load on the center body that is otherwise inherently associated with the change in operating condition.

This talk will present first experimental results, mainly in the form of flashback limits that have been measured for a wide range of conditions. Trends in flashback propensity as a function of pressure, preheat temperature, bulk flow velocity and hydrogen content will be discussed and compared to existing correlations aiming at predicting flashback limits.



References
1. Kalantari, A., & McDonell, V. (2017). Boundary layer flashback of non-swirling premixed flames: Mechanisms, fundamental research, and recent advances. Progress in Energy and Combustion Science, 61, 249–292.
2. Nauert, A., Petersson, P., Linne, M., & Dreizler, A. (2007). Experimental analysis of flashback in lean premixed swirling flames: conditions close to flashback. Experiments in Fluids, 43(1), 89–100.
3. Baumgartner, G., & Sattelmayer, T. (2013). Experimental investigation of the flashback limits and flame propagation mechanisms for premixed hydrogen-air flames in non-swirling and swirling flow. In proceedings of asme turbo expo (pp. 1–10).
4. Ebi, D., & Clemens, N. T. (2016). Experimental investigation of upstream flame propagation during boundary layer flashback of swirl flames. Combustion and Flame, 168, 39–52.

Sequential combustion in gas turbines – the key technology for burning high hydrogen contents with low emissions

M. Bothien
Ansaldo Energia Switzerland, Baden

Gas turbines already play an important role in power generation, and in the light of increasing energy demand it is foreseen that their role will continue to grow alongside renewables to meet near term growth. In addition, the volatility of renewables in generating and dispatching power entails a new focus on electricity security. Consequently, gas turbines are bound to reinforce their role as guarantors of grid reliability in modern power systems by compensating the intermittency of renewables.

Using excess energy from renewables to produce hydrogen, e.g. by electrolysis, is commonly termed Power-to-Gas. Hydrogen features the unique capability to store energy for medium to long storage cycles. It can be either stored pure in large underground facilities or blended through injection into the existing natural gas pipeline infrastructure. Another possibility is to produce methane, through methanation by the addition of CO_2, with the resulting fuel being supplied to existing gas turbines. An even more efficient way to utilise hydrogen is to burn it directly in gas turbines allowing for completely CO_2-free combustion.

The main challenge of hydrogen combustion in gas turbines lies in its increased reactivity, i.e. burning velocity. Consequently, when burning hydrogen the flame moves upstream compared to the case of natural gas, thus increasing the risk of flashback. All conventional premix combustion systems fail to handle hydrogen's special features without compromising performance: by injecting less fuel, the flame temperature is reduced, mitigating flashback risks by moving the flame back to its design position. As a result, however, the combustor exit temperature gets lower and engine performance is severely reduced. Today, commercially only diffusion type combustors are used to generate electricity with 100% hydrogen (by power). However, large amounts of diluents (nitrogen, steam) need to be added and NOx emissions can only be kept below the limits by using selective catalytic reduction (SCR), both significantly reducing the efficiency of the plant.

In this presentation, it is shown how these drawbacks can be overcome by using sequential combustion. Ansaldo Energia's reheat gas turbines consist of two combustion chambers arranged in series: one conventional premixed stage followed by an auto-ignited second stage overcoming the limits of traditional combustion systems. A shift of fuel from first to second stage compensates the higher fuel reactivity on both stages: the first stage flame location is maintained thanks to its lower temperature, while the resulting lower inlet temperature of the second stage keeps its flame at the desired location despite an increased fuel flow. This can be achieved as the second stage flame is stabilised by auto-ignition, strongly driven by the inlet temperature and less sensitive to the flame temperature which can be maintained at full F- and H-class levels. This approach unleashes hydrogen combustion's full potential. It is shown that in the range from 0% to 70% (vol.) hydrogen, stable combustion is achieved at full nominal exit temperature, i.e. without any derating and thus clearly outperforming other available conventional premixed combustors. Operation between 70% and 100% is possible as well and only requires a mild reduction of the combustor exit temperature. Hence, Ansaldo Energia's GT36 H-Class gas turbine can be operated on fuels containing unprecedented concentrations of hydrogen while maintaining excellent performance and low emissions both in terms of NOx and CO_2.

References

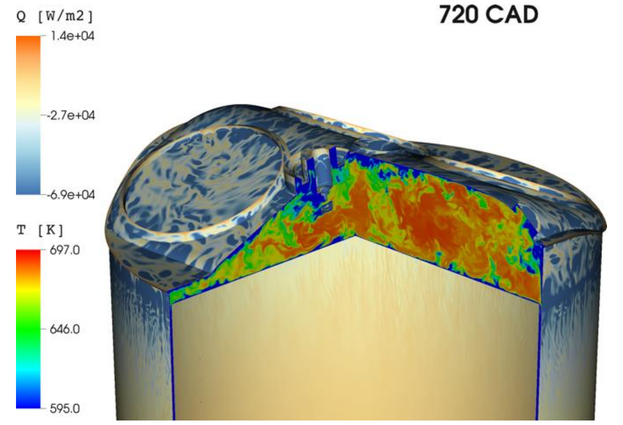
1. Bothien, M. R., Ciani, A., Wood, J. P., Fruechtel, G., (2019) "Sequential combustion in gas turbines – the key technology for burning high hydrogen contents with low emissions". GT2019-90798.
2. Ciani, A., Bothien, M. R., Bunkute, B., Wood, J. P., and Früchtel, G., 2019, "Superior fuel and operational flexibility of sequential combustion in Ansaldo Energia gas turbines". Proceedings of Global Power and Propulsion Society – Technical Conference 2019, GPPS-TC-2019-0032.
3. https://www.ansaldoenergia.com/business-lines/hydrogen-technology
4. https://www.ansaldoenergia.com/PublishingImages/Idrogeno/Ansaldo-Energia-H2.pdf
5. https://youtu.be/Ut2khz8C_dc

Extreme scale computing in combustion: contributions to physical understanding, theory and modelling

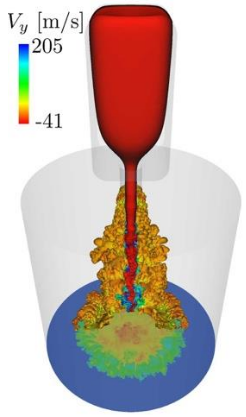
G. Giannakopoulos, C. Frouzakis, K. Boulouchos
ETH Zurich, Zurich

Combustion is a fascinating multi-physics process occurring over multiple temporal and spatial scales. The quest for novel fuel-flexible devices with higher efficiency and reduced emissions leads to new combustion regimes that are poorly understood at the fundamental level. Enabled by advances in computational resources, direct numerical simulations (DNSs) allow for the resolution of all relevant spatial and temporal scales, and provide an accurate description, which, in combination with theory and experiments, can lead to valuable physical insights into the complex interaction of the underlying physical and chemical processes.

After briefly discussing our high-order low Mach number reactive flow solver and its scalability on today‘s high-performance computing architectures, we will present selected examples were DNS was used to (i) assess the validity and accuracy of theoretical assumptions and predictions for premixed flames, and (ii) complement experiments in single-cylinder optical engines as well as in the optical prechamber setup designed and operated at LAV. The generated high-quality DNS datasets are also been used to validate and tune models existing in commercial and open source codes, and establish best practices for engineering-type simulations.



DNS of the compression stroke in the TU Darmstadt optical engine*: Temperature stratification and wall heat flux distribution during motored operation. Simulations performed on Argonne Leadership Computing Facility’s (ALCF) supercomputer *Theta* using 32,768 cores. Funded by the Swiss Office of Energy (BfE) and the German Research Association for Combustion Engines (FVV).



Instantaneous distribution of methane mass fraction isosurfaces colored by the vertical velocity component in the LAV optical prechamber. Simulations performed on the Swiss National Supercomputing Center (CSCS) system *Piz Daint*. Fundding provided by the Swiss Office of Energy (BfE).

References

1. G. Giannakopoulos, A. Gatzoulis, C. Frouzakis, M. Matalon, A. Tomboulides, Consistent definitions of ”Flame Displacement Speed” and „Markstein Length” for premixed flame propagation, Combust. Flame 162 (4) (2015) 1249–1264.
2. G. Giannakopoulos, C. Frouzakis, S. Mohan, A. Tomboulides, M. Matalon, Consumption and Displacement Speeds of Stretched Premixed Flames - Theory and Simulations, Combust. Flame (under review).
3. M. Schmidt, C.P. Ding, B. Böhm, A. Dreizler, G.K. Giannakopoulos, J. Koch, C.E. Frouzakis, Y.M. Wright and K. Boulouchos, “Characterizing the evolution of boundary layers in IC engines by combined laser-optical diagnostics, direct numerical and large-eddy simulations”, Large Eddy Simulations for Internal Combustion Engines (LES4ICE), Paris, France, December 2018.
4. S. Benekos, G. K. Giannakopoulos, C. E. Frouzakis, K. Boulouchos, An exploratory parametric 2-D DNS study of prechamber ignitio: Part I. Effect of thermochemical state & Part II. Effect of geometry, spark location and initial flow field, Combustion and Flame, (in preparation)

Functionality and potentials of the novel electro-hydraulical valve train "FlexWork"

P. Soltic[1], N. Zsiga[1], A. Omanovic[1], W. Schneider[2]
[1] Empa, Dübendorf
[2] Wolfgang Schneider Ingenieurbüro, Thun

Variabilities are key elements for optimizing efficiency and minimizing pollutant emissions for an internal combustion engine. While variablilities in boosting and fuel injection are establised technologies, full flexibility in gas exchange valve actuation has not yet found its way to mass-production. There are technologies on the market which enable some dregree of flexibility by using camshafts with phasing devices and mechanical or hydraulical interlinks but these solutions are complex and still rather limited in their performance. Empa has developed, in close cooperation with Wolfgang Schneider Ingenieurbüro, the novel electro-hydraulical valve train "FlexWork" which is completely cam-less, offers full flexibility regarding valve lift and –timing, does not need any feedback-control of the lift and seating process and shows a low demand of energy. Figure 1 (left) shows its design. A four cylinder spark ignition engine with a displacement of 1.4 liters has been equipped with the FlexWork valve train and has been put on the engine test bench (Figure 1, right). One speciality is that the valve train is designed for the use of water - ethylene glycol mixture as the hydraulic fluid. This choice was done mainly because of the higher stiffness of this fluid compared to a classical oil-based hydraulic fluid. To date, the system has performed several millions valve activations on the fired engine without any problems. The FlexWork valve train enables, as an example, throttle-free load control. By doing so, the brake efficiency of the engine was increased from 20.9% to 24.0%. By adding cylinder deactivation (two cylinder operation), the effieiency can further be increased to 26.4%.

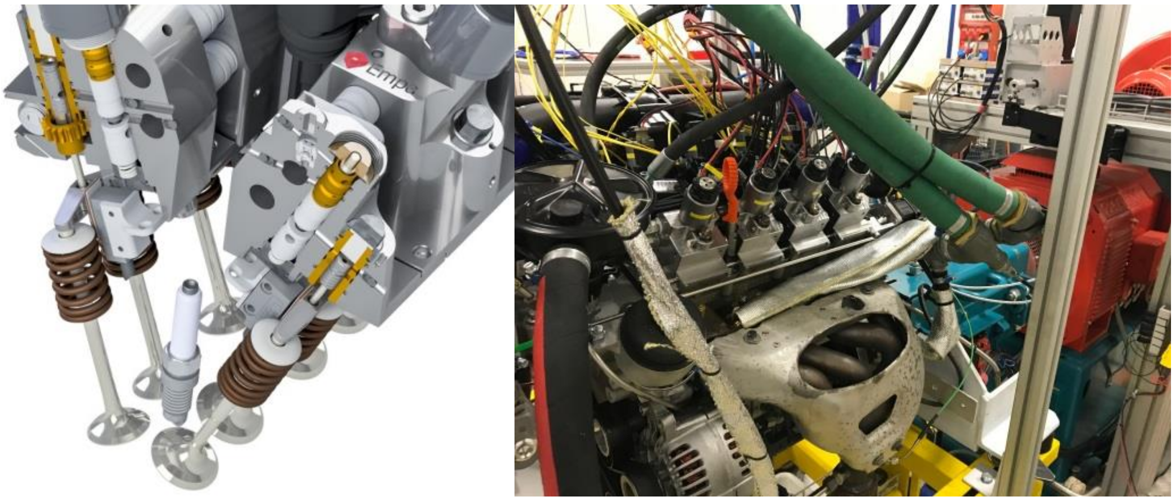


Figure 1: CAD rendering of the FlexWork valve train (left) and FlexWork-equipped engine on the test bench (right)

References

1. Zsiga N, Omanovic A, Soltic P, Schneider W, FlexWork - Lastregelung bei einem Motor mit elektrohydraulischem, vollvariablen Ventiltrieb, 11. MTZ-Fachtagung «Ladungswechsel und Emissionierung», Stuttgart 2018.
2. Zsiga N, Omanovic A, Soltic P, Schneider W, Wirkungsgradvorteile beim Ottomotor unter Verwendung einer nockenwellenlosen, vollvariablen Ventilsteuerung gegenüber gedrosseltem Betrieb, 8. VDI-Fachtagung Ventiltrieb und Zylinderkopf, Würzburg 2019.
3. Zsiga N, Omanovic A, Soltic P, Schneider W, Funktionsweise und Potenziale eines neuartigen, elektrohydraulischen Ventiltriebs, MTZ Motortechnische Zeitschrift 09/2019.

Research challenges and commercial opportunities in the large marine combustion engine segments

D. Schneiter
Winterthur Gas & Diesel Ltd., Winterthur

The global marine transport sector is currently undergoing a slow but irreversible transition. The increasing public pressure on environmental impact has led not only to several International Maritime Organisation (IMO) based regulations, but also clear defined targets from the cargo owners according UN sustainability charters.

The IMO has recognised the achievements in the research field and has recently issued greenhouse gas reduction targets. In the defined charter, the IMO is requesting global shipping to reduce its global GHG footprint by 50% in 2050. As global transportation is constantly growing, a reduction of >70% intensity per vessel is required.

Ship operators are challenged to meet the regulatory and customer expectations while keeping the freight rates at competitive levels. Additionally, local regulations come into place. Norway as example, has released zero carbon vessel requirements starting from 2026 for inland and coastal water transportation.

Due to the power density of the engines, and the energy density of the used fuels, for long-haul oceanic shipping, the internal combustion engine will not be easily replaced by other technologies. Consequently, the aim is to make a propulsion system with an internal combustion engine and add on technology GHG neutral.

After several decades of little development, this situation has caused a hike of new technologies introduced. Such technologies include at one end emission abatement for the traditional diffusion cycle engine, addressing the gaseous emissions of heavy fuel oil (HFO) like sulphur oxide (SOx), Nitrogen oxide (NOx), and particulate matters (PM).

At the other end and more sustainable are new fuels and electrification. Currently, the focus is mainly on liquid natural gas (LNG), which is generally seen as the bridging fuel to the zero-emission future. Many organizations are currently investing in the needed infrastructure to make the fuel available on a global scale. Besides reducing all before mentioned local, toxic gaseous emissions, LNG can additionally reduce the greenhouse gas (GHG) footprint by 15 – 20%. The improvement is mainly achieved by burning LNG in a lean burning cycle. As a technical detail, marine LNG engines are conceptualized as dual fuel engines and switch between diffusion cycle and lean burning cycle, or apply a mix of both.

Pure electrification of a big deep-sea container vessel is not seen as a viable approach for the moment, electrical hybridisation however is coming. Developments go into smarter systems that better integrate the total energy management on board in the most efficient way, and by utilising model based and self-learning controls that combine various sources and consumers of energy.

To further reduce the GHG footprint, developers have started to look more into sustainable fuel developments. The first vessel operators start to run test sequences with liquid biofuels burned in diffusion cycles or bio-LNG utilising the advantages of lean burning concept.

Beside the complementation with electricity and batteries, hydrogen or ammonia drop in into fossil fuels from sustainable sources will help to gradually reduce the GHG impact in future.

In a mobile application like shipping, such sustainable fuels shall be produced on board either by solar, wind or wave energy, or when including better and smarter system integration by available waste energy, i.e.: waste heat recovery systems.

Consequently, WinGD is proposing that combustion research shall focus on synthetic fuel generation and its combustion in traditional internal combustion engines. It shall address the challenge of fuel and combustion cycle mixes and come up with ways to simulate mixed combustions accurately. The indefinite aim to have more efficient combustion at zero emissions will prevail for a long time in future.

List of Posters

1. **Influences of butanol blend fuels on combustion and emissions of diesel engines**
   D. Engelmann, H. Nauroy, J. Czerwinski
   AFHB, University of Applied Sciences, Biel-Bienne

2. **Decomposition pathways of alternative fuels studied with synchrotron radiation: dimethyl carbonate**
   M. Steglich, A. Bodi, P. Hemberger
   Paul Scherrer Institute, Villigen

3. **Optical investigation of the combustion of OME under engine relevant conditions**
   C. Schürch[1], M. Parravicini[1], C. Barro[1], K. Boulouchos[1], J. Rosenberg[2], P.Cartier[2], K. Herrmann[2]
   [1] ETH Zurich, Zurich
   [2] ITFE, FHNW, Windisch

4. **Combustion characteristics of different fuel blends to improve CO_2 emissions of a heavy duty diesel engine**
   M. Parravicini, C. Barro, P. Kyrtaos, K. Boulouchos
   ETH Zurich, Zurich

5. **A comprehensive methodology for pre-chamber gas engine model development**
   K. Bardis[1], P. Kyrtatos[1], D. Humair[2], S. Benekos[1], A. Denisov[2], M. Bolla[1], Ch. Frouzakis[1], G. Xu[1,3], G. Giannakopoulos[1], K. Herrmann[2], K. Boulouchos[1]
   [1] ETH Zurich, Zurich
   [2] FHNW, Windisch
   [3] Liebherr Machines Bulle SA, Bulle

6. **Radiative heat transfer in large two-stroke marine diesel engines**
   S. Geringer[1], M. Bolla[1], C. Paul[2,3], D.C. Haworth[2], K. Boulouchos[1]
   [1] ETH Zürich, Zurich
   [2] PennState University, University Park
   [3] Gamma Technologies LLC

7. **Microwave heated, additive manufactured catalytic converters for zero impact emission powertrains**
   V. Papetti, P. Dimopoulos Eggenschwiler
   Empa, Dübendorf

8. **Flow and dual-fuel combustion diagnostics at the new optical engine facility Flex-OeCoS**
   S. Herzig[1], A. Denisov[1], K. Herrmann[1], R. Bombach[2], Ch. Schürch[3]
   [1] ITFE, FHNW, Windisch
   [2] Paul Scherrer Institute, Villigen
   [3] ETH Zurich, Zurich

9. **Accelerated methane combustion with high velocity pre-chamber ignition jet**
   D. Humair[1], A. Denisov[1], Ch. Frouzakis[2], S. Benekos[2]
   [1] FHNW, Windisch
   [2] ETH Zurich, Zurich

10. **In-Nozzle Flow & Spray Morphology Investigations of Marine Diesel Injectors**
    R. Balz[1,2], A. Schmid[1], D. Sedarsky[2]
    [1] Winterthur Gas & Diesel Ltd., Winterthur, Switzerland
    [2] Combustion and Propulsion Systems Division, Chalmers University, Gothenburg, Sweden

Influences of butanol blend fuels on combustion and emissions of diesel engines

Verbrennungstagung ’19; BfE/ETHZ 24.06.2019

Bern University of Applied Sciences
Biel-Bienne Switzerland
AFHB | IC-Engines and Exhaust Gas Control

Influences of Butanol Blend Fuels on Combustion and Emissions of Diesel Engines

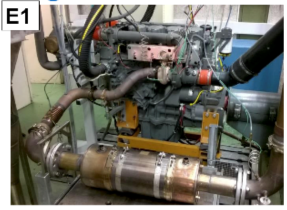
D. Engelmann, H. Nauroy and J. Czerwinski, AFHB, University of Applied Sciences, Biel-Bienne, CH

Abstract

Butanol, a four-carbon alcohol, is considered in the last years as an interesting alternative fuel, both for Diesel and for Gasoline application. Like Ethanol, Butanol can be produced as a biomass-based renewable fuel or from fossil sources.

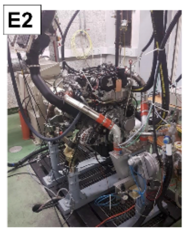
In the research project, DiBut (Diesel and Butanol) addition of Butanol to Diesel fuel was investigated from the points of view of engine combustion and of influences on exhaust aftertreatment systems and emissions. One investigated engine (E1) was with emission class "EU Stage 3A" for construction machines, another one, engine (E2) was HD Euro VI. The operation of engine (E1) with Bu30 was instable at lower part load due to the lower Cetane Number of the blend fuel. The electronic control system of the engine (E2) compensated very well the varying properties of fuels.

Engines



Manufacturer / type	Liebherr Machines Bulle S.A./ D 934 S
Emission level	97/68/EG step 3A; EPA/CARB Tier 3
Cylinder number and configuration	4 cylinders in-line
Rated power / Rated speed (present EDC setting)	105 [kW] @ 2000 [min^{-1}]
Low idle speed / high idle speed	800 [min^{-1}]; 2170 [min^{-1}]
Overall displacement	6.36 [dm^3]
Compression ratio	17 [-]
Year of manufacture	2005
Cooling medium	water
Combustion process	direct injection
Fuel system type	unit pump Bosch
Speed governor	EDC
Method of air aspiration	turbo charging
Charge air cooling system	Intercooler

Test engine (E1) Liebherr D934S on the engine dynamometer



Manufacturer	IVECO, Torino Italy
Type, emission level	F1C Euro VI
Displacement	3.0 liters
Cylinder number and configuration	4 cylinders in-line
Engine speed	Max. 4200 rpm
Rated power	107kW@3500 rpm
Combustion process	direct injection
Fuel system type	Common Rail Bosch LWR-20
Method of air aspiration	turbo charging
Charge air cooling system	Intercooler

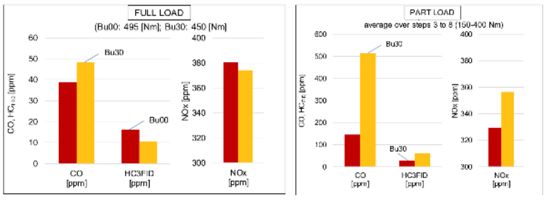
Iveco F1C engine (E2) on the engine dynamometer

Fuels

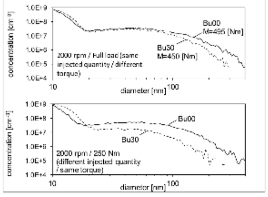
	Ref. Diesel	Bu05	Bu15	Bu30	Bu50
Density at 15°C in kg/m³	833-837	833	832	828	822
Net calorific value in MJ/l	35.3	34.9	34.0	32.8	31.4
Stoichiometric air/fuel ratio	14.6	14.4	14.0	13.5	12.9
Oxygen content in wt.-%	<0.03	1.1	3.1	6.4	10.7
H:C ratio (molar)	0.157	0.160	0.165	0.170	0.179
Cetane number	52-54	≈ 51	≈ 48	≈ 43	≈ 35

Data of Diesel fuel, Butanol and their blends

Emissions Engine E1

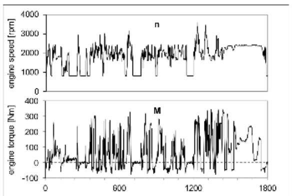


Comparison of Emissions Bu00 & Bu30 at full load and at part load (w DPF DiSiC), E1

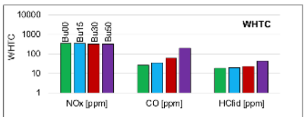


SMPS – size spectra, without DPF, E1

Emissions Engine E2



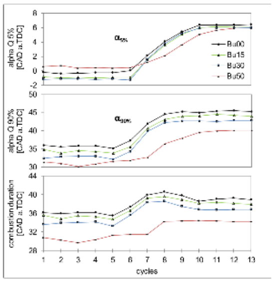
Torque & engine speed (E2) in WHTC



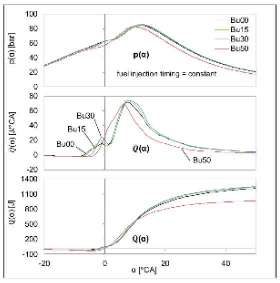
WHTC				
Bu xx	0	15	30	50
NOx [ppm]	339	343	333	330
CO [ppm]	27	36	63	200
HCfid [ppm]	18	20	23	44

Emissions with different Butanol rate in transient operation WHTC, engine (E2)

Combustion Engine E2



Indication statistics of load jump 40-90% at 1500 rpm w/o ATS, w/o EGR, engine (E2)



Indicated pressure and heat release before load jump (cycle nbr.2) w/o ATS, w/o EGR, engine (E2)

Conclusions

For engine (E1), production of the year 2005:

- The operation of this engine with Bu30 is instable at lower part load due to the lower Cetane Number of the blend fuel. Bu30 is considered as a limit of the blending ratio for this engine.
- The PM-emissions with Bu30 are lower, so the soot loading of DPF takes a longer time.
- The regeneration step test (according to SN277206) shows for both fuels similar results: the balance point is attained in the 6th step (at 60% engine load) with the balance point temperature 371-374°C.
- The emissions of CO and HC with Bu 30 at engine part load are higher and the emissions of PN at full load with Bu30 are lower than with Bu0.
- The lower overall heat value of Bu30-blend leads to a respectively lower full load torque without corrections of the injected fuel quantity.

For engine (E2), production of the year 2017:

- With higher Butanol content, there is a lower heat value of the fuel and there is lower torque at FL.
- The repeatability of results at constant operating points (FL), and in dynamic operation (WHTC) is very good.
- At transient operation (WHTC), CO and HC increase with higher BuXX and NO_x stays constant.
- At steady state operation (constant OP's), CO decreases with higher BuXX, HC and NO_x slightly increase.
- The dynamic answer of the engine – performance of the load increase during 4 working cycles – is equal for all three fuels: Bu0/15/30.
- The electronic control system of the engine, (FMO), compensates very well the varying properties of the fuels Bu0/15/30, so that in the combustion diagnostics no differences of heat release can be noticed.
- With Bu50, the engine electronic control cannot entirely compensate the deviating fuel parameters, the dynamic answer of the engine is slower and weaker.
- There are influences of Bu-rate on the inflammation phase and on the combustion duration; there are partly controversial effects of lower self-ignition aptitude (lower CN) and of quicker mixing and higher portion of premixed combustion.
- At stationary part load operating condition with higher Bu-content the start of heat release is slightly retarded (0.5-2 deg CA due to lower CN), but due to the higher portion of premixed fuel, the premixed phase of combustion is much quicker which may overcompensate the later start for BuXX < 30%.
- The operation with Bu50 was only possible for research purposes thanks to the external strong starting system (dynamic brake). A field application of this high Bu-rate is not recommendable.

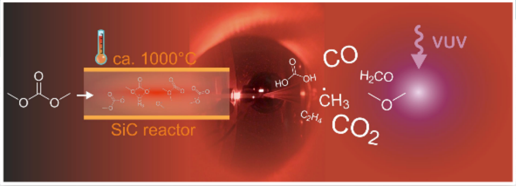
Further information: herve.nauroy@bfh.ch, danilo.engelmann@bfh.ch

Decomposition pathways of alternative fuels studied with synchrotron radiation: dimethyl carbonate

PAUL SCHERRER INSTITUT

Decomposition Pathways of Alternative Fuels Studied with Synchrotron Radiation: Dimethyl Carbonate

Mathias Steglich, Andras Bodi, Patrick Hemberger
Contact: firstname.lastname@psi.ch; VUV Spectroscopy Group, Paul Scherrer Institute, CH-5232 Villigen PSI



I. Introduction

Sustainably produced fuel can aid in reducing the accumulation of greenhouse gases in the atmosphere caused by transportation. For example, dimethyl carbonate (DMC, $C_3H_6O_3$) can be synthesized from biological sources or from CO_2.[1] Its molecular structure (high oxygen, no C-C bonds) facilitates a clean combustion with low soot-forming tendencies.[2] It also reduces smoke and soot emissions when blended into diesel and gasoline, is low in toxicity and biodegradable.

The initiation of fuel combustion is determined by the chemistry of the unimolecular dissociation, i.e., the very early decomposition stages, which we investigate directly at our VUV beamline at the Swiss Light Source. The isomer-selective identification of the radicals, intermediates, and dissociation products is achieved by probing the molecular beam from a flash vacuum pyrolysis with synchrotron radiation in a photoelectron photoion coincidence spectrometer (PEPICO).

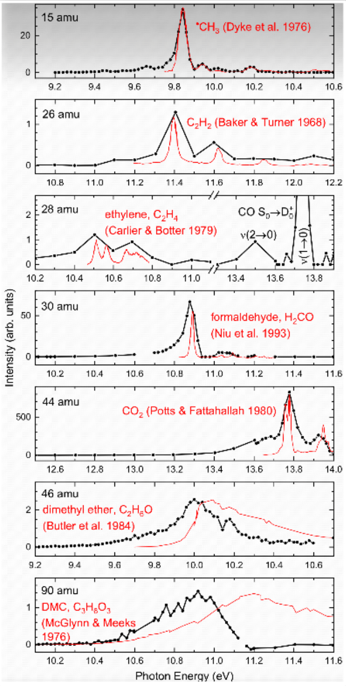
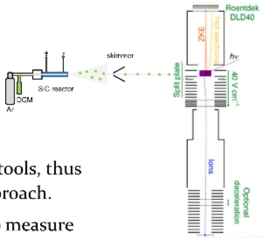


Fig. 1. Mass-selected TPE spectra of DMC pyrolysis products (black) identified by comparison with literature PE spectra (red).

II. Spectroscopic Detection



- A hot tubular micro-reactor is used to simulate the early combustion chemistry.
- After thermal decomposition a molecular beam is formed, which travels into the spectrometer chamber.
- Sampling of reactive intermediates requires sensitive detection tools, thus ionization to yield charged particles is ideally suited for this approach.
- We detect both ions and electrons in coincidence, permitting to measure photoion mass-selected threshold photoelectron spectra (PEPICO).
- PEPICO offers universal, sensitive and multiplexed chemical analysis that enables the isomer-selective detection of elusive and short-lived species.

III. Decomposition Chemistry Deciphered

- Major components, created in DMC pyrolysis, are CO_2, CO, H_2CO (formaldehyde), $^\bullet CH_3$, and C_2H_6O (dimethyl ether, DME; Fig. 1).
- This confirms the two major dissociation pathways as obtained from quantum chemical theory (Fig. 3): (1) CO_2 loss to form DME and (2) a series of β-scissions to create $^\bullet CH_3$, $^\bullet H/H_2$, CO_2, H_2CO, and CO
- In addition, we tentatively identified a minor route, initiated by a H transfer reaction, that forms C_2H_4, C_2H_2, and H_2CO_3 (carbonic acid; Figs. 2,3).
- The elusive, chemically bound carbonic acid is difficult to analyze due to rapid conversion into CO_2 + H_2O, despite being an essential intermediate for biological processes (respiration, carbonate buffer) and for the oceans' CO_2 uptake.[3]

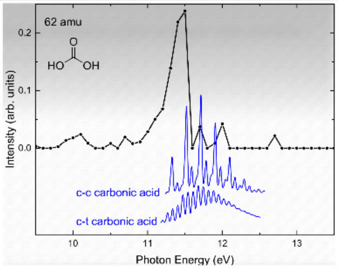


Fig. 2. *Tentative* identification of the elusive carbonic acid. Calculated PE spectra of the two dominant rotamers are printed in blue.

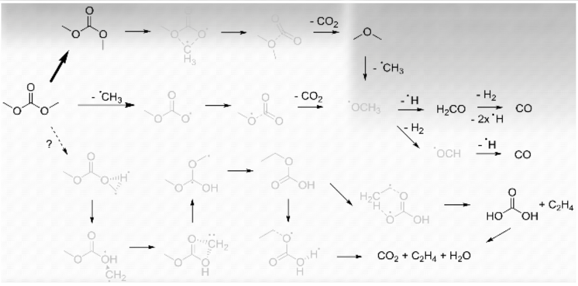


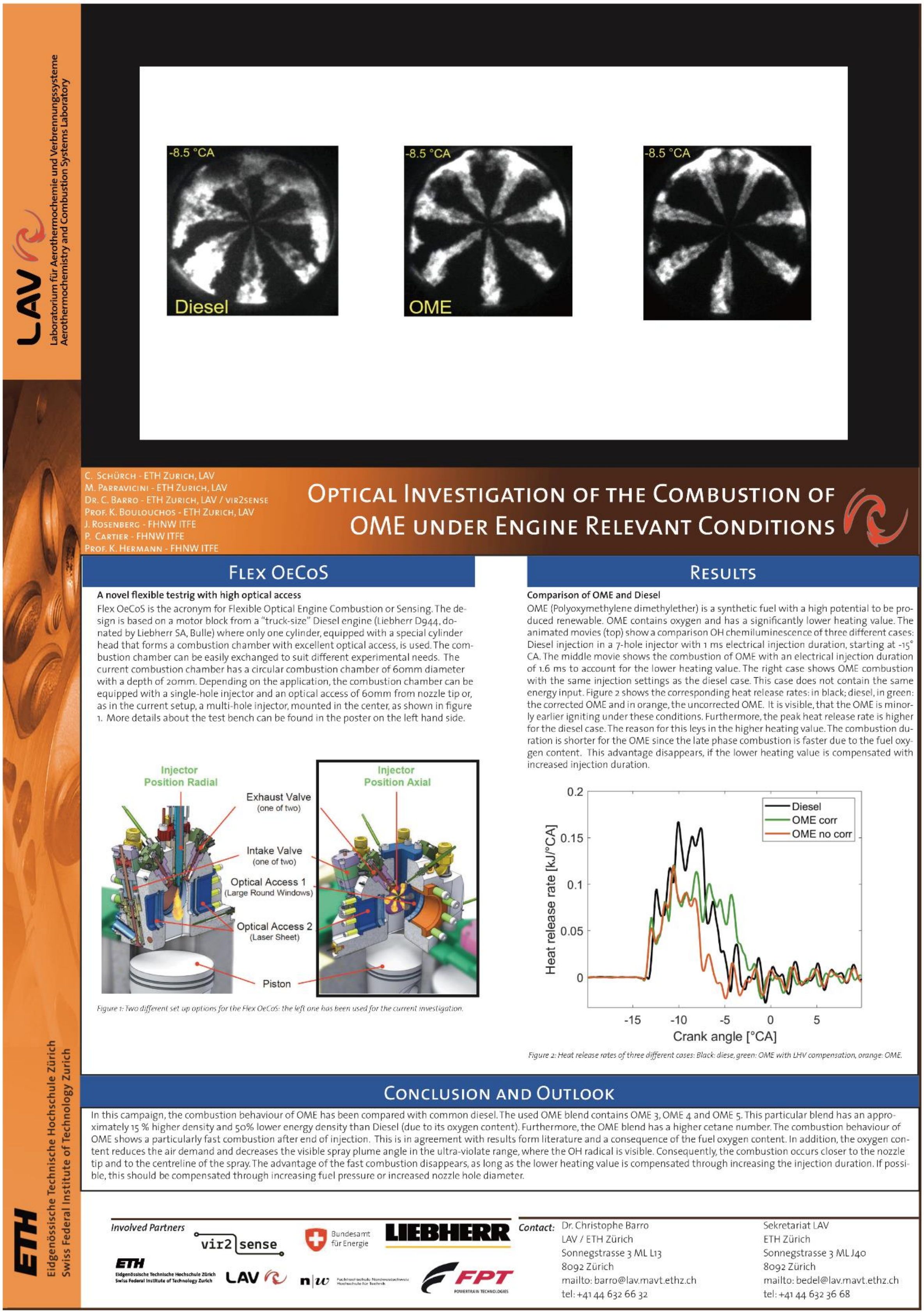
Fig. 3. *Unimolecular* dissociation pathways of DMC. Transition states and intermediate structures *not* identified spectroscopically are printed in grey.

IV. Capabilities of VUV Spectroscopy Group

- In collaboration with external users, we perform research on chemical reaction dynamics in harsh environments such as flames and reactors as well as in the cationic state.
- We investigate chemical dynamics, energetics, and the thermochemistry of stable and weakly bound species along with radicals and carbenes, which govern, e.g., ignition.
- The versatile PEPICO endstation can be combined with different effusive and molecular beam sources that incorporate sample evaporation and gas phase synthesis (high T oven, aerosol source, pyrolysis, catalysis, photolysis, flames, discharge).

References (1) Pacheco & Marshall, Energy & Fuels 11 (1997) 2-29. (2) Alexandrino et al., Fuel 183 (2016) 64-72. (3) Reddy & Balasubramanian, Chem. Commun. 50 (2014) 503-514.

Optical investigation of the combustion of OME under engine relevant conditions



C. Schürch - ETH Zurich, LAV
M. Parravicini - ETH Zurich, LAV
Dr. C. Barro - ETH Zurich, LAV / vir2sense
Prof. K. Boulouchos - ETH Zurich, LAV
J. Rosenberg - FHNW ITFE
P. Cartier - FHNW ITFE
Prof. K. Hermann - FHNW ITFE

OPTICAL INVESTIGATION OF THE COMBUSTION OF OME UNDER ENGINE RELEVANT CONDITIONS

FLEX OECOS

A novel flexible testrig with high optical access

Flex OeCoS is the acronym for Flexible Optical Engine Combustion or Sensing. The design is based on a motor block from a "truck-size" Diesel engine (Liebherr D944, donated by Liebherr SA, Bulle) where only one cylinder, equipped with a special cylinder head that forms a combustion chamber with excellent optical access, is used. The combustion chamber can be easily exchanged to suit different experimental needs. The current combustion chamber has a circular combustion chamber of 60mm diameter with a depth of 20mm. Depending on the application, the combustion chamber can be equipped with a single-hole injector and an optical access of 60mm from nozzle tip or, as in the current setup, a multi-hole injector, mounted in the center, as shown in figure 1. More details about the test bench can be found in the poster on the left hand side.

Figure 1: Two different set up options for the Flex OeCoS: the left one has been used for the current investigation.

RESULTS

Comparison of OME and Diesel

OME (Polyoxymethylene dimethylether) is a synthetic fuel with a high potential to be produced renewable. OME contains oxygen and has a significantly lower heating value. The animated movies (top) show a comparison OH chemiluminescence of three different cases: Diesel injection in a 7-hole injector with 1 ms electrical injection duration, starting at -15° CA. The middle movie shows the combustion of OME with an electrical injection duration of 1.6 ms to account for the lower heating value. The right case shows OME combustion with the same injection settings as the diesel case. This case does not contain the same energy input. Figure 2 shows the corresponding heat release rates: in black; diesel, in green: the corrected OME and in orange, the uncorrected OME. It is visible, that the OME is minorly earlier igniting under these conditions. Furthermore, the peak heat release rate is higher for the diesel case. The reason for this leys in the higher heating value. The combustion duration is shorter for the OME since the late phase combustion is faster due to the fuel oxygen content. This advantage disappears, if the lower heating value is compensated with increased injection duration.

Figure 2: Heat release rates of three different cases: Black: diese, green: OME with LHV compensation, orange: OME.

CONCLUSION AND OUTLOOK

In this campaign, the combustion behaviour of OME has been compared with common diesel. The used OME blend contains OME 3, OME 4 and OME 5. This particular blend has an approximately 15 % higher density and 50% lower energy density than Diesel (due to its oxygen content). Furthermore, the OME blend has a higher cetane number. The combustion behaviour of OME shows a particularly fast combustion after end of injection. This is in agreement with results form literature and a consequence of the fuel oxygen content. In addition, the oxygen content reduces the air demand and decreases the visible spray plume angle in the ultra-violate range, where the OH radical is visible. Consequently, the combustion occurs closer to the nozzle tip and to the centreline of the spray. The advantage of the fast combustion disappears, as long as the lower heating value is compensated through increasing the injection duration. If possible, this should be compensated through increasing fuel pressure or increased nozzle hole diameter.

Involved Partners
vir2sense
Bundesamt für Energie
LIEBHERR
ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich
LAV
n|w
FPT POWERTRAIN TECHNOLOGIES

Contact:
Dr. Christophe Barro
LAV / ETH Zürich
Sonnegstrasse 3 ML L13
8092 Zürich
mailto: barro@lav.mavt.ethz.ch
tel: +41 44 632 66 32

Sekretariat LAV
ETH Zürich
Sonnegstrasse 3 ML J40
8092 Zürich
mailto: bedel@lav.mavt.ethz.ch
tel: +41 44 632 36 68

Combustion characteristics of different fuel blends to improve CO$_2$ emissions of a heavy duty diesel engine

MATTEO PARRAVICINI - ETH ZURICH, LAV
DR. C. BARRO - ETH ZURICH, LAV / VIR2SENSE
DR. P. KYRTATOS - VIR2SENSE
PROF. K. BOULOUCHOS - ETH ZURICH, LAV

COMBUSTION CHARACTERISTICS OF DIFFERENT FUEL BLENDS TO IMPROVE CO2 EMISSIONS OF A HEAVY DUTY DIESEL ENGINE

Laboratorium für Aerothermochemie und Verbrennungssysteme
Aerothermochemistry and Combustion Systems Laboratory

CHARACTERIZATION OF ALTERNATIVE FUELS

The use of alternative fuels in Diesel engines opens new opportunities regarding the reduction of fuel consumption and pollutant emissions. Those fuels can [1]

- be (partially) renewable;
- have different combustion characteristics;
- have different emission behaviours.

For these reasons simply changing from conventional Diesel oil to an alternative compound ① is not the best possible solution, in fact, for example, the yield of NOx could increase while reducing the soot level. The consequences would be:

- Large DPF back pressure (unnecessary)
- **Insufficient SCR effectiveness**

This suggests that when, changing the fuel, also a change of operating strategy ② must be adopted allowing

- reduction of aftertreatment effort
- lower fuel consumption

To this end the fuel must be properly characterized. Blends of polyoxymethylene dimethyl ether (OME) are investigated. In order to understand the fuel effect only, the smaller LHV compared to Diesel is compensated through an increase of the number of injector nozzles.

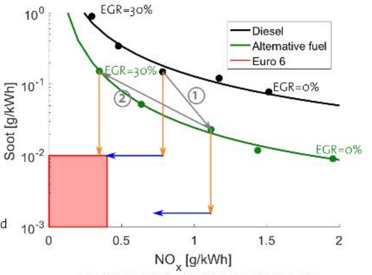


Figure 1: Comparison of the Soot-NOx trade-off of conventional Diesel oil and of an alternative fuel. The red shape indicates the Euro 6 emissions standard for HD engines

Investigated fuels:

	x_{OME} [vol%]	ρ [kg/m3]	LHV [MJ/kg]
Diesel	0	827	43.51
B23	22.7	876.8	36.96
B42	42.6	918.1	32.08

[1]:Barro C., Parravicini M., Boulouchos K., Liati A., Neat polyoxymethylene dimethyl ether in a diesel engine; part 2: Exhaust emission analysis Fuel 234, pp 1414-1421, 2018

ENGINE SPECIFICATIONS

Engine: MTU 396, 1 Cyl, 4-stroke, Diesel engine

Displacement:	3.96l (Bore/Stroke: 165/185mm)
Compression ratio:	13.77

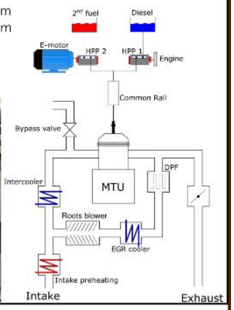
Test bench limitations

Intake pressure:	<4.5bar
Intake temperature:	20-100°C
Exhaust temperature:	<700°C

Fuel supply: double fuel system

Injection pressure:	<1600 bar
Injector nozzles:	7x0.24 mm 8x0.24 mm 9x0.24 mm

Exhaust analysis
NOx/CO/CO2/O2/HC: Standard
Soot: FSN/DMS 500



DIESEL OME BLENDS WITH CONSTANT INJECTION PARAMETERS [2]

The **heat release rate** of the three fuels (Figure 2) reveals

- No influence of OME on the ignition delay
- OME increases the premixed peak due to the lower AFR_{stoich} requiring less oxygen entrainment
- OME also accelerates the diffusion combustion rate

The diffusion combustion curves of B23 and B42 sink earlier than the one of diesel even though the injection timing was deliberately chosen to be identical . A closer investigation of the characteristic mixing rate is therefore required.

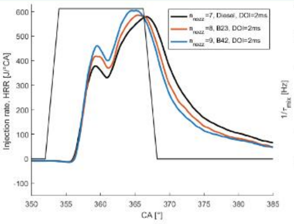


Figure 2: Heat release rate of the three tested fuel. IMEP=9 bar, Speed=1000 rpm SOI=10 °CA bTDC, p_{rail}=1000bar

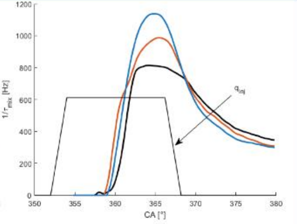


Figure 3: Characteristic mixing rate of the operating conditions shown in figure 2

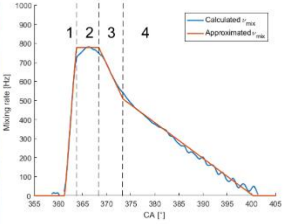


Figure 4: Characteristic mixing rate of a typical Diesel combustion. 4 phases can be recognized:
1: Onset of diffusion combustion
2: Stable diffusion combustion
3: Re-entrainment of burnt gases
4: Late phase combustion

The **characteristic mixing rate** is defined as

$$\nu_{mix}(t) = \frac{1}{\tau_{mix}(t)} = \frac{HRR_{dff}(t)}{\int_0^t \left(q_{inj}(t) - HRR(t)\right)}$$

The analysis of the characteristic mixing rate is performed according to the scheme illustrated in figure 4. Two parameters are particularly interesting:

- The magnitude of $\boldsymbol{\nu_{mix}}$ during phase 2 (stable diffusion combustion) is a measure of the maximum attainable diffusion combustion rate
- The begin of the re-entrainment of burnt gases (end of phase 2) is an indication of the temporal sustainability of the maximum combustion rate.

The **maximum attainable characteristic mixing rate** (see figure 5)

- increases with the blending ratio due to the vicinity of the reaction zone to the nozzle where the turbulence are higher
- decreases when the EGR rate becomes higher due to the reaction zone moving fartehr from the nozzle
- is a characteristic of the fuel, as demonstrated by the 8 and 9 holes nozzles operated with conventional diesel.

The **re-entrainment of burnt gases**

- is less dependent on the EGR rate
- is a merely geometric question, as shown by the 8 and 9 holes diesel cases

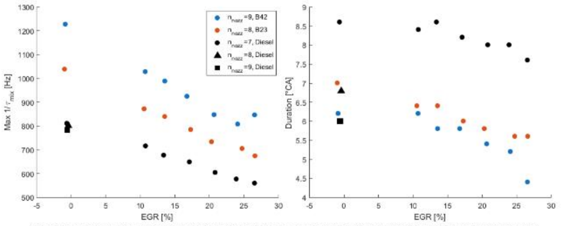


Figure 5: Left: Magnitude of phase 2 of the mixing rate for the three tested fuels over a variation of EGR. Right: Duration of phase 2. The triangle and square markers indicates conventional Diesel operating conditions measured with the 8 and the 9 holes nozzle, respectively.

Moreover it was found that, through the shorter combustion duration, B23 reduces the **indicated specific energy consumption** by 3% while B42 by 5.3% .

[2] Parravicini M., Barro C., Boulouchos K., *Compensation for the differences in LHV of diesel-OME blends by using injector nozzles with different number of holes: Emissions and combustion*, Fuel (2019), Submitted for publication

CONCLUSION AND OUTLOOK

Three fuels were investigated in the present study: conventional Diesel oil, a blend of Diesel and 22.7 *vol*% OME and a blend with 42.6 *vol*% OME. In order to compensate for the smaller lower heating value of OME, nozzles with different amount of holes were used in order to characterize the combustion without changing the fuel inejction pressure and duration. The analysis of the heat release rate showed a faster diffusion combustion of the blends. This behaviour was explained with the help of the characteristic mixing rate that showed how the presence the oxygenated compound allows the mixing to proceed faster. Moreover, the characteristic mixing rate also clarified how the duration of the maximum attainable combustion rate is solely dependent on the geometry of the injection and not on the fuel type. As a consequence of the increased combustion rate, the specific energy consumption was remarkably reduced.
The next step of the present study will be the investigation of other possible alternative fuels such as GTL and HVO using the tools developed during this work.

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Involved Partners
ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich
LAV
Empa
BFE
vir2sense virtual sensor technology
combustion and flow solutions GmbH

Contact: Matteo Parravicini
LAV / ETH Zürich
Sonnegstrasse 3 ML L13
8092 Zürich
mailto: parravicini@lav.mavt.ethz.ch
tel: +41 44 632 23 50

Sekretariat LAV
ETH Zürich
Sonnegstrasse 3 ML J40
8092 Zürich
mailto: bedel@lav.mavt.ethz.ch
tel: +41 44 632 36 68

A comprehensive methodology for pre-chamber gas engine model development

LAV

Laboratorium für Aerothermochemie und Verbrennungssysteme
Aerothermochemistry and Combustion Systems Laboratory

A comprehensive methodology for pre-chamber gas engine model development

Lean burn gas engines operating with natural gas (NG) can significantly contribute to the overall reduction of the combustion-generated CO_2 emissions. However, the low ignitability of lean mixtures causes significant cycle-to-cycle variations (CCV) that have to be compensated with the use of large ignition energy or distributed ignition sources. Pre-chamber ignition, otherwise known as turbulent jet ignition, where the spark plug is located inside a small volume (1-5% of the clearance volume) that is connected with the main chamber via several nozzles, is one such promising technology. This project aims to enhance our understanding over the prechamber combustion and to, ultimately, propose reduced order models suitable for the optimization of such systems. A comprehensive research methodology has been developed, spanning from fundamental investigations in an optically accessible prechamber (OPC) and a rapid compression expansion machine (RCEM) to emission and performance measurements in a near-production one-cylinder gas engine. The numerical work comprised of Direct Numerical Simulations (DNS) [1] that shed light into the underlying processes and are used for the development of the 3D LES /RANS combustion models. The RANS data are further used for the extensive validation of the 0D-1D phenomenological sub-models [2].

Konstantinos Bardis, LAV, ETH Zurich, bardis@lav.mavt.ethz.ch
Dr. Panagiotis Kyrtatos, LAV, ETH Zurich, kyrtatos@lav.mavt.ethz.ch
David Humair, FHNW, david.humair@fhnw.ch
Sotirios Benekos, LAV, ETH Zurich, benekos@lav.mavt.ethz.ch
Dr. Alexey Denisov, FHNW, alexey.denisov@fhnw.ch
Dr. Michele Bolla, LAV, ETH Zurich, bolla@lav.mavt.ethz.ch
Dr. Christos Frouzakis, LAV, ETH Zurich, frouzakis@lav.mavt.ethz.ch
Dr. Guoqing Xu, LMB & ETH Zurich, guoqing.xu@liebherr.com
Dr. George Giannakopoulos, LAV, ETH Zurich, georgeg@lav.mavt.ethz.ch
Prof. Kai Herrmann, FHNW, kai.herrmann@fhnw.ch
Prof. Dr. Konstantinos Boulouchos, LAV, ETH Zurich, boulouchos@lav.mavt.ethz.ch

Introduction

The low carbon-to-hydrogen ratio of the natural gas and its high knock resistance make it particularly suitable for use in high compression ratio lean burn gas engines. Combination of a high compression ratio with simultaneous use of lean air-fuel mixture allows for higher engine efficiency and lower NOx emissions thanks to the low combustion temperatures. Nevertheless, lean mixtures ignitability is low and the early flame is more susceptible to turbulence, resulting in high cyclic combustion fluctuations and unburned hydrocarbon (UHC) emissions, a potent green house gas (GHG). The prechamber offers both a protected environment for the early flame growth and multiple ignition locations for the establishment of a flame front in the main chamber, counteracting combustion fluctuations, increasing flame consumption speed and reducing the CH_4 slip.

Engine Investigations – CTI, LMB

The single-cylinder engine offers high flexibility and controlled conditions for testing different prechambers in terms of performace (efficiency, CCV) and emissions (mainly CO_2, NOx, UHC). Data obtained from the single cylinder engine serve as validation source for the 0D model and evaluation of the newly desgined prechambers.

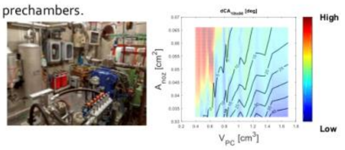


Fig.1: View of the 1-cyl engine (left) and the combustion duration as predicted by the 0D model for a range of prechamber volumes and nozzle areas (right). The 0D optimization results have been used for the design of the new prechambers.

RCEM Investigations - CTI, LMB & EU, GasOn

The optical investigations in RCEM under engine relevant conditions enhance the understanding of the main chamber combustion mechanisms. In addition, the optical data aim to provide a validation for the LES/RANS simulations [3].

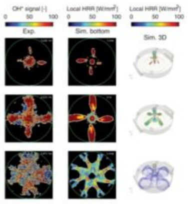


Fig.2: Comparison of OH* chemiluminescence (left column) and heat release rate (HRR) as obtained using reactive RANS simulations (middle column) at different time instants after spark time. The HRR along the flame iso-surface is shown in the right column.

Generic Investigations – SFOE & CTI, LMB

A constant volume divided chamber with a single hole nozzle is used for fundamental investigations. This state-of-the-art set-up allows optical access in both the pre- and the main-chamber, scavenging of the prechamber (extra fueling of the prechamber) and a variable nozzle diameter. Consequently, the combustion characteristics under a variety of conditions, including different combustion regimes even with flame extinction/re-ignition, can be investigated.

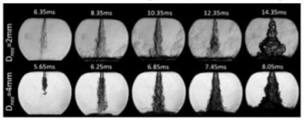


Fig.3: Schlieren imaging from the optical prechamber test rig showing single jet penetration into the main chamber for two different nozzle diameters. Time t=0 is at ignition. The sequence shows the hot jet from exit up to main chamber ignition, indicating slower ignition with a smaller nozzle. Initial conditions: T=350K, P=5bar, Φ_{PC}=1, Φ_{MC}=0.75

Reactive DNS Simulations – SFOE

The Reactive Direct Numerical Simulations is the prime numerical tool for an in-depth understanding of the physics associated with the in-prechamber processes (flame propagation and interaction with the chamber walls), the flame passage through the nozzle, the main chamber ignition through the reactive jets and the turbulent flame propagation inside the main chamber. Both 2D and 3D simulations for a variety of conditions/designs were performed to investigate their effect on combustion characteristics.

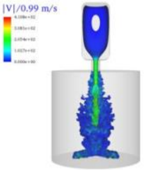


Fig.4: 3D reactive DNS simulation of the generic single-hole prechamber geometry. The plotted surface depicts the iso-contour of stoichiometric mixture, showing the mixture pushed out of the prechamber (main chamber) and the flame surface where the fuel is consumed (prechamber and main chamber). Color scale shows velocity magnitude. Initial conditions: T=500K, P=1bar, Φ_{PC}=1, Φ_{MC}=0.75

Expected Impact

The outcome of this research activity is expected to enhance the current understanding of the complex prechamber combustion physics and enable the optimization of prechamber engines operating with natural gas. In addition to the significant reduction of CO_2 emissions through the use of natural gas, the expansion of the lean limit operating window, the increase of the power density and the reduction of CH_4 slip are further benefits from the optimal design of the prechambers. Future research will be focused on the testing of alternative fuels produced from power-to-gas processes to allow the complete removal of GHG emissions from power generation using gas engines.

References

[1] S. Benekos, G. K. Giannakopoulos, C. E. Frouzakis, K. Boulouchos, An exploratory parametric 2-D DNS study of prechamber ignition: Part I. Effect of thermochemical state & Part II. Effect of geometry, spark location and initial low field, Combustion and Flame, (in preparation)

[2] Bardis, Konstantinos, et al. *A Zero Dimensional Turbulence and Heat Transfer Phenomenological Model for Pre-Chamber Gas Engines*. No. 2018-01-1453. SAE Technical Paper, 2018.

[3] Xu, Guoqing, et al. "Experimental and numerical investigations of the unscavenged prechamber combustion in a rapid compression and expansion machine under engine-like conditions." *Combustion and Flame* 204 (2019): 68-84.

Partners

LAV
n|w
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Bundesamt für Energie BFE
KTI/CTI
DIE FÖRDERAGENTUR FÜR INNOVATION
THE INNOVATION PROMOTION AGENCY
LIEBHERR
GAS ON
European Commission

Radiative heat transfer in large two-stroke marine diesel engines

S. Geringer geringer@lav.mavt.ethz.ch
Dr. M. Bolla mbolla@lav.mavt.ethz.ch
Prof. K. Boulouchos boulouchos@lav.mavt.ethz.ch
Dr. C. Paul Pennsylvania State University
Prof. D. C. Haworth Pennsylvania State University

Laboratorium für Aerothermochemie und Verbrennungssysteme
Aerothermochemistry and Combustion Systems Laboratory

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Radiation in Marine Diesel Engines

Radiative heat transfer in large two-stroke marine diesel engines.

Radiative heat transfer in piston engines has received increased attention in recent years. Conventional wisdom has been that radiative heat transfer contributes significantly to overall heat losses in large bore engines due to the involved large length- and time-scales and that radiation in engines is generally dominated by soot. However, recent studies [3,4] for small and medium size diesel engines have shown that at operating pressures and soot levels typical of modern diesel engines, gas phase radiation (especially CO2 and H2O) can become more important than soot radiation. Furthermore, there is a complex spectral interplay between soot (broadband-type nature) and gas phase (selective spectra) radiation reabsorption which influences radiation reaching the wall (contributing to wall heat losses) and in-cylinder temperature redistribution. In view of more stringent emission legislation, in particular on NOx, the temperature redistribution can have a significant impact on NOx emissions due to the non-linear temperature dependency of the NOx formation rate.

Experimental Setup

The spray combustion chamber SCC (Ø500 x 150 mm) owned by Winterthur Gas & Diesel is an optically accessible constant volume chamber representative for smaller 2-stroke as well as larger 4-stroke marine diesel engines. At start of injection, realistic operating conditions are achieved by a pressure vessel/heat regenerating system (see Figure 1, left) providing heated and pressurized air through inclined inlet ports into the chamber. The SCC enables the investigation of in-cylinder processes at relevant conditions (up to 20 MPa peak firing pressure) such as fuel spray propagation and evaporation, ignition, combustion and emission formation [1].

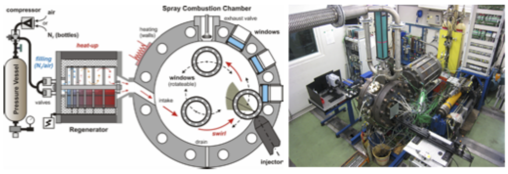


Figure 1: Left: Principle/schematic of the experimental setup, exemplifying the operational (filling, heat up, swirl, injection) and functional aspects (window position, exhaust valve). Right: Impression of the spray combustion chamber test facility.

Spectral Properties of Gases and Soot

The principal emitter and absorber of radiation in piston engines are CO2, H2O and CO together with soot (particulate matter). The spectral radiation absorption coefficients of CO2, H2O and CO are composed of millions of individual narrow bands (lines) at specific wavenumbers (see figure 2), therefore showing a strong spectral dependence. High pressures, as encountered in diesel engines, lead to a broadening of the individual lines (i.e. an overlapping of lines) and increase the radiative emission and absorption in proportion to the total pressure. Contrary to molecular gases, soot acts as a broadband emitter and absorber over a wide part of the spectrum. The interplay of soot and gas phase radiation results in a redistribution of energy within the combustion chamber, where a portion of the radiation originating from soot (formed in the fuel rich part of the flame) is reabsorbed at specific wavenumbers by CO2, H2O and CO in the combustion products.

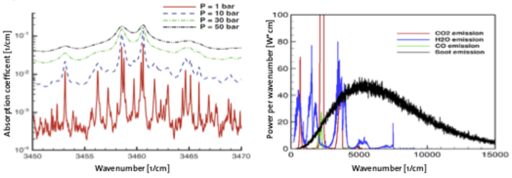


Figure 2: Left: Spectral absorption coefficient of a mixture containing 1% CO2 and 2% H2O at varying total pressures for a small region of the spectrum (Source: [2]). Right: Spectral emitted power per wavenumber interval of main combustion products and soot at conditions typical of marine diesel engines.

Computational Setup

The required thermo-chemical fields for the radiation analysis were generated using the following StarCD model:

- SCC geometry with two 3-hole injectors (d=0.875mm)
- Conditions at start of injection: p=90bar, T=900K
- n-heptane as fuel surrogate
- RANS k-ε turbulence model
- Flamelet Generated Manifold combustion model
- Soot concentration based on correlation for CO

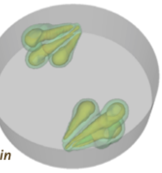


Figure 3: Visualization of the computational domain with mixture fraction contours.

Radiation Analysis

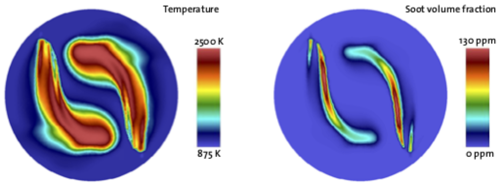
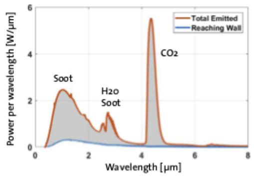


Figure 4: Examples of temperature (left) and soot volume fraction (right) fields at t=15ms which served as basis for the radiation analysis.

In this study, the radiation analysis is performed in a post-processing manner, i.e. for individual time steps without radiative source term coupling with the flow field. The required composition and temperature fields are based on the results of a RANS-FGM combustion model with a correlation based on CO for the soot field. The employed radiation model is a Photon Monte Carlo (PMC, i.e. ray tracing) with a detailed line-by-line spectral model, giving access to full spectral properties. The considered radiative species are CO2, H2O and CO in addition to soot, whose spectral properties are based on the small particle assumption. The combustion chamber wall is treated as cold and black in terms of radiation, meaning that the wall does not emit radiation and all radiation reaching the wall is absorbed completely.

Radiation Results

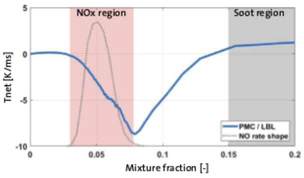
Calculations with the detailed PMC/Line-by-Line model show that only a minor part of the emitted radiation reaches the wall (around 9 %) and a significant part of the emitted radiation is reabsorbed (91 %) within the doamin before reaching the wall (see figure 5), underlining the importance of reabsorption at these conditions. The radiation reaching the wall is dominated by soot (80.7 %) and H2O (14.1 %), whereas most of the emitted CO2 radiation, with its characteristic peak around 4.3 μm, is reabsorbed before reaching the wall.



	Total emitted [MW] (share %)	Reaching wall [MW] (share %)	Percentage of self emission that reaches wall
Total	6.21 (100 %)	0.56 (100 %)	9.0 %
Soot	3.51 (56.6 %)	0.45 (80.7 %)	12.8 %
CO_2	1.96 (31.5 %)	0.03 (4.7 %)	1.4 %
H_2O	0.68 (11.0 %)	0.08 (14.1 %)	11.5 %
CO	0.06 (0.9 %)	0.003 (0.5 %)	4.9 %

Figure 5: Radiative power over wavelength spectrum at t=15ms. The orange line shows the total emitted radiation, the blue curve shows the radiation reaching the wall. The shaded area between the curves indicates that part of the emitted radiation that is reabsorbed before reaching the wall.

The impact of radiation on temperature redistribution was assessed by calculating an averaged net radiative temperature source term in mixture fraction space (see figure 6). A negative source term is observed in the region where NOx is formed (red region in figure 6), implying that radiation could affect NOx formation. Further investigations with radiative source term coupling in the energy equation are required to quantify the time integrated effect on NOx.



$$T_{net} = \frac{\dot{Q}_{abs} - \dot{Q}_{emi}}{\rho \cdot c_p}$$

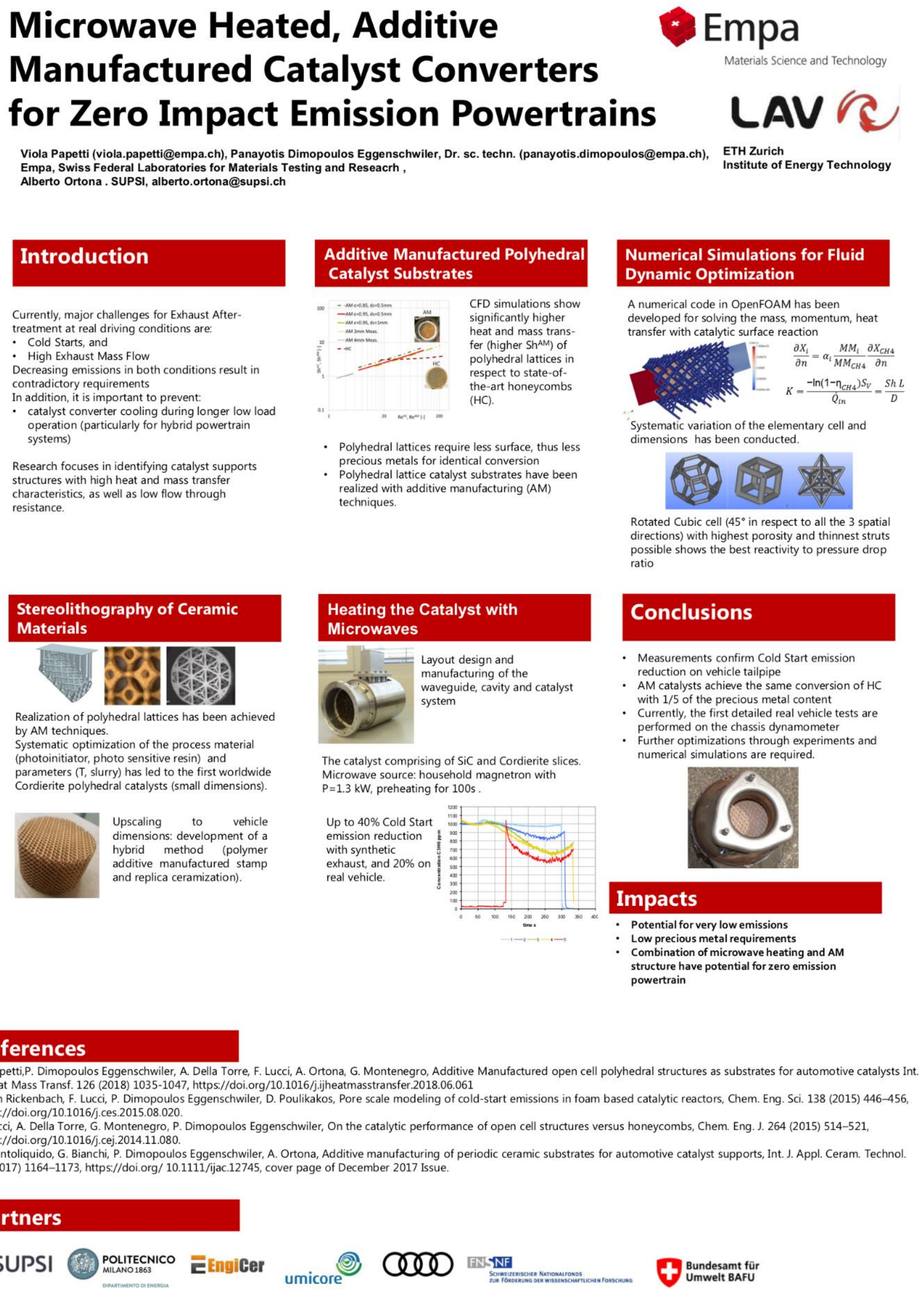
Figure 6: Net effect of radiation on temperature in mixture fraction space at t=15ms, shown as a temperature source in K/ms. The red area highlights where NOx is formed, indicated by the shape of the NO formation rate (dotted line).

References

[1] Herrmann K., von Rotz B., Schulz R., and Weisser G., ISME 2011, 9th International Symposium on Marine Engineering, Kobe, Japan, October 2011
[2] M.F. Modest, D.C. Haworth, „Radiative heat transfer in turbulent combustion systems: theory and applications", Springer, 2016.
[3] C. Paul, et al., „A detailed modeling study of radiative heat transfer in heavy-duty diesel engine", Combustion and Flame 200 (2019) pp. 325-341.
[4] C. Paul, et. al., „A simplified CFD model for spectral radiative heat transfer in high-pressure hydrocarbon-air combustion systems", Proceedings of the Combustion Institute 37 (2019), pp. 4617-4624.

Funding The present work has been conducted in cooperation with Winterthur Gas & Diesel under the CTI project „Modeling of NOx and soot formation and radiation in large 2-stroke marine diesel engines". Financial support by the Swiss Commission for Technology and Innovation (CTI) is gratefully acknowledged.

Microwave heated, additive manufactured catalytic converters for zero impact emission powertrains



Microwave Heated, Additive Manufactured Catalyst Converters for Zero Impact Emission Powertrains

Empa
Materials Science and Technology

LAV

Viola Papetti (viola.papetti@empa.ch), Panayotis Dimopoulos Eggenschwiler, Dr. sc. techn. (panayotis.dimopoulos@empa.ch),
Empa, Swiss Federal Laboratories for Materials Testing and Reseacrh ,
Alberto Ortona . SUPSI, alberto.ortona@supsi.ch

ETH Zurich
Institute of Energy Technology

Introduction

Currently, major challenges for Exhaust After-treatment at real driving conditions are:

- Cold Starts, and
- High Exhaust Mass Flow

Decreasing emissions in both conditions result in contradictory requirements

In addition, it is important to prevent:

- catalyst converter cooling during longer low load operation (particularly for hybrid powertrain systems)

Research focuses in identifying catalyst supports structures with high heat and mass transfer characteristics, as well as low flow through resistance.

Additive Manufactured Polyhedral Catalyst Substrates

CFD simulations show significantly higher heat and mass transfer (higher Sh^{AM}) of polyhedral lattices in respect to state-of-the-art honeycombs (HC).

- Polyhedral lattices require less surface, thus less precious metals for identical conversion
- Polyhedral lattice catalyst substrates have been realized with additive manufacturing (AM) techniques.

Numerical Simulations for Fluid Dynamic Optimization

A numerical code in OpenFOAM has been developed for solving the mass, momentum, heat transfer with catalytic surface reaction

$$\frac{\partial X_i}{\partial n} = \alpha_i \frac{MM_i}{MM_{CH4}} \frac{\partial X_{CH4}}{\partial n}$$

$$K = \frac{-\ln(1-\eta_{CH4}) S_V}{\dot{Q}_{in}} = \frac{Sh\,L}{D}$$

Systematic variation of the elementary cell and dimensions has been conducted.

Rotated Cubic cell (45° in respect to all the 3 spatial directions) with highest porosity and thinnest struts possible shows the best reactivity to pressure drop ratio

Stereolithography of Ceramic Materials

Realization of polyhedral lattices has been achieved by AM techniques.
Systematic optimization of the process material (photoinitiator, photo sensitive resin) and parameters (T, slurry) has led to the first worldwide Cordierite polyhedral catalysts (small dimensions).

Upscaling to vehicle dimensions: development of a hybrid method (polymer additive manufactured stamp and replica ceramization).

Heating the Catalyst with Microwaves

Layout design and manufacturing of the waveguide, cavity and catalyst system

The catalyst comprising of SiC and Cordierite slices.
Microwave source: household magnetron with P=1.3 kW, preheating for 100s .

Up to 40% Cold Start emission reduction with synthetic exhaust, and 20% on real vehicle.

Conclusions

- Measurements confirm Cold Start emission reduction on vehicle tailpipe
- AM catalysts achieve the same conversion of HC with 1/5 of the precious metal content
- Currently, the first detailed real vehicle tests are performed on the chassis dynamometer
- Further optimizations through experiments and numerical simulations are required.

Impacts

- **Potential for very low emissions**
- **Low precious metal requirements**
- **Combination of microwave heating and AM structure have potential for zero emission powertrain**

References

V. Papetti,P. Dimopoulos Eggenschwiler, A. Della Torre, F. Lucci, A. Ortona, G. Montenegro, Additive Manufactured open cell polyhedral structures as substrates for automotive catalysts Int. J. Heat Mass Transf. 126 (2018) 1035-1047, https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.061

J. von Rickenbach, F. Lucci, P. Dimopoulos Eggenschwiler, D. Poulikakos, Pore scale modeling of cold-start emissions in foam based catalytic reactors, Chem. Eng. Sci. 138 (2015) 446–456, https://doi.org/10.1016/j.ces.2015.08.020.

F. Lucci, A. Della Torre, G. Montenegro, P. Dimopoulos Eggenschwiler, On the catalytic performance of open cell structures versus honeycombs, Chem. Eng. J. 264 (2015) 514–521, https://doi.org/10.1016/j.cej.2014.11.080.

O. Santoliquido, G. Bianchi, P. Dimopoulos Eggenschwiler, A. Ortona, Additive manufacturing of periodic ceramic substrates for automotive catalyst supports, Int. J. Appl. Ceram. Technol. 14 (2017) 1164–1173, https://doi.org/ 10.1111/ijac.12745, cover page of December 2017 Issue.

Partners

SUPSI
POLITECNICO MILANO 1863 DIPARTIMENTO DI ENERGIA
EngiCer
umicore
FNSNF Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung
Bundesamt für Umwelt BAFU

Flow and dual-fuel combustion diagnostics at the new optical engine facility Flex-OeCoS

Flow and dual-fuel combustion diagnostics at the new optical engine facility Flex-OeCoS*

Stefan Herzig[1], Alexey Denisov[1], Kai Herrmann[1], Rolf Bombach[2], Christian Schürch[3]

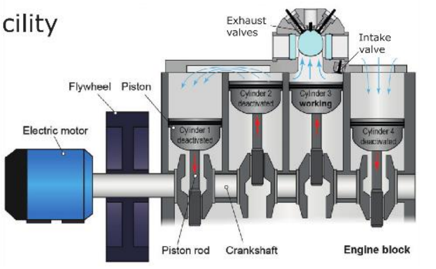
[1] Institute for Thermal and Fluid Engineering (ITFE), FHNW, Windisch
[2] Paul Scherrer Institute, Villigen
[3] Aerothermochemistry and Combustion Systems Laboratory (LAV), ETH, Zürich

Introducing the new optical engine facility

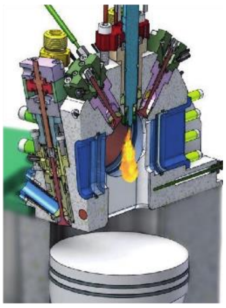
The novel "optical engine" test facility "Flex-OeCoS" enables the investigation of pilot spray ignition and the ensuing transition to a turbulent premixed flame.

The experimental test facility features ability to achieve engine relevant compression/combustion pressures and temperatures at variable speeds (flow, turbulence) for an adjustable range of gas/air charge composition. Process conditions are tunable with high procedure variance (variable valve timing, number of cycles) to approach characteristic conditions for ignition and combustion influencing parameters.

The optically accessible combustion chamber offers enormous flexibility to apply optical measurement methods to acquire ignition and flame propagation.



CR 13.8, compression pressure up to 160 bar (max. 240 bar)
Compression temperature: 1000 K
Flow/turbulence depending on rpm (200-1200; max. 1800 rpm)
Wide range of fuel-air-ratios

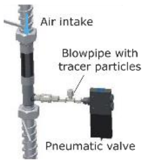


Optical chamber:
Ø60 mm ◇ 20 mm

Characterizing flow field and turbulence

High-speed particle image velocimetry was applied to study the evolution of flow field in Flex-OeCoS during the compression cycle.

Boron nitride powder (1 Njm) was used for tracer particles, as it is stable up to 900°C.
The powder was seeded into the air intake flow using four single-shot blowpipes, manually reloaded after each cycle (with 200 cycles per operation point).

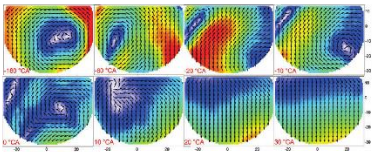


The instantaneous flow field ( ) for any given point can be represented as a combination of average, coherent and turbulent flow components:

$$(\;) = \;+\;+\;$$

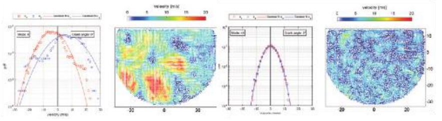
Turbulent kinetic energy can be defined as the magnitude of the fluctuations averaged over all cycles:

$$= \frac{1}{}\,\frac{(\;)^{2}}{2} = \frac{1}{}\,\frac{\;+\;+\;}{2}$$

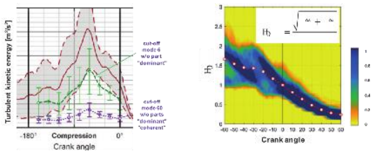


Average flow field: a vortex created by the air intake flow is squished into the chamber as the piston goes up, and dissipates shortly after the top dead center (0°CA).

Using proper orthogonal decomposition (POD) to separate coherent components from turbulence:



Low-order modes (left) contain coherent flow regions, whereas velocities of high-order modes (right) are randomly distributed.



Combining the POD modes below the cut-off allows to calculate the turbulent kinetic energy and a spatial pdf analysis leads to a key figure value.

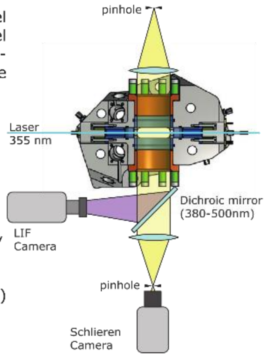
Detecting low-temperature ignition with Schlieren and CH_2O-LIF

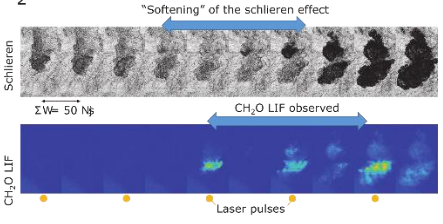
The ignition delay of the pilot fuel jet in dual-fuel combustion increases compared to pure diesel combustion. The delay consists of two stages: low- and high-temperature ignition. The first stage can be identified by the appearance of CH_2O LIF. [1]

Edgewave IS400 YAG laser provided 7 mJ pulse energy at 355 nm at 10 kHz repetition rate. Laser-induced fluorescence (LIF) was recorded by a non-intensified high-speed camera.

To distinguish LIF signal from flame luminosity, the camera recorded images at 20kHz, so that only every second image contains LIF signal.

OME pilot fuel and lean methane mixture (N∌2.5) were used to avoid soot formation.





LIF signal is observed right after the "softening" of the schlieren effect.

Under the non-sooting conditions we expect that the observed LIF signal comes from CH_2O and not from PAH. Flame luminosity under these conditions has been shown to stem from broadband CO_2^* chemiluminescence at 300-600 nm [2].

References

1. S. A. Skeen, J. Manin, and L. M. Pickett, *Proceedings of the Combustion Institute* **2015**, *35* (3), 3167–3174.
2. A. Srna, G. Bruneaux, B. von Rotz, R. Bombach, K. Herrmann, and K. Boulouchos, *SAE Int. J. Engines* **2018**, *11* (6), 1049–1068.

This work was supported by the Swiss Federal Office of Energy projects SI/501546 and SI/501628 as well as by the SCCER Mobility program

---

* Flexibility regarding Optical engine Combustion diagnostics and/or investigation of Sensing devices

Accelerated methane combustion with high velocity pre-chamber ignition jet

Fachhochschule Nordwestschweiz
Hochschule für Technik
ETH zürich

Accelerated methane combustion with high velocity pre-chamber ignition jet

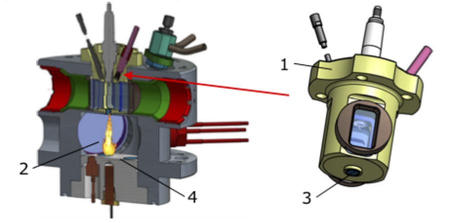
David Humair[1], Alexey Denisov[1], Sotirios Benekos[2], Christos E. Frouzakis[2]
[1]**Institute for Thermal and Fluid Engineering (ITFE), FHNW;** [2]Aerothermochemistry and Combustion Systems Laboratory (LAV), ETHZ

Improved ignition behavior

Methane-air mixtures of different initial pressures and temperatures were ignited using a high-velocity pre-chamber (PC) ignition jet. The jet velocity was found to have a strong effect on the chemical state of the transient turbulent jet and the combustion behavior of the premixed main chamber (MC) charge. Using extensive optical diagnostics and physical measurement techniques, the characteristics of the ignition, propagation as well as the heat release and wall heat loss were analyzed. The experiments complement ongoing numerical investigations.

Method overview

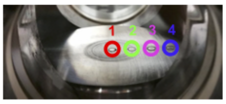
The Optical Pre-Chamber (OPC)[1] test rig consists of two chambers, connected via a cylindrical nozzle with a diameter d_j which can be varied. Both chambers are optically accessible and can be filled individually with mixtures of different composition. The combustion is ignited by a spark plug at the top of the PC.



1: Optical pre-chamber
2: Flame jet into the main chamber
3: Nozzle
4: Lower wall with heat flux sensors

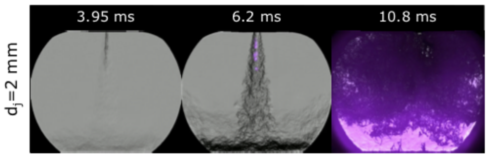
The test rig is equipped with three high-speed cameras to capture the flame luminosity in the PC as well as Schlieren images and OH* chemiluminescence in the MC.

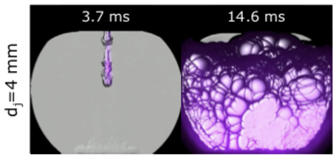
The spatial distribution of the heat flux on the lower wall, is measured using four heat flux sensors[2] fitted along its radius.



Results

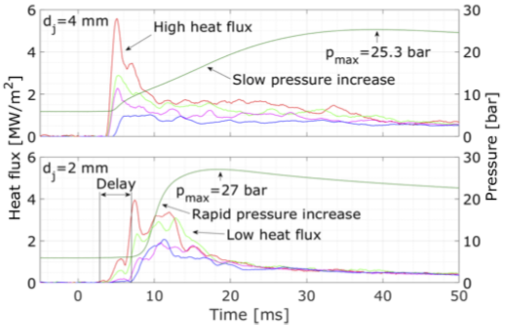
The velocity of the hot jet was, as expected, much higher for nozzles of smaller diameter (initial velocity: ~105 m/s for d_j=4 mm, ~235 m/s for d_j=2 mm). The slower jet resulted in a jet flame exiting into the MC (violet shading in the pictures below), while flame kernels in the faster jet only appeared after the jet decelerated to approximately 50 m/s. Higher jet velocity led to increased fine-scale turbulent mixing in the main chamber, visible in the Schlieren images. Although combustion in the main chamber started later for the d_j=2 mm nozzle, the reaction progressed much faster, overtaking the wider nozzle.



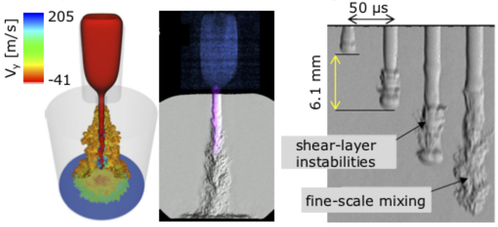


Initial conditions:
Pressure 5 bar
Temperature 450 K
Fuel-air ratio φ:
Pre-chamber 1
Main chamber 0.75

This is also reflected on the slope of the pressure trace, representing the heat release rate. Combustion is considered complete when the peak pressure is reached. The total heat loss (integrated heat flux) is significantly lower for the d_j=2 mm nozzle, for which the PC flame appears quenched and ignition in the MC is delayed.



For a detailed description of jet formation, mixing and main chamber ignition, 3-D direct numerical simulation (DNS) and large eddy simulations (LES) are currently performed to complement the experimental investigations.



The images compare the initial jet penetration from the DNS (left) and the experiment (right). The simulations reveal the detailed jet dynamics and provide highly-resolved data describing mixing and ignition in the main chamber. The wall heat flux measurement will contribute to the understanding of flame-wall interactions and provide much-needed validation data.

Conclusions

Ignition by a turbulent jet generated in a pre-chamber is a promising technology for efficient and stable combustion of lean natural gas in next-generation gas engines. The ignition of the main chamber charge is strongly linked to the condition of the pre-chamber jet. High jet velocities may result in thermal quenching and increased radical formation inside the nozzle. The subsequent increased reactivity of the quenched jet contents associated with high turbulence and fine-scale mixing lead to high heat release rates and rapid combustion.

References

[1] B. Schneider, P. Kyrtatos, LAV, ETHZ
[2] Dr.-Ing. M. Müller, Dr. Müller Instruments GmbH & Co. KG

Financial support & computational resources

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra
Bundesamt für Energie BFE
Swiss Federal Office of Energy SFOE

- "Investigation of heat transfer by modern gas combustion processes", SI/501546
- "DNS of ignition flame propagation in future engines", SI/501301

CSCS
Centro Svizzero di Calcolo Scientifico
Swiss National Supercomputing Centre

- CSCS project number s753

WIN GD
Simply a better different

CHALMERS
UNIVERSITY OF TECHNOLOGY

In-Nozzle Flow & Spray Morphology Investigations of Marine Diesel Injectors

Reto Balz[1,2], Andreas Schmid[1] and David Sedarsky[2]

1 – Winterthur Gas & Diesel Ltd., Winterthur, Switzerland
2 – Combustion and Propulsion Systems Division, Chalmers University, Gothenburg, Sweden

Introduction

Injector geometries of large marine two-stroke diesel engines differ extensively from typically used configurations in diesel engines. The injector nozzle bores are asymmetrically arranged as all the bores face a similar direction. Due to this geometric setup, the nozzle bores are also distributed eccentric with respect to the central main bore of the injector nozzle. Experiments have shown that sprays from such orifices propagate non-symmetrical to the nominal axis of the nozzle bore [1]. Those spray deviations can lead to wall wetting which increases fuel consumption, emissions, component temperatures and loss of lubrication film.

Additional experiments and CFD simulations using a cavitation model have been applied to further understand the relation of fluid-dynamic effects and spray morphology [1]. It has been shown that the inhomogeneous flow profile at the nozzle bore exit leads to the observed non-symmetrical spray propagation.

To further investigate the in-nozzle flow and how it affects the spray morphology for large marine two-stroke diesel engine injectors, a new project with the partners Combustion Engine Research Center (CERC), Chalmers University of Technology and Winterthur Gas & Diesel Ltd. has been started. In a first phase of the project, the in-nozzle flow will be investigated using transparent nozzles and real condition injection pressures and air density of up to 80 MPa and 33 kg/m³, respectively. The feasibility of transparent nozzles for marine diesel applications has been shown using a special injector design developed by [2] at Chalmers University of Technology. By using diesel and nozzles made of acrylic, the indices of refraction can be matched allowing optical detection of cavitation within the nozzle [2]. Additionally, the breakup of the spray will be investigated simultaneously using ballistic imaging, an optical measurement technique used to reveal details of the liquid core [4].

In the second phase of the project, the geometries used for the transparent nozzles will be made of metal and used in the Spray Combustion Chamber (SCC) at Winterthur Gas & Diesel Ltd. under engine similar conditions. The SCC is an optically accessible constant volume chamber with a diameter of 500 mm that is representative of dimensions of large marine diesel engines. It is designed for pressures up to 20 MPa and temperatures up to 950 K what allows the investigation of the ignition behaviour of the injected fuel.

In-nozzle flow & spray morphology

A new transparent nozzle holder (TNH) has been built to perform qualitative in-nozzle flow investigations based on a line-of-sight optical measurement technique like Shadowgraphy. To cope with the high fuel pressures during the quasi-steady-state injection process, the transparent nozzle is braced in the TNH. External forces are applied from all sides to the rectangular shaped, transparent nozzle made of acrylic as investigations have shown that this decreases the failure probability significantly. Figure 1 depicts schematic illustrations of the TNH: top view (i), side view (ii) and detailed, sectional view around the transparent nozzle (iii), with pressure sensor (a), side clamp (b), top clamp (c), sapphire brick (d), transparent nozzle (e), main body (f) and injector mount (g). The detailed, sectional view (iii) also depicts the approximate location of the used field of view (FOV) of the optical measurements.

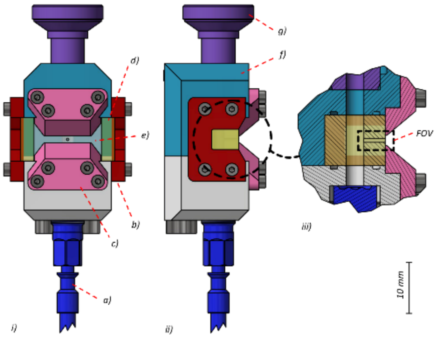


Figure 1: Schematic illustration of the transparent nozzle holder with top view (i), side view (ii) and detailed, sectional view through the transparent nozzle (iii) indicating the field of view around the nozzle bore, with pressure sensor (a), side clamp (b), top clamp (c), sapphire brick (d), transparent nozzle (e), main body (f) and injector mount (g).

The experimental results depicted in figure 2 i) uses a transparent nozzle with an eccentrically arranged, 90° angled nozzle bore with a diameter of 0.75 mm which is a standard nozzle bore size for large marine two-stroke diesel engines. The images shown in figure 2 i) show shadowgraphy photographs of the nozzle bore with increasing inlet radii between main and nozzle bore from left (sharp-edged) to right (maximal inlet radii). The images show an single image during the quasi-steady-state injection period, 8 ms after start of injection. The applied rail pressure was 50 MPa and the back-pressure was atmospheric. The diesel flow enters the main bore of the transparent nozzle from the left side and enters the nozzle bore from above, leaving it at the bottom of the images. Dark areas indicate areas where the light is refracted off the optical axis and therefore the gaseous phase of the diesel (viz. cavitation flow), while bright areas indicate the liquid diesel phase. As the refractive indices of acrylic and diesel are not perfectly identical, one can see the walls of the bores in the acrylic appearing slightly darker as well.
The strong cavitation in the nozzle bore is decreasing significantly with increasing inlet radii (from left to right). The eccentrically arranged nozzle geometry induces a strong swirl motion in the nozzle bore which is clearly visible with increasing inlet radii (see image on the right in figure 2 i)).
The corresponding spray images are depicted in figure 2 ii) and are acquired at the same instant in time (8 ms after start of injection), however, the spray images are scaled down by a factor of 25 for visualization reasons. One can clearly see how the spray morphology changes significantly in angle, axis and density distribution with changing in-nozzle flow (depicted above the sprays, in figure 2 i)).

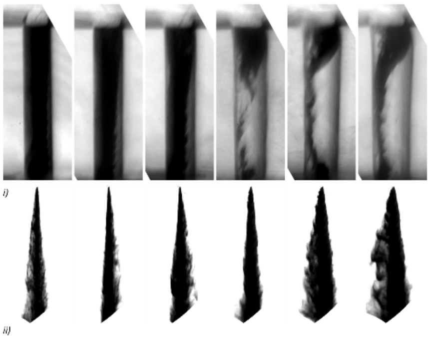


Figure 2: In-nozzle flow visualizations of eccentric nozzle with different levels (left: no radius, sharp edged to right: max. radii) of inlet radii between main and nozzle bore (i) and matching, scaled down, spray images (ii) taken at 50 MPa rail pressure and atmospheric back pressure. Dark areas in the in-nozzle images indicate diesel in the gaseous state, viz. cavitation.

Although the in-nozzle and spray images shown in figure 2 are single-shot images, the experiments were acquired using high-speed cameras recording with 20 kHz. The quantitative evaluation of the spray morphology is ongoing and the nozzle geometries used are reproduced out of metal to perform combustion experiments and investigate the behaviour of the different in-nozzle flow cavitation patterns on the combustion process during engine-like gas temperatures and pressures.

References

[1] *A. Schmid, et al., "Influence of in-nozzle flow of spray morphology", 26th ILASS-Europe, 2014*
[2] *Z. Falgout, M.A. Linne, "Cavitation Inside High-Pressure Optically Transparent Fuel Injector Nozzles", Journal of Physics: Conference Series 656.1, 2015*
[3] *K. Herrmann, et al., "Reference Data Generation of Spray Characteristics in Relation to Large 2-Stroke Marine Diesel Engine Using a Novel Spray Combustion Chamber Concept", 23th ILASS-Europe, 2010*
[4] *M.A. Linne, et al., "Ballistic Imaging of the Flow in the Interior of the Near-Field of an Effervescent Spray", Experiments in Fluids 49.4: 911, 2010*

Contact: Reto Balz (reto.balz@wingd.com)
Winterthur Gas & Diesel Ltd.
Schützenstrasse 1-3
CH-8401 Winterthur

CERC
Combustion Engine Research Center

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

BFE
OFEN
UFE
SFOE

Project INFLOSCOM,
Vertragsnummer:
SI/501299-01

List of Participants

First name:	Name:	Organisation:	E-mail:
Georgios	Alexopoulos	ABB Turbo Systems AG	georgios.alexopoulos@ch.abb.com
Carina	Alles	Bundesamt für Energie	carina.alles@bfe.admin.ch
Yousef	Asadi-Khiavi	IBAKH GMBH	yousef.asadi-khiavi@ibakh.ch
Agim	Asani	sa-charging solutions AG	a.asani@sa-charging.com
Christian	Bach	Empa	christian.bach@empa.ch
Reto	Balz	Winterthur Gas and Diesel Ltd.	reto.balz@wingd.com
Konstantinos	Bardis	ETH Zürich	bardis@lav.mavt.ethz.ch
Valter	Bellucci	Winterthur Gas and Diesel Ltd.	valter.bellucci@wingd.com
Sotirios	Benekos	ETH Zürich	benekos@lav.mavt.ethz.ch
Andrea	Bertola	KISTLER Instrumente	andrea.bertola@kistler.com
Sthavishtha	Bhopalam Rajakumar	ETH Zürich	sbhopala@student.ethz.ch
Michele	Bolla	ETH Zürich	mbolla@ethz.ch
Rolf	Bombach	Paul Scherrer Institut	rolf.bombach@psi.ch
Giacomo	Bonciolini	ETH Zürich	giacomob@ethz.ch
Peter	Bonsack	Federal Office for the Environment	peter.bonsack@bafu.admin.ch
Mirko	Bothien	Ansaldo Energia Switzerland	mirko.bothien@ansaldoenergia.com
Konstantinos	Boulouchos	ETH Zürich	boulouchos@lav.mavt.ethz.ch
Michael	Bronner	Eugen Seitz AG	mbronner@seitz.ch
David	Brunner	i4 engineering	david.brunner@i4eng.ch
Philippe	Buchecker	ETH Zürich	bucheckp@lav.mavt.ethz.ch
Valentina	De Rosa	ETH Zürich	vaderosa@student.ethz.ch
Anton	Demarmels	Swissmem	a.demarmels@swissmem.ch
Potis	Dimopoulos Eggenschwiler	Empa	panayotis.dimopoulos@empa.ch
Daniel	Gao	ETH Zürich	gaod@student.ethz.ch
Markus	Gass		lucmar@sunrise.ch
Gil	Georges	ETH Zürich	gil.georges@lav.mavt.ethz.ch

Didier	Gerber	Eco Analytics AG	didier.gerber@ecoanalytics.ch
Stefan	Geringer	ETH Zürich	geringer@lav.mavt.ethz.ch
Georgios	Giannakopoulos	ETH Zürich	georgeg@lav.mavt.ethz.ch
Valentin	Giddey	ETH Zürich	vgiddey@ethz.ch
Christoph	Gossweiler	Fachhochschule Nordwestschweiz	Christoph.gossweiler@fhnw.ch
Timothy	Griffin	Fachhochschule Nordwestschweiz	timothy.griffin@fhnw.ch
Yi	Guo	Queensland University of Technology	y8.guo@hdr.qut.edu.au
Richard	Haefeli	Ganser Common Rail Systems	richard.haefeli@ganser-crs.ch
Daniel	Hagen	BEETRON GmbH	dh@beetron.ch
Gilles	Hardy	FPT Motorenforschung AG	gilles.hardy@cnhind.com
Maximilian	Held	ETH Zürich	held.maxi@web.de
Kai	Herrmann	Fachhochschule Nordwestschweiz	kai.herrmann@fhnw.ch
Peter	Heusser	I.C.E. AG	p.heusser@iceag.com
Thomas	Hilfiker	Empa	thomas.hilfiker@empa.ch
Alphons	Hintermann		Alphons.hintermann@gmx.ch
Alessandro	Innocenti	GE Power	alessandro.innocenti@ge.com
Peter	Jansohn	Paul Scherrer Institut	peter.jansohn@psi.ch
Markus	Kerellaj	Fachhochschule Nordwestschweiz	markus.kerellaj@hispeed.ch
Karri	Keskinen	ETH Zürich	keskinen@lav.mavt.ethz.ch
Martin	Kessler	Helbling	martinkessler73@bluewin.ch
Jann	Koch	ABB Turbo Systems AG	jann.koch@ch.abb.com
Panagiotis	Kyrtatos	Vir2sense GmbH	kyrtatos@vir2sense.com
Christian	Lämmle	combustion and flow solutions GmbH	laemmle@combustion-flow-solutions.com
Sandra	Lehmann	BEETRON GmbH	sl@beetron.ch
Yujun	Liao	Winterthur Gas and Diesel Ltd.	yujun.liao@wingd.com
Anthi	Liati	Empa	anthi.liati@empa.ch
George	Lustgarten	Technology & Strategy Consulting	george@lustgarten.onmicrosoft.com
Thomas	Lutz	ETH Zürich	thomas.lutz@alumni.ethz.ch

Pavel	Malach	ETH Zürich	malachp@student.ethz.ch
Michael	Malicet	UT99 AG	michael.malicet@ut99.com
Ioannis	Mantzaras	Paul Scherrer Institut	ioannis.mantzaras@psi.ch
Teresa	Marchione	GE Power	teresa.marchione@ge.com
Lebius	Matthews	Swissmid LLC	lm@swissmid.com
Andreas	Mayer	TTM	ttm.a.mayer@bluewin.ch
Marco	Mazzetta	Winterthur Gas and Diesel Ltd.	marco.mazzetta@wingd.com
Thomas	Membrez	I.C.E. AG	th.membrez@iceag.com
Amewu A.	Mensah	IAC ETH	amewu.mensah@env.ethz.ch
Franco	Merli	BEETRON GmbH	fm@beetron.ch
Laura	Merotto	Empa	laura.merotto@empa.ch
Vincenzo	Mulone	University of Rome Tor Vergata	mulone@uniroma2.it
Imre Gergely	Nagy	Winterthur Gas and Diesel Ltd.	imregergely.nagy@wingd.com
Hervé	Nauroy	University of Applied Sciences	herve.nauroy@bfh.ch
Christian	Nellen	University of applied sciences of Western Switzerland	christian.nellen@hefr.ch
Andreas	Nohl	Antrova AG	andreas.nohl@antrova.com
Nicolas	Noiray	ETH Zürich	noirayn@ethz.ch
Viola	Papetti	Empa	viola.papetti@empa.ch
Hyunchun	Park	ETH Zürich	phc0112@lav.mavt.ethz.ch
Daniel	Peitz	Hug Engineering	daniel.peitz@hug-engineering.com
Sotiris	Pratsinis	ETH Zürich	pratsinis@ethz.ch
Miriam	Rabaçal	ETH Zürich	miriam.rabacal@lav.mavt.ethz.ch
Frank	Radmacher	Hoval AG	frank.radmacher@hoval.com
Harald	Raupenstrauch	Montanuniversitaet Leoben	harald.raupenstrauch@unileoben.ac.at
Juergen	Reith	TSI GmbH	Juergen.reith@tsi.com
Stephan	Renz	Renz Consulting	info@renzconsulting.ch
Michel J.	Rossi	PSI/EPFL	michel.rossi@psi.ch
Thomas	Roth	Antrova AG	thomas.roth@antrova.com
David	Sakellarakis	ETH Zürich	sakdavid@lav.mavt.ethz.ch

Stephanie	Schlatter	combustion and flow solutions GmbH	schlatter@combustion-flow-solutions.com
Martin	Schmid	Ökozentrum	martin.schmid@oekozentrum.ch
Rolf	Schmitz	Bundesamt für Energie	rolf.schmitz@bfe.admin.ch
Bruno	Schneider	ETH Zürich	schneider@lav.mavt.ethz.ch
Dominik	Schneiter	Winterthur Gas and Diesel Ltd.	dominik.schneiter@wingd.com
Christian	Schürch	ETH Zürich	schuercc@ethz.ch
Edoardo	Scoletta	ISAE-ENSMA	edo.scoletta@gmail.com
Clemens	Seeholzer		c_seeholzer@bluewin.ch
Benz	Simon	ETH Zürich	simon_benz@web.de
Arthur	Sottopietra	Umweltinstitut	arthur.sottopietra@vorarlberg.at
Matthias	Stark	Winterthur Gas and Diesel Ltd.	matthias.stark@wing.com
Mathias	Steglich	Paul Scherrer Institut	mathias.steglich@psi.ch
Robert	Stucki	Micropower Technology GmbH	robertstucki@bluewin.ch
Martial	Suchet	Liebherr Machines Bulle SA	martial.suchet@liebherr.com
Pascal	Süess	Fachhochschule Nordwestschweiz	pascal.sueess@fhnw.ch
Thomas	Sütterlin	Bosal Energy Conversion Industry	tom.sutterlin@bosal.com
Jean-François	Tissot	ABB IATU-T1	jean-francois.tissot@ch.abb.com
Walter	Vera-Tudela	ETH Zürich	wveratudela@lav.mavt.ethz.ch
Dietrich	Vogel	Schmid AG	dietrich.vogel@schmid-energy.ch
Beat	von Rotz	Paul Scherrer Institut	beat.von-rotz@psi.ch
Moyu	Wang	Empa	moyu.wang@empa.ch
Philipp	Weiss	ETH Zürich	weissph@student.ethz.ch
Markus	Widenhorn	Antrova AG	markus.widenhorn@antrova.ch
Yuri M.	Wright	ETH Zürich	wright@lav.mavt.ethz.ch
Thomas	Würms	Valoya Energie	thomas.wuerms@valoya.ch
Silas	Wüthrich	Fachhochschule Nordwestschweiz	silas.wuethrich@fhnw.ch
Guoqing	Xu	Liebherr Machines Bulle SA	guoqing.xu@liebherr.com
Kilian	Zimmermann	Ganser Common Rail Systems	kilian.zimmermann@ganser-crs.ch