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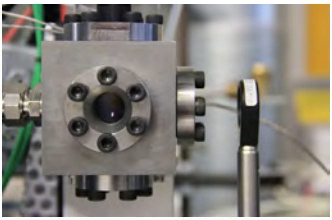
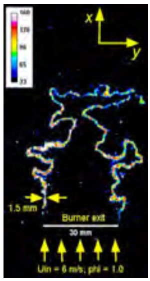
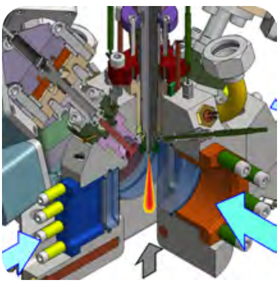
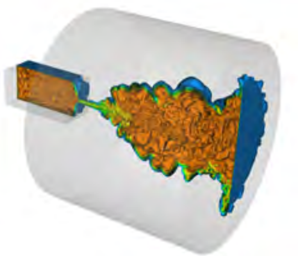
Tagung
Verbrennungsforschung in der Schweiz

Datum:	**Donnerstag, 7. September 2017**
Ort:	ETH Zürich, Zentrum
Uhrzeit:	9:00 bis 17:10 Uhr









Verbrennungsforschung in der Schweiz

Datum: 7. September 2017
Zeit: 09:00 bis 17:10 Uhr
Ort: ETH Zürich, Zentrum (ML D 28)

Verbrennungsbasierte Energiesysteme sind nach wie vor die Schlüsseltechnologie zur Sicherstellung der weltweiten Energiebedürfnisse. Die **Herausforderungen** zur Reduktion der Treibhausgasemissionen und vermehrten Nutzung erneuerbarer Energien haben sich weiter akzentuiert. Die Verbesserung der Effizienz der Systeme, die Verwendung von CO_2-armen Brennstoffen sowie die Reduktion der Emissionen sind die bekannten Anforderungen. Hinzu kommen eine hohe Einsatzflexibilität und Leistungsvariabilität. Beispielsweise bezüglich eingesetzter Brennstoffe, für die Kombination mit anderen Antriebssystemen oder zur Stabilisierung der Stromversorgung bei der Nutzung fluktuierender Stromerzeugung.

Die Kompetenz der Schweizer **Verbrennungsforschenden** aus Industrie und Hochschulen ist international anerkannt und in vielen Bereichen führend. Relevant dafür sind die in der Schweiz tätigen aber weltweit agierenden Unternehmen der **Verbrennungsindustrie.** Dies als Zulieferer von Schlüsselkomponenten, als Hauptentwicklungscenter und sogar als Motorenhersteller.

Alle zwei Jahre führen wir deshalb die Tagung der **Verbrennungsforschung in der Schweiz** durch. Ziel ist der Informationsaustausch über die **neuesten Herausforderungen und aktuellen Forschungsprojekte** von Hochschulen und der Industrie. Der Anlass soll aber auch Ihren **Netzwerkaktivitäten** dienen und jungen Forschenden Kontakte zur Industrie ermöglichen.

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Programm

08:30 Registrierung ▪ Kaffee

09:00 Begrüssung

09:05 **Potential of combustion engine powertrains from an energy and environmental point of view**
Thomas Koch, Karlsruhe Institute of Technology, Karlsruhe

09:45 **Research challenges for advanced IC engine combustion processes**
Konstantinos Boulouchos, ETH Zurich, Zurich

10:25 Kaffeepause ▪ Poster ▪ Networking

Gas Engine Session

10:55 **Prechamber ignition for lean burn gas engine**
Michele Bolla, ETH Zurich, Zurich

11:30 **Dual fuel combustion for IC engines**
Christophe Barro, ETH Zurich, Zurich

12:05 **Ignition- and combustion concepts for lean operated passenger car natural gas engines**
Patrik Soltic, Empa, Dübendorf

12:30 Mittagessen ▪ Poster ▪ Networking

Gas Turbine Session

14:00 **New sequential combustion technologies for heavy-duty gas turbines**
Nicolas Noiray, ETH Zurich, Zurich

14:25 **Flashback phenomena in lean premixed flames**
Dominik Ebi, Paul Scherrer Institut (PSI), Villigen

14:50 **Development of the GT36 sequential combustor**
Gerhard Früchtel, Ansaldo Energia, Baden

15:15 Kaffeepause ▪ Poster ▪ Networking

Diesel Engine Session

15:45 **Novel insights into diesel combustion under long ignition delay conditions**
Panagiotis Kyrtatos, ETH Zurich, Zurich

16:10 **Application of advanced technologies for the development of large 2-stroke marine diesel engines**
Sebastian Hensel, Winterthur Gas & Diesel Ltd (WIN GD), Winterthur

16:35 **Herausforderungen und Ziele an die Verbrennungsforschung aus der Sicht von Liebherr Machines Bulle SA**
Martial Suchet, Liebherr Machines Bulle SA, Bulle

17:00 Zusammenfassung, Verabschiedung

17:10 Schluss der Veranstaltung

Abstracts Liste

Potential of combustion engine powertrains from an energy and environmental point of view

Th. Koch
Karlsruhe Institute of Technology, Karlsruhe

Intensive discussions about the future of the combustion engine are currently ongoing. The exceeding of NO_2-immission values has led to the question, how there might be a future of the internal combustion engine.

Additionally countries like Great Britain or France very intensively evaluate the possibility to forbid the combustion engine technology.

How is the real immission situation? How is the potential of yesterdays, todays, futures combustion engine? Is there a chance to further reduce the current immission values? Which technologies must be applied in order to solve the situation? Basically the major question is of interest, whether there is a future for the combustion engine or not? How is the impact of soot, particulate emissions? These questions will be part of the discussion.

Especially the important impact of the legislation on the emissions situation has to be evaluated as well. Therefor the new Real Driving Emission legislation and the influence of portable emission measurement devices (PEMS) will be discussed additionally.

Finally a brief comparison and evaluation of pure electrical solutions will be accomplished. What are advantages but also disadvantages of electrical approaches. CO_2, toxicity, resources, taxes and other issues need to be evaluated.

Research challenges for advanced IC engine combustion processes

K. Boulouchos
ETH Zurich, Zurich

IC Engines do indeed exist for more than 100 years so that one would think that the combustion technologies involved would be mature with marginal innovation potential. This is however anything but true, if one considers the challenges lying ahead for IC engines in the field of greenhouse gas and pollutant emissions in a variety of applications ranging from cars through trucks and construction prime movers up to marine and decentralized cogeneration. An emerging field of interest is in addition the joint optimization of future engines with prospective renewable/synthetic fuels, originating not only from biomass but also (and primarily) from renewable-excess-electricity, possibly including CO_2-recycling processes.

Progress in this field will be only possible in the future on the basis of an advanced understanding of fundamental physico-chemical mechanisms underlying unsteady engine combustion. The involved physics, in particular the complex interactions between turbulent flow and thermochemistry over several orders of magnitude of time and space scales are admittedly still not understood in sufficient depth. Both experimental and simulation methods at the current state of the art have shed light into several of those processes but as challenges increase, so do the requirements for quantitative description of IC engine flow, mixing, combustion and emission generation processes as well.

In this talk we will discuss challenges related to turbulence evolution, unsteady boundary layers and wall heat transfer as well as turbulent flame kernel development and flame propagation in IC engines. To this end we will refer to potential and limitations of advanced experimental techniques and will subsequently focus our attention on detailed numerical simulation methods with emphasis on the huge potential that LES and in particular DNS techniques bear for the future. Finally we will comment on the necessary boundary conditions that are essential for successful and quantitative very large scale DNS calculations of application relevance in the field of future IC engines.

Prechamber ignition for lean-burn gas engine

M. Bolla, P. Kyrtatos, S. Benekos, K. Bardis, G. Xu, M. Kotzagianni, Y.M. Wright, G. Giannakopoulos, C.E. Frouzakis and K. Boulouchos
ETH Zurich, Zurich

Lean-burn gas engines aiming at low NOx emissions require large ignition energy and distributed ignition sources in order to ignite and consume the lean premixed main charge, aiming to maximize efficiency and reduce unburned hydrocarbon emissions. A widely used technology in these engines is pre-chamber ignition systems, where the ignition source is located in a separate small volume, connected to the main chamber via small orifices. Research in the field of pre-chamber combustion has been extensive in the past years, encompassing both experimental and numerical investigations, e.g. [1-3]. Nevertheless, the complex processes of heat transfer, turbulent jet ignition and combustion phenomena are still not well understood. In the design of pre-chamber ignition systems, commercial as well as research computational fluid dynamics codes are often used. The development of combustion and heat transfer models to be applied in such codes is often hampered by unavailability of reliable and detailed data. Recent advances in numerical modeling and increases in computational power and availability have allowed the use of direct numerical simulations (DNS) for the retrieval of reliable and detailed data for the improvement of physical and chemical process understanding of such complex phenomena.

The LAV hierarchical approach for pre-chamber ignition is a concentrated effort from multiple research areas, which try to identify and comprehend relevant processes using modern experimental and computational tools. It combines on the one side the near-application experiments and 0-D simulations, which forms a connection to the commercial engine design and development. On the other side this approach extends to increasingly simplified and generic experiments and detailed simulations (including reactive DNS), which allow the accurate description of individual processes. The final aim of the hierarchical approach is to close the cycle from application to fundamentals back to application.

This is effectively done through a dual approach:

- To provide phenomenological understanding of processes involved in order to assist in the empirical design and simplified/0D modeling for design and control purposes
- To provide high-fidelity data for combustion model development at near-engine conditions, which will be used at a later stage for engine design purposes

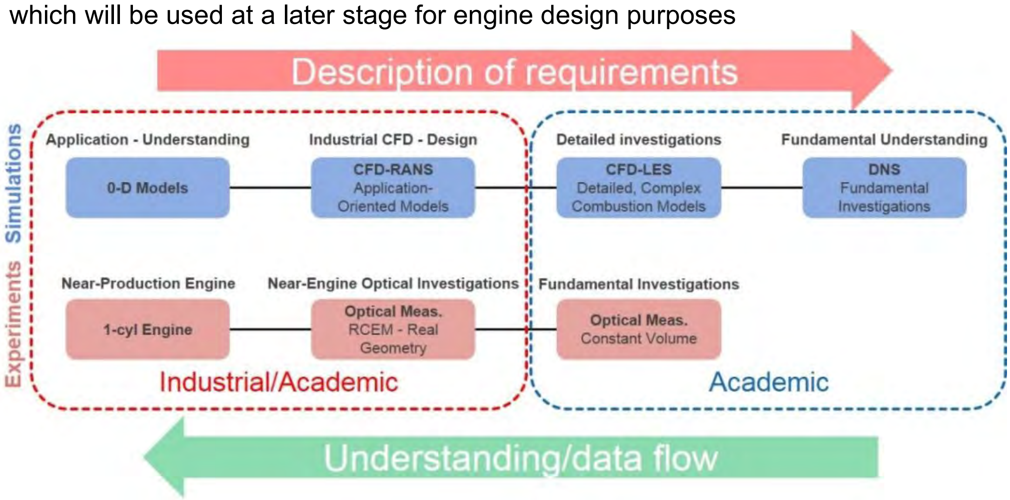

Figure 1: The LAV hierarchical approach for pre-chamber ignition: data flow

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Dual fuel combustion for IC engines

C. Barro[1,2], A. Srna[3], D. Sakellarakis[1], S. Pandurangi[1], W. Vera-Tudela[1], D. Farrace[1], Y.M. Wright[1], K. Boulouchos[1]
[1] ETH Zurich, Zurich
[2] Vir2sense GmbH, Zurich
[3] Paul Scherrer Institut, Villigen

Dual fuel combustion allows simultaneous operation with gaseous and liquid fuels. Depending on the combustion system and the engine load, the share of the two fuels can vary within a broad range. This provides high flexibility in operation and opportunities for CO_2 emission reduction depending on the availability of the individual fuels. The resulting complexity of the involved processes and their interaction leads to current lack in understanding and challenging modelling approaches.

The present work focuses on experimental process insights and different modelling approaches for different dual fuel operating strategies. The investigated operating strategies includes conventional dual fuel operation with premixed natural gas as substrate fuel, ignited by a direct injected pilot diesel fuel as well as high pressure direct gas injection, ignited by a pilot diesel injection. A simplified description of conventional dual fuel operation splits the combustion in two major phases; the auto-ignition of the pilot spray with the trapped (entrained) substrate gas, followed by a flame propagation phase outside the spray plume. The understanding of these processes are of high importance in order to predict optimum operation. For the conventional dual fuel strategies, the focus lies on the investigation of ignition delay and location under the presence of different substrate air-to-fuel ratios. Furthermore, the transition from the auto-ignition zone to flame propagation is another area of high interest. The investigations include experiments in a rapid compression expansion machine (RCEM) with high optical access and simulations ranging from detailed 3D model development to fast application oriented process descriptions.

The experimental investigation of the conventional dual fuel operation in the RCEM shows a significant dependency of the ignition behaviour on the substrate air-to-fuel ratio. As the source of this influence the chemical interaction of methane with OH radical during the 'cool' flames ignition stage has been identified [1]. The ignition process and the auto-ignition combustion phase of the plume, mixed with dodecane (used as a diesel surrogate) has also been investigated and validated using 3D-CFD in combination with a flamelet generated manifold (FGM) approach, capable of accounting simultaneously for auto ignition and premixed flame propagation.

The governing process understanding has been used for the development of a simplified fast model, using a spray model for the evaluation of the individual combustion modes. The model shows adequate results over a very broad variation of operating parameters on a 4 cylinder, 2 litre Volkswagen Industrial Diesel Engine, modified to include natural gas port injection. The model shows a strong dependency on the ignition delay which is itself challenging to model. Consequently the accuracy of predicted combustion characteristics are limited to the accuracy of the modelled ignition delay [2].

A second area of investigation concentrates on high-pressure gas injection. The ignition of the gas jet is performed using a simultaneous diesel pilot injection. The gas is mainly converted in mixing-controlled combustion fashion. The current study includes the experimental and numerical investigation of the behaviour of the gas jet under different gas and background pressure conditions. The focus lies on comprehending complex phenomena in under-expanded jets, such as mixing under the presence of Mach discs and oblique density shocks.

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Ignition- and combustion concepts for lean operated passenger car natural gas engines

P. Soltic[1], Th. Hilfiker[1], S. Hänggi[2], R. Hutter[2]
[1] Empa, Automotive Powertrain Technologies Laboratory, Dübendorf
[2] ETH, IDSC, Zurich

Natural gas is of increasing interest in the mobility sector as this low-carbon-fuel offers distinct CO_2 advantages [1]. Additionally, renewable methane can be produced and stored in cost-effective ways which gives biogenic and synthetic natural gas an ecologic and economic long-term perspective. Natural gas is also an attractive fuel for the automotive industry [2] which is faced with increasingly stricter CO_2 and emission regulations worldwide.

Today's commercially available natural gas engines for passenger cars are based on petrol engines, ideally with some adaptations (e.g. increased compression ratio, increased boost pressure, adapted valve seats, high-temperature turbines). Those adaptations do not fully take the advantageous properties of natural gas into account as for example the peak combustion pressure limitation of typically around 100 bar remains from the basic petrol engine. For pollutant emission reasons, passenger car natural gas engines are nowadays operated stoichiometrically which leads in combination with three-way-catalysis to very low emissions, also in real-world operation [3], and natural gas has the potential for practically zero emissions [4]. Stoichiometric operation, however, leads to reduced efficiencies compared to lean operation.

In the project described here, the above-mentioned limitations (combustion peak pressure, stoichiometric operation) were omitted to find the potentials and limitations for natural gas combustion for engines of passenger car size. To do so, a diesel engine was used as an experimental basis as modern diesel engines can cope with peak pressures in the magnitude of 200 bar. High combustion pressures involve also high ignition energies and a special focus was therefore put on the ignition systems. Three very different ignition systems were used: an inductive ignition system using a well-insulated spark plug, an inductive ignition system in a prechamber which could be used with or without prechamber gas injection, and a diesel pilot injection system. The main goal was to come as close as possible to Diesel engine efficiency levels by combining lean premixed combustion and Diesel-like compression ratios.

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Funding

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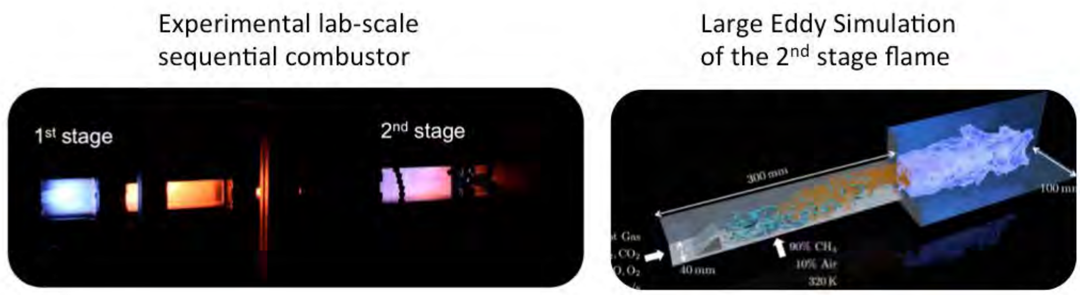
New sequential combustion technologies for heavy-duty gas turbines

N. Noiray, O. Schulz
ETH Zurich, Zurich

Combustion represents more than 80 percent of worldwide energy production and will continue to be the dominant source for power generation over the upcoming decades. In parallel, renewable sources capacities are also constantly growing and their integration into the existing networks affects the grid stability because of their intermittent nature. One therefore needs fast and powerful enough technologies capable of compensating the rapid changes in power demand due to fluctuating wind and solar sources. Gas turbine platforms exhibit faster start-up, loading and de-loading capabilities than coal and nuclear power plants. In addition, their CO_2, NOx and SO_2 emissions are respectively two, four and fifty times lower that coal- or oil- fired plants. For these reasons, it is foreseen that gas-turbine-based power plants will play a key role in the future energy networks. The main requirements for the next generation of gas turbine combustors are: Operational flexibility with fast loading capability allowing to reach baseload (hundreds of megawatts) from idle in about 10 minutes; Fuel flexibility enabling the operator to burn conventional gas as well as syn(thetic)-gas on demand; High efficiency for less CO_2 emissions (the most advanced plants approaching now 65 percent in combined cycle); Reliability and robustness for longer intervals between inspections and more availability; Ultra low NOx and CO emissions over the entire operating concept. One of the most promising short-term approaches to meet these requirements is based on axial fuel staging. These technologies differ from conventional single-stage combustion chambers in that the combustors are composed of two distinct reaction zones in series. The design and optimization of these sequential combustors significantly relies on the capability to accurately understand and simulate the corresponding combustion modes. In particular, it poses the challenge of correctly capturing turbulence-chemistry interactions and autoignition phenomena at various operating pressure. In this presentation, we will focus on the second stage of these sequential combustors and show that the operating pressure defines the dominant anchoring mechanism of the flame: autoignition front, flame propagation or a combination of these two combustion modes. We will also discuss about the nonlinear response of these flames to temperature fluctuations of the reactants, which affects the thermoacoustic stability of the combustion process. This research is motivated by the fact that the combination of acoustic field and entropy waves allows the first and second stage flames to talk to each other, which leads to intense thermoacoustic fields that are detrimental to the mechanical components and significantly reduce their lifetime.



Flame flashback in swirl burners: How high-speed laser diagnostics reveal previously hidden information on such a transient combustion phenomenon

D. Ebi
Laboratory for Thermal Processes and Combustion, Paul Scherrer Institut, Villigen

The current generation of burners employed in gas turbines was developed to operate primarily on natural gas and is limited to narrow operational windows in terms of fuel/air ratio to prevent operability issues. These burners are challenged by the desire to run gas turbines on alternative fuels, which typically contain large amounts of hydrogen.

A key technical issue when burning fuels containing large amounts of hydrogen is to prevent flame flashback into the premix section. Preventing flashback has not been the major design challenge for burners operating on natural gas owing to the low reactivity of methane. However, designing flashback resistant, lean-premix burners for more reactive fuels is significantly more challenging resulting in a clear need for a better fundamental understanding of the mechanisms facilitating flashback combined with improved models to predict flashback limits.

This talk will give a brief overview on experimental investigations applying high-speed laser diagnostics to study the flow-flame interaction during flashback events. The time-resolved measurements provide the basis for an improved fundamental understanding of the physical mechanisms facilitating flashback, which may lead to improved swirl burner designs.

Development of the GT36 sequential combustor

G. Früchtel, D. Pennell
Ansaldo Energia Switzerland, Baden

The presentation introduces the Constant Pressure Sequential Combustor (denoted CPSC) applied to the new Ansaldo Energia GT36 H-class gas turbines.

The CPSC was evolved from the well proven sequential combustion system of the GT26 gas turbine and designed to extend turndown, operational flexibility and fuel flexibility. It improves the combustion performance of GT26 to cover H-class firing temperature ranges, whilst simplifying the overall GT architecture.

The CPSC consists of a first conventional premix combustion system to create the matching boundary conditions for the sequential burner derived from the GT26 SEV. The SEV rapid auto ignition fired combustion allows high turbine inlet temperatures at baseload using a correspondingly short combustor and at the same time CO burnout at low load operation by simply increasing the SEV inlet temperature.

The main features of the canular CPSC, its differences to the annular GT26 sequential combustor as well as its development and validation will be presented.

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Novel insights into diesel combustion under long ignition delay conditions

P. Kyrtatos, C. Brückner, S. Pandurangi, M. Bolla, Y.M. Wright and K. Boulouchos
ETH Zurich, Zurich

The focus of diesel engine combustion development in the past decade has been placed on the reduction of engine-out NOx emissions. This has been mainly achieved using various methods which reduce the flame temperature, resulting in lower NOx formation rate during combustion. Some of these measures also result in an increase in ignition delay. The reduction of charge temperature in particular, which can be achieved by changes in engine design and/or valve timing to reduce the effective compression ratio, results in an exponential increase in ignition delay, which causes some undesirable effects on combustion and emission formation.

The aim of this work is to extend the understanding of the effects of increased ignition delay on combustion for single block injections. Single injections are used in most applications where component longevity is of outmost importance, such as heavy-duty and medium-speed diesel engines used in power generation and marine installations. The investigation uses measurements from a single-cylinder heavy-duty research diesel engine and 3D Computational Fluid Dynamics (CFD). The latter provides local quantities during combustion which are imperative for the understanding of local phenomena occurring under these conditions.

The study focuses on two observed phenomena: the increase of cycle-to-cycle variations of combustion and emissions under long ignition delay conditions, and the reversal of the expected monotonic reduction of NOx with decreasing reactant temperature. Randomly occurring in-cylinder pressure fluctuations have been identified as the cause of the increase in cyclic variation. These fluctuations appear on the indication diagram as super-imposed pressure waves, and result from the excitation of the first radial mode of vibration of the cylinder gases due to the rapid premixed combustion after a long ignition delay period [1, 2]. Cycles with high-intensity fluctuations present faster diffusion combustion, resulting in higher cycle peak pressure, as well as higher measured exhaust NO concentrations [2-4].

The increase in NOx emissions with decreasing charge temperature is partly attributed to the cyclic variations, but the observed level of increase cannot be ascribed solely to this process. Investigations using 3D CFD of the engine show that for long ignition delay operating conditions, the improved mixture preparation and increased time before ignition leads to reduced mixing rates during and after combustion [5]. Both the improved mixture preparation before ignition and the instantaneous increase of charge mass at high temperatures after start of combustion are due to compression heating of the burned gases, which remain at high temperatures for longer times due to the decreased mixing rates. This allows these burned gas packets to approach the equilibrium concentrations of NO before they are mixed with colder charge, leading to higher engine-out NO emissions.

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Application of advanced technologies for the development of 2-stroke low-speed marine diesel engines

S. Hensel, A. Schmid, M. Wenig, Ch. Blomberg, E. Cakir, P. Scrocco, R. Balz
Winterthur Gas & Diesel Ltd., Winterthur

Increasingly stringent emission legislations and the ongoing demand for reducing fuel consumption have pushed ship engine manufactures towards increasing the energy efficiency of their products while expanding and updating their overall engine portfolios. For example, as a consequence of the introduction of emission control areas Winterthur Gas & Diesel (WinGD) has doubled its diesel engine portfolio within the last 3 years to provide engines meeting Tier II and Tier III regulations. Furthermore, the increased availability of LNG (liquefied natural gas) and other alternative fuels has led to the development of new technologies: the dual-fuel (DF) engine and fuel flexible injection systems.

Due to the high customization in the shipping business and the potential to optimize the overall ship system and energy management, each project is handled separately and fully tailored to the ship design and the expected routing of the vessel. At the same time production schedules have become more compressed and the lead times of vessels and engines have been reduced substantially. Together with the high cost for experimental investigations – due to the size and overall fuel consumption of the products – extensive testing and adaptation of the engines to the customer demands on the engine test bed is not a profitable option. This has led towards increased efforts inside WinGD in the past decade to improve engine and combustion system layout tools and to develop also new tools to reduce cost and effort, while still permitting high engine customization.

The engine layout process usually starts with the definition of the thermodynamic parameters such as bore, stroke, port height, etc. for a desired power output and speed range. These parameters are defined with predictive process simulation tools. The calculated performance data is on the one hand used as input for the design (powertrain, structure, scavenging system) and pre-calculation of the tuning parameters and on the other hand as input for contractual obligations towards customers. After development of the engine and manufacturing of the first prototype, the engine combustion system and tuning parameters are finally adjusted and emission compliance is demonstrated whilst meeting the contracted fuel consumption. This also demonstrates the importance of the accuracy of the applied layout tools and models.

For the layout of the engine, commercially available tools such as GT-Power (for 1D modelling) and StarCD (for 3D-CFD modelling) are modified and adapted for their application to 2-stroke marine diesel engines. The codes are extended by special heat transfer, scavenging, combustion and emission formation models. Furthermore, the tools have also been adopted to investigate phenomena in transient operation, as for example the heating-up procedure of SCR (selective catalytic reduction) systems upstream or downstream of the turbocharger. Increased interest regarding hybrid systems, overall energy management and optimization also represents a huge field for further investigations. Here WinGD scientists are currently performing in-depth analyses in order to define the next generation of engines.

The combustion system layout – where more detail regarding local in-cylinder effects is often needed – is usually done by CFD simulations. Engine component geometry studies are also possible with CFD, aiding in the overall engine design process. Of high importance is the development of predictive models (e.g. spray or combustion models) and their application for engine development. The state of the art facilities at WinGD provide an excellent basis for the development and validation of these models, where the effects of e.g. different fuels, new injection systems, spray patterns, cavitation, ignition timing/location and flame lift-off can be measured and quantified.

Thanks to the combination of experimental investigations on the test engine in Winterthur with the application of recently developed simulation tools, WinGD has been able to increase the efficiency of the diesel engine portfolio within the last 2 years by about 2-3 g/kWh, which corresponds to an increase of engine efficiency of roughly 1.5-2%. This is mainly based on the optimization of the thermodynamic process in combination with adaptations of the combustion and injection system. Current engine tests and simulations have been made which show the possibility to reduce the BSFC (brake specific fuel consumption) of the engine portfolio by an additional 2-3 g/kWh within the next years. This further highlights the importance and the potential of WinGD's engine development process by means of close collaboration between experiments and simulations.

Herausforderungen und Ziele an die Verbrennungsforschung aus der Sicht von Liebherr Machines Bulle SA

M. Suchet
Liebherr Machines Bulle SA, Bulle

The research and development of engines with a serial production in accordance with worldwide sales and service activities is challenging for LMB and the whole the industry.

The balance between costumer expectation, different legislation per region and competitiveness in terms of performance and costs is an important driver within or research and development activities, on of the main factors are the TCO (total cost of owner ship), the legislation (emission) and the globalization.

Engines are often a system relevant component and the heart of a machine. Therefore the engine is seen in his cost perspective over his whole lifetime. Costumers put a very high focus not only in the initial investment of the engine also on the costs of the whole lifetime. Therefore, we have to include and optimize already in our research and development activities different concepts for the whole lifetime. This effects aftersales concepts, service intervals and remanufacturing concepts to extend the lifetime of the engine. The challenge for us is to produce an engine which is useable worldwide, with different fuel "quality" (sulfur contain) and also for a multitude of applications (mobile crane, dozer, excavator, genset, industrial application, etc.).

As the engine is a major component of a machine the engine is very important for the whole system. This is why we analyze already in our R&D activities the whole integration into the machine and see how we can make the whole system more efficient. To increase efficiency of the engine and give a better performance on fuel consumption is only one part. By optimizing the whole system in accordance with the engine offers a large potential of optimization.

Service, maintenance and spare parts are major factors as well as service intervals, which are, defined during the R&D process, are a main driver of the total cost of ownership. For example oil change intervals or spark plug changes on a gas engine can have a high impact of the TCO and therefore decide if a product is competitive on the market.

At the end, the biggest challenge is to anticipate what would be the future fuel:
1. Electricity, Diesel, gasoil, gas in different form, OME
2. Each one has advantage and disadvantage. Probably we are going to get a mix from this different energy sources
3. OME offer good perspective to reduce the particulate emission and fulfill the future emission limit.

Posterausstellung

1. **In-silico combustion: Direct numerical simulations of combustion phenomena and processes**
   M. Jafargholi, S. Benekos, G.K. Giannakopoulos, C.E. Frouzakis, K. Boulouchos
   ETH Zurich, Zurich

2. **Flex-OeCoS: A new, flexible research facility for optical engine combustion diagnostics and corresponding sensor development at Aerothermochemistry and Combustion Systems Laboratory, ETH Zurich**
   M. Hangartner[1,2], B. Schneider[1]
   [1] ETH Zurich, Zurich
   [2] University of Applied Sciences and Arts Northwestern Switzerland, Brugg-Windisch

3. **Water-in-fuel emulsion – constant volume vessel experiments and engine tests**
   D. Wüthrich, A. Srna, B. von Rotz, P. Jansohn
   Paul Scherrer Institut, Villigen

4. **Analysis of PM and PN in dual fuel engine, fuelled with natural gas and OME**
   C. Barro[1,2], F. Möri[1], R. Hutter[1], K. Boulouchos[1], J. Burger[3]
   [1] ETH Zurich, Zurich
   [2] Vir2sense GmbH, Zurich
   [3] Technische Universität Kaiserslautern, Kaiserslautern

5. **Heavy duty diesel engine combustion with fully flexible EGR configuration**
   G. Hardy[1], P. Soltic[2], R. Suteekarn[3]
   [1] FPT Motorenforschung AG, Arbon
   [2] Empa, Dübendorf
   [3] Eaton Germany GmbH, Baden-Baden

6. **In-nozzle flow and spray morphology investigations of marine diesel injectors**
   R. Balz[1,2], A. Schmid[1], D. Sedarsky[2]
   [1] Winterthur Gas & Diesel Ltd., Winterthur
   [2] Combustion Division, Chalmers University, Gothenburg

7. **Gas prechamber combustion modeling**
   P. Kyrtatos, M. Bolla, S. Benekos, K. Bardis, G. Xu, M. Kotzagianni, Y.M. Wright, G.K. Giannakopoulos, C.E. Frouzakis, K. Boulouchos
   ETH Zurich, Zurich

8. **High-pressure gas injection**
   D. Sakellarakis, W. Vera-Tudela, Y.M. Wright, K. Boulouchos
   ETH Zurich, Zurich

9. **Thermoelectric on-board power generation from exhaust heat**
   T. Durand, P. Dimopoulos Eggenschwiler, C. Battaglia, D. Landmann, Y. Tang
   Empa, Dübendorf

10. **Hydrogen enriched methane combustion**
    J. Koch[1], T. Kammermann[2], Ch. Schürch[1], P. Soltic[2], Y.M. Wright[1], K. Boulouchos[1]
    [1] ETH Zurich, Zurich
    [2] Empa, Dübendorf

11. **A new method for accurate droplet density estimation in droplet-laden turbulent flows**
    D. Meyer, Ph. Weiss, P. Jenny
    ETH Zurich, Zurich

LAV ETH zürich
in collaboration with
ITFE n|w

Flex-OeCoS

***Flex**ible research facility for **O**ptical **E**ngine **Co**mbustion diagnostics and c**o**rresponding **S**ensor development*

Motivation

New combustion types for IC engines like dual-fuel or RCCI systems place new demands on test rigs used for corresponding experimental investigations. The currently available test rigs at LAV / ETH Zürich (constant volume cell and rapid compression machine) are only partially able to meet those demands.

Therefore a new test rig has been developed in the context of the CCEM project "FlexFiDual" that is especially suitable (but not limited to) experimental investigations in the context of dual-fuel combustion systems. Its name, "Flex-OeCoS", is derived from its **Flex**ibility regarding **O**ptical **E**ngine **Co**mbustion diagnostics and/or the development of c**o**rresponding **S**ensing devices and applications.

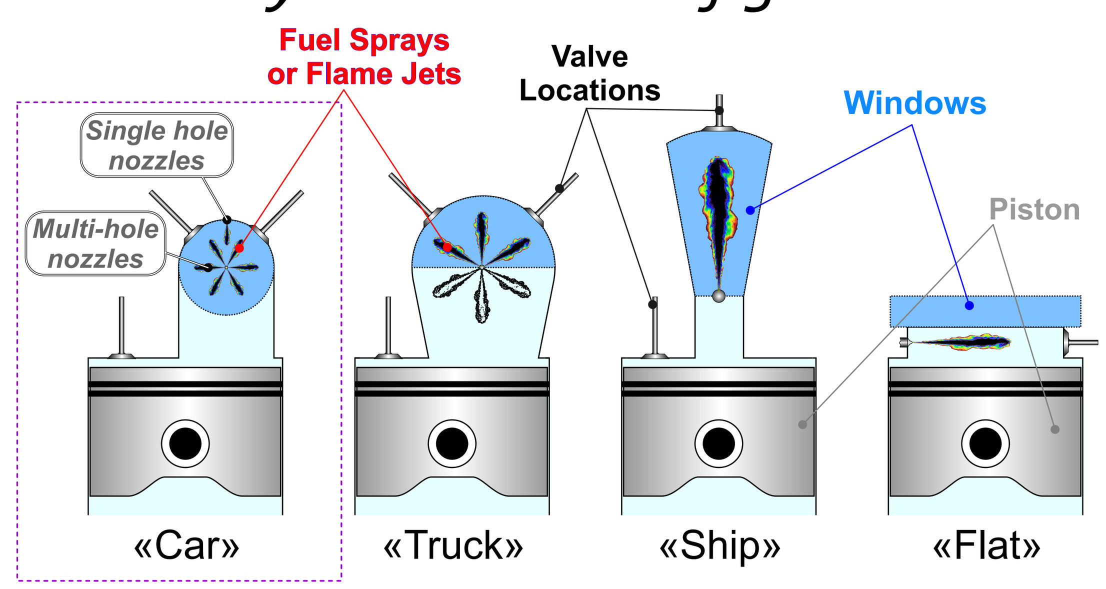
Research Topics

- Processes relevant for premixed, dual fuel and compression ignited combustion systems:
  - *Flow and turbulence, mixture formation, ignition processes and flame propagation*
- Data relevant for sensor development:
  - *In-cylinder pressure (chamber and cylinder), wall heat transfer resp. heat flux*

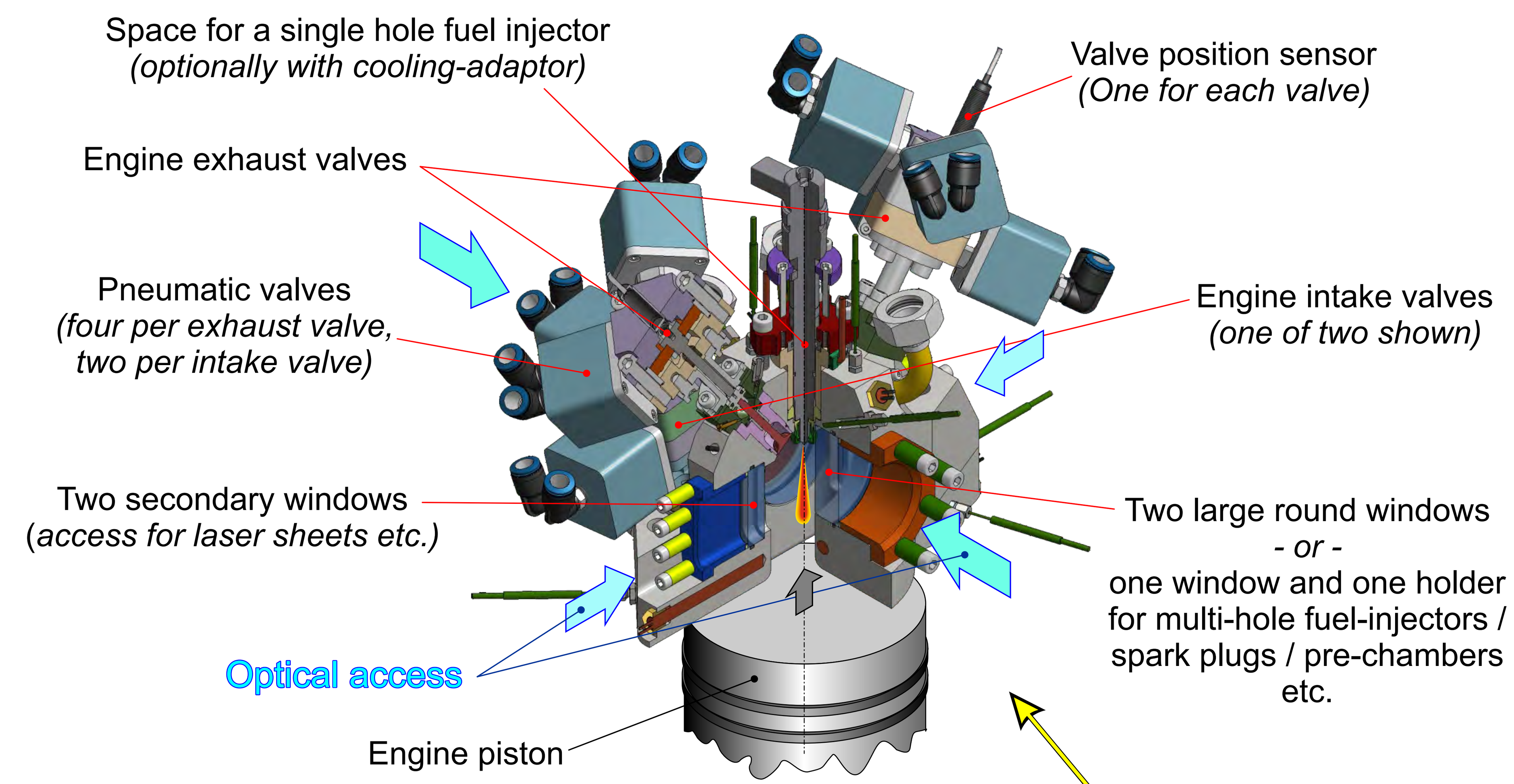
Development Goals for the New Test Rig

- Adaptable to all fuel types (liquid and gaseous)
- Adaptable to all combustion-types (premixed, dual-fuel and diffusion controlled, external ignition or auto/compression-ignition)
- Excellent optical access for optical and laser-optical measurement techniques
- Engine like flow fields and turbulence levels (can be influenced by crank shaft speed, valve timings and experiment timing)
- End of compression pressure ≥ 100bar
- End of compression temperature ≥ 1000K
- Peak combustion pressure ≥ 200bar
- Combustion chamber (i.e. cylinder head) exchangeable for different experimental requirements (*current configuration = «Car» type*)

Possible cylinder head configurations:



Cylinder Head / Combustion Chamber:



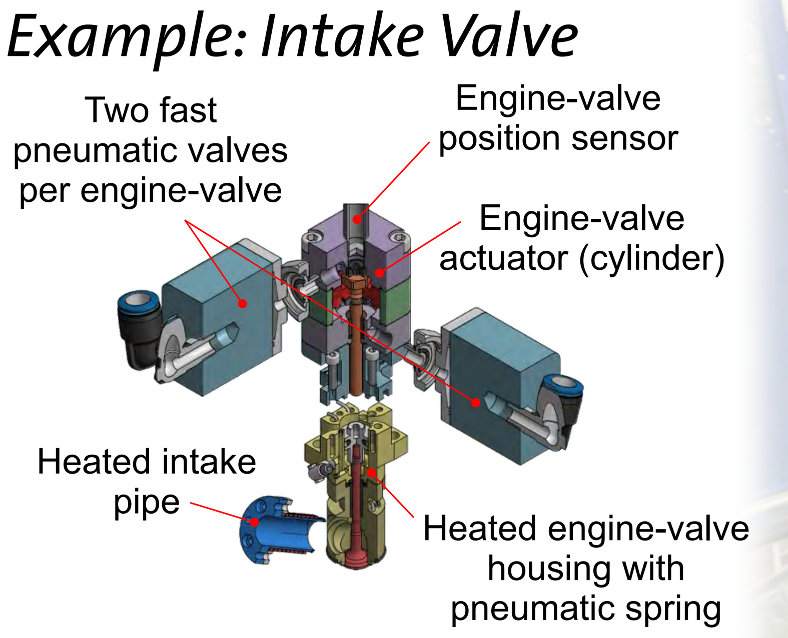
Engine Air Supply

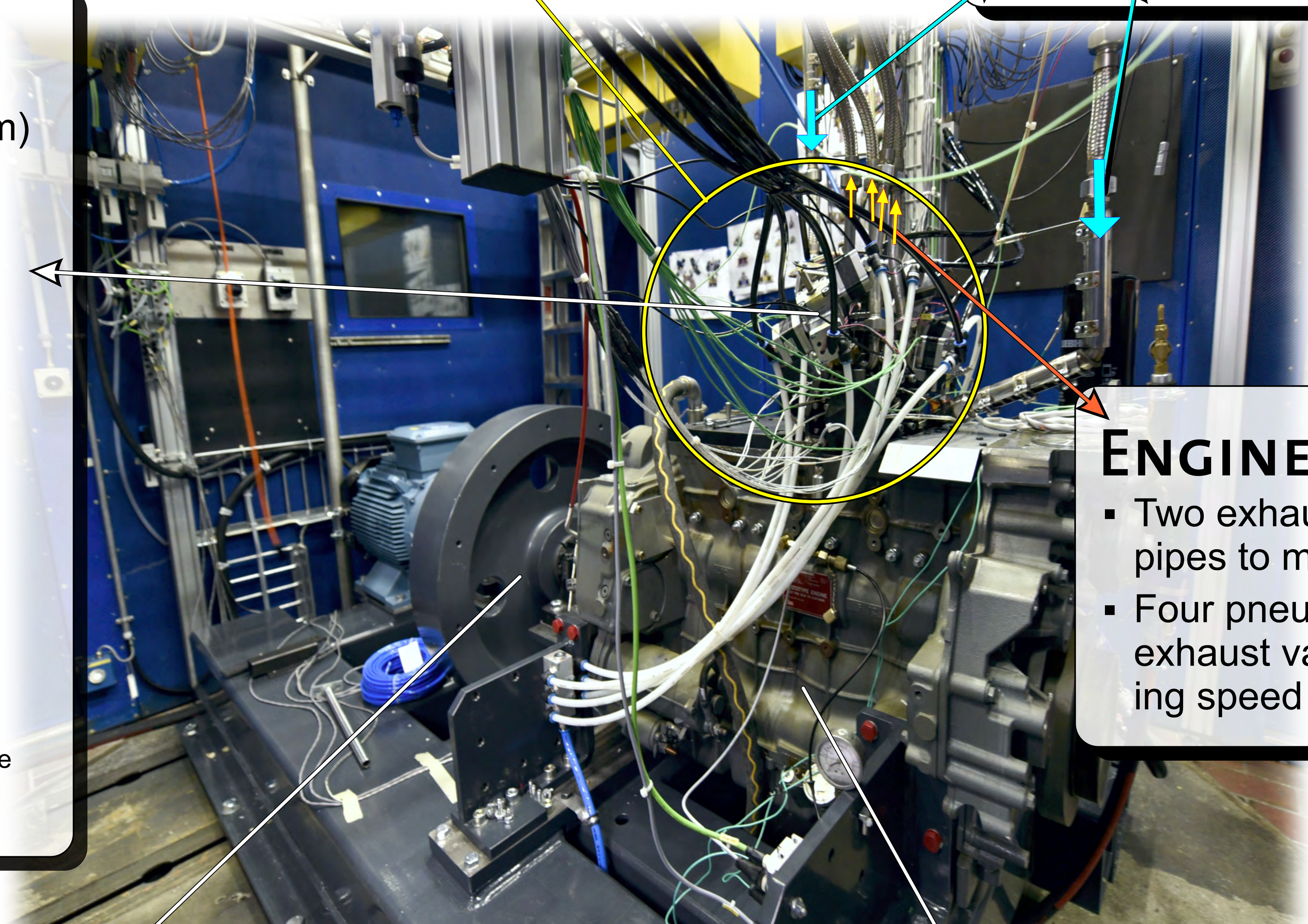
- Pressurized and preheated air
- Maximum intake pressure ≤ 6.5bar
- Maximum intake temperature ≥ 200°C
- *Optional:* Gas injection in front of the intake valves for premixed / dual fuel combustion experiments

Engine Valves

- Fully variable valve timing (National Instruments FPGA system)
- Two intake- and two exhaust valves
- Pneumatically actuated
- Pneumatic valve springs

Example: Intake Valve





Engine Exhaust

- Two exhaust valves with four pipes to minimize back pressure
- Four pneumatic valves for each exhaust valve for maximum opening speed

Drive Train

- 55kW electric motor / generator
- Maximum speed 1800 $^{1}/_{min}$
- Massive flywheel (420kg, 48kgm^2)
- Gear coupling between drive train and crank shaft (to break torsional vibrations)

Engine Block

- Liebherr D944 *(donated by Liebherr SA, Bulle)*
- 2l per cylinder (Ø130mm, stroke 150mm)
- Maximum cylinder pressure 230bar
- Three cylinders deactivated

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ccem.ch
Project:
"FlexFiDual" (901)

BFE OFEN UFE SFOE
Projects:
"Dual-Fuel Verbrennungssysteme"
"Next-ICE"

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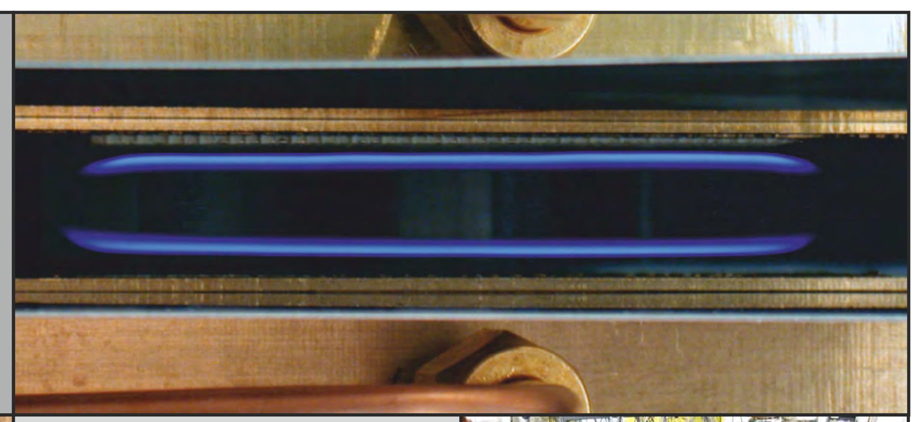
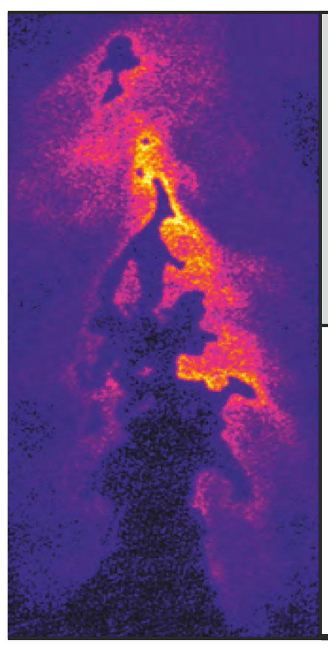
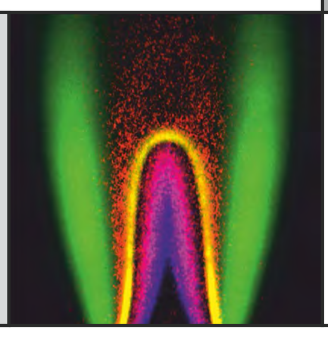
School of Engineering
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

PAUL SCHERRER INSTITUT

ENERGY AND ENVIRONMENT DEPARTMENT
THERMAL PROCESSES AND COMBUSTION LABORATORY







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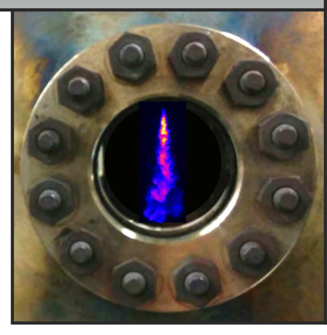
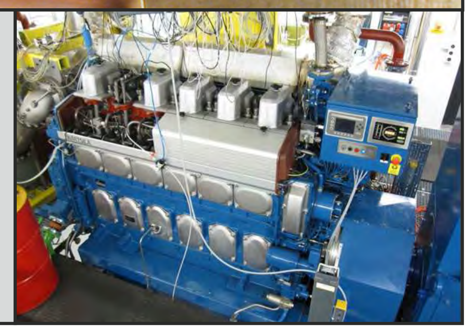




Water-in-Fuel Emulsion – Constant Volume Vessel Experiments and Engine Tests

Dario Wüthrich†, Aleš Srna, Beat von Rotz, Peter Jansohn

ABSTRACT

We conducted measurements employing water-in-fuel emulsions (WFE) with low water contents in the high-temperature/pressure constant volume combustion vessel (HTDZ) at PSI to study spray and combustion morphology, such as time resolved spray vapor penetration length and cone angle, flame lift-off length and soot/PM optical density (KL), respectively. These fundamental spray combustion experiments were put into context with engine tests conducted in the Large Engine Research Facility (LERF) at PSI. In both conducted test campaigns, the use of WFE reduced soot/PM emission during the combustion in comparison to the reference Diesel-fuel case. Further, the engine tests showed the WFE`s potential to additionally lower the NO_x emissions.

TEST CONDITIONS (HTDZ)

WFE spray studies were conducted for engine relevant ambient conditions at the start of injection (SOI).

Ambient Conditions	Dimension	Set Point
Temperature	[K]	860
Pressure	[MPa]	5.75
Density	[kg/m^3]	22.8

A constant base fuel (n-dodecane) mass flow for the WFEs has been achieved by increasing fuel pressure. The chemical energy of the injected fuel was kept constant by setting the injector energizing time to 1.5 ms resulting in an hydraulic injection duration of ca. 3.1 ms.

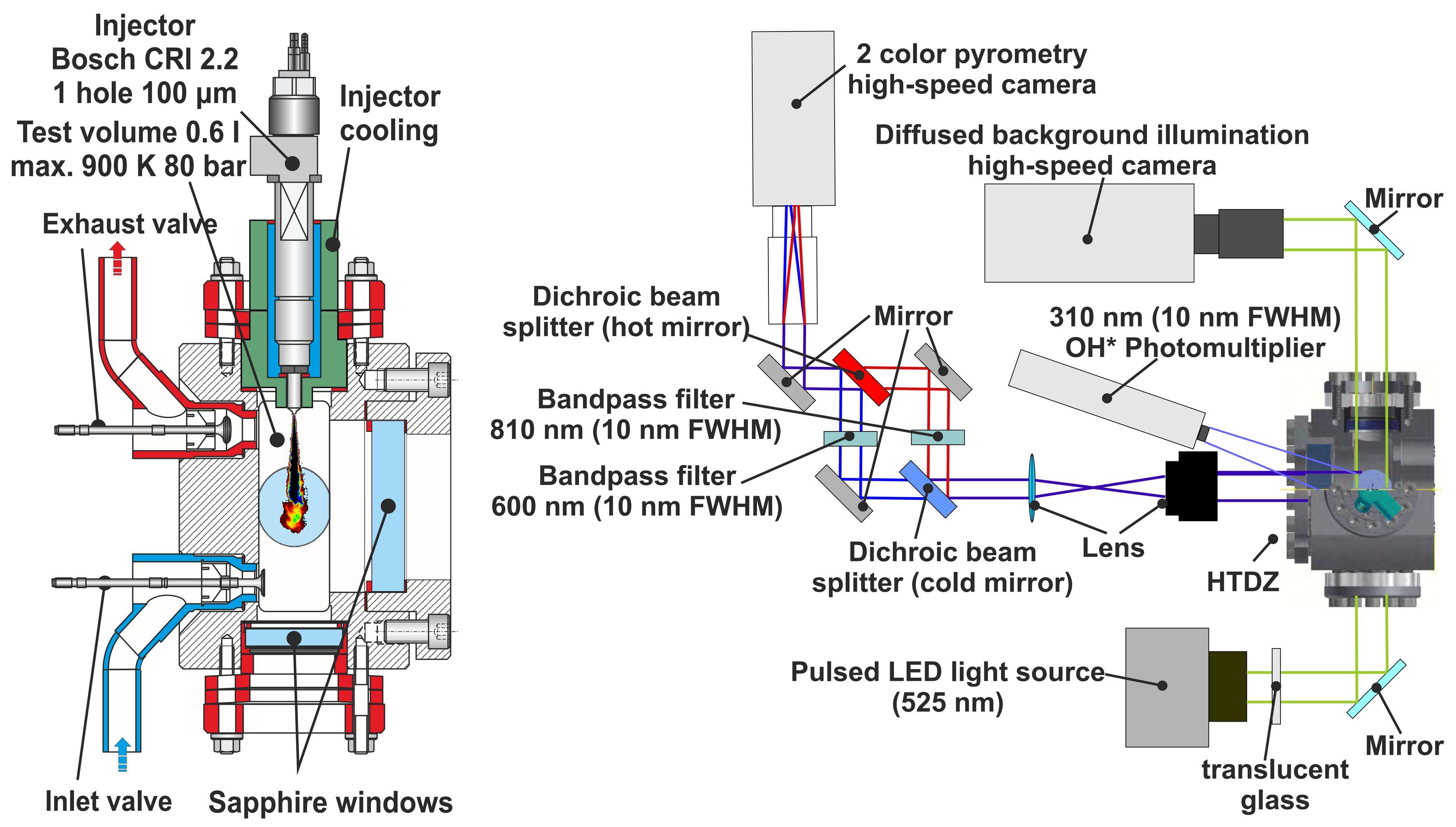
Fuel	Injection Pressure [Mpa]
n-Dodecane	100
WFE 2.5% water	106
WFE 5.0% water	110
WFE 10.0% water	119

EMPLOYED MEASUREMENT TECHNIQUES

HTDZ: Well established Schlieren technique was used to determine the vapor spray contour. Ignition delay and flame lift-off length were detected via OH* chemiluminescence using an intensified high-speed camera and bandpass filter. In order to measure soot optical density two-color pyrometry was employed.

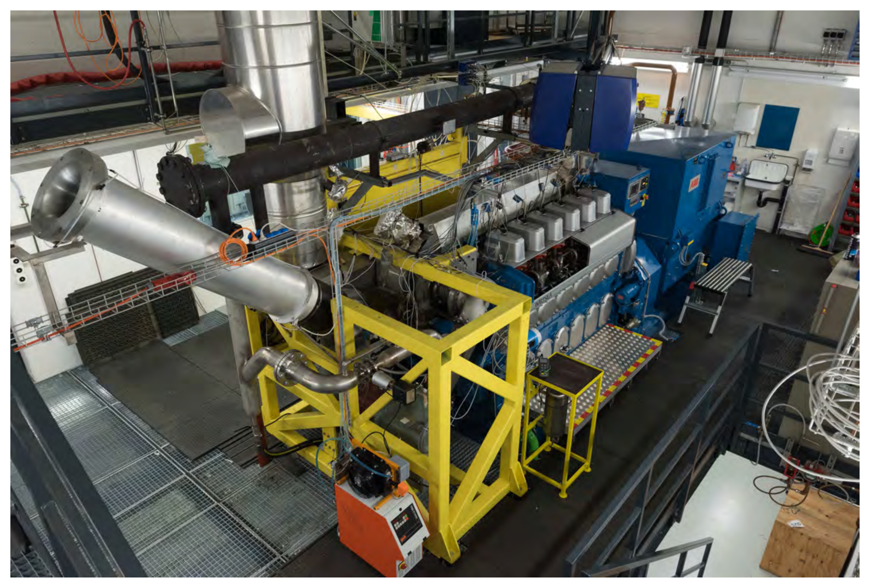
LERF: The exhaust gases are sampled directly in the exhaust pipe with a FTIR spectrometer (AVL SESAM). The device allows simultaneous and time-resolved measurement of multiple species (spectral resolution of 0.5 cm^{-1}) and a sampling rate of 1 Hz. The particulate mass emission were measured by an AVL Smoke Meter. This filter-based measurement device estimates the mass concentration by measuring the paper blackening with a reflectometer.

EXPERIMENTAL SETUP CONSTANT VOLUME CELL (HTDZ)



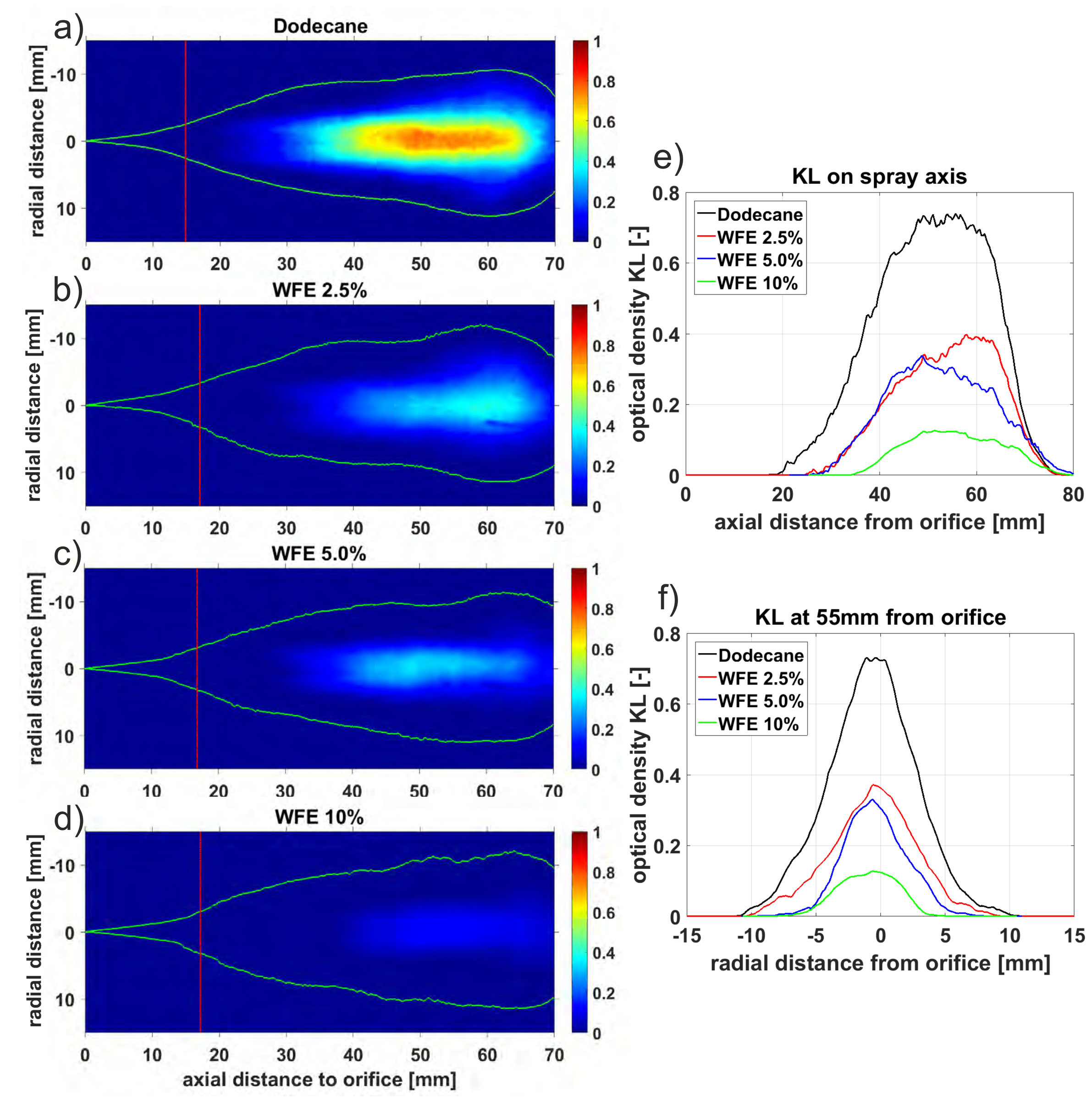
LARGE ENGINE RESEARCH FACILITY (LERF)

Bore	mm	200
Stroke	mm	280
Number of Cylinders		6
Displacement Volume	l	8.8 (52.8)
Number of Cylinders		6
Compression Ratio		16
Nominal Speed	rpm	1000
Rated Power	kW	1080 (1278 kVA)



The LERF was designed and built for research into low emission technologies as well as new turbocharging and combustion concepts on marine diesel engines [1]. The test engine is a Wärtsilä 6L20CR, 4-stroke, medium speed marine Diesel engine with a common rail fuel injection system from L'Orange GmbH. Furthermore, the engine is equipped with a prototype 2-stage turbocharger system (from ABB Turbo Systems Ltd.) and variable inlet closure (Miller timing).

RESULTS HTDZ

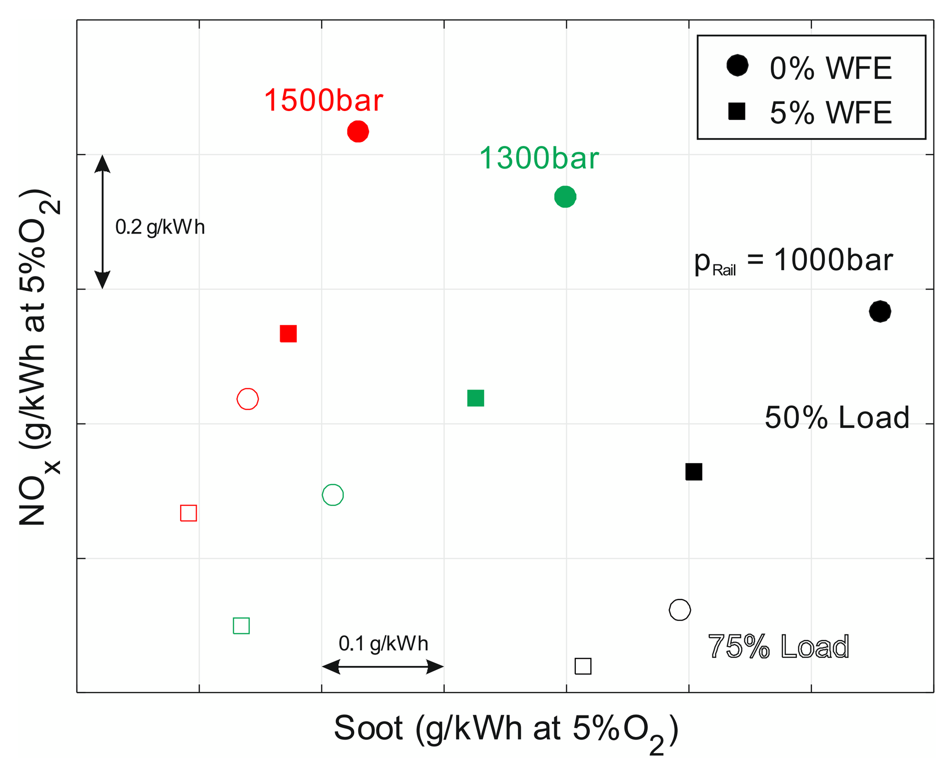


(a-d) green line - spray contour; red line - flame lift-off length (LOL) during quasi-steady mixing-limited combustion phase; false color image - optical soot density (KL); (e) axial and (f) radial KL values for base fuel and WFE with increasing water contents.

Larger amounts of water in WFEs increase the flame lift-off length and therefore lead towards a lean lifted flame combustion (ϕ(LOL)<2) [3].

RESULTS LERF

NO_x/soot emission of rail pressure variation at engine operation without (diesel) and with 5% WFE at 50 and 75% load, 22% EGR and const. SOI (10°CA bTDC) [2].



The increasing rail pressure results in a higher emission of NO_x, but lowering the soot concentration.

The mixing of 5% (mass fraction) water into the fuel is additionally lowering both NO_x as well as soot and a similar rail pressure dependency can be recognized.

The improved spray atomization and its better dispersion when increasing injection pressure promote a quicker mixture formation prior to ignition. As a result, the premixed share during heat release is increased and the main combustion duration is shortened.

CONCLUSIONS AND OUTLOOK

WFE engine tests at the LERF were performed and an experimental study in the HTDZ allowed to gain a detailed understanding of involved spray combustion phenomena related to the soot formation/oxidation.

- Increasing injection pressure leads to lower soot/PM emissions due to an enhanced spray break-up
- WFE increases flame LOL, due to additional required latent heat of water, leading to leaner mixing-limited combustion and hence, decreased soot emissions
- Engine tests showed the capability of WFE to lower NO_x /soot emissions for constant injection pressures

Next steps include the variation of WFE`s water mass fractions in LERF tests and the evaluation of the fuel-to-air-ratios (ϕ) of HTDZ spray experiments to further improve the understaning of measured trends and characteristics when applying WFE.

REFERENCES

[1] Kyrtatos *et al.*, CIMAC, 2013
[2] von Rotz *et al.*, COMODIA, 2017
[3] Pickett & Siebers, SAE 2004-01-1399, 2004

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F. Möri - ETH Zurich, LAV
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Jprof. J Burger - Uni Kaiserslautern, LTD

Analysis of PM and PN in Dual Fuel Engine, Fuelled with Natural Gas and OME

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Aerothermochemistry and Combustion Systems Laboratory

Eidgenössische Technische Hochschule Zürich
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Dual Fuel Engines

Introduction

The investigated natural gas-diesel engine is a gas engine where the premixed air-gas mixture is ignited by a small amount of directly injected diesel fuel. The concept can be realized by modifying a production type diesel engine slightly through the addition of natural gas port injectors.

The natural gas-diesel engine has proven its potential of highly efficient operation with low CO_2 emissions on the test-bench of the Institute for Dynamic Systems and Control.

The used engine is a Volkswagen industrial engine with 2 litres displacement volume and 4 cylinder. Since the used engine is a converted conventional Diesel engine, the operation strategy has been adapted in the operation range according to figure 2. Figure 3 shows the energetic share of natural gas and pilot Diesel fuel. Even though, the end of injection of pilot fuel is long time before start of combustion, with high share of pilot fuel, significant soot emissions are produced. In the used strategy, this occurred at the lower load range.

Ott T, Onder C, Guzzella L. Hybrid-Electric Vehicle with Natural Gas-Diesel Engine. Energies; 2013; 6: 3571-3592.
Florian Zurbriggen, Richard Hutter, and Christopher Onder. Diesel-Minimal Combustion Control of a Natural Gas-Diesel Engine. Energies, (2016) Basel: MDPI.

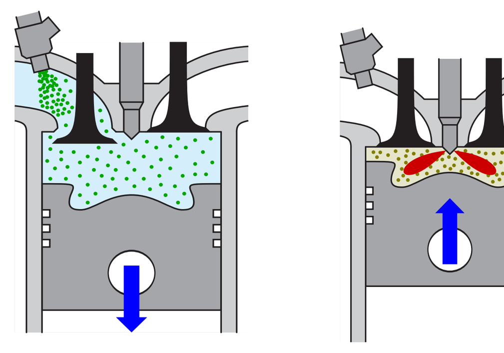


Figure 1: Dual fuel engine, operation principal

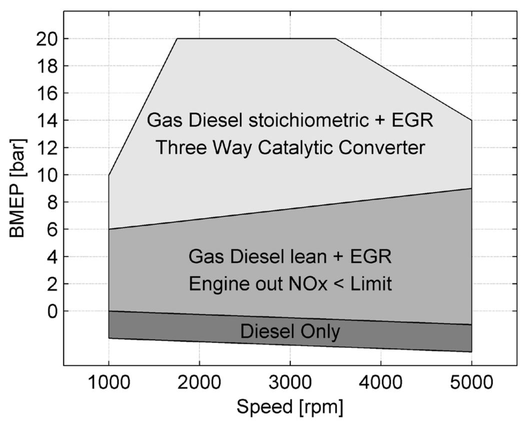


Figure 2: Dual fuel engine, operation strategy

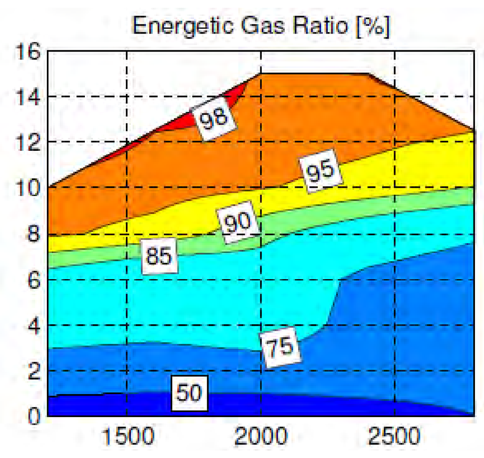


Figure 3: Dual fuel engine, main fuel share

OME as an Alternative Fuel

OME is the acronym of Polyoximethyldimethylether. The injection, ignition and combustion properties allow the operation in a standard diesel engine without major modifications. The precursors are products from a power to liquid process with a very small CO_2 footprint.

Structure of OMEn:

$CH_3 - O - [CH_2 - O]_n - CH_3$

For the synthesis two building blocs are required:

CH_3 – Cap groups: from Methanol (CH_3OH) or DME (CH_3OCH_3)

CH_2O – Monomers: from Formaldehyde (CH_2O) or Trioxane ($C_3H_6O_3$)

Present production route via Trioxane/OME1:

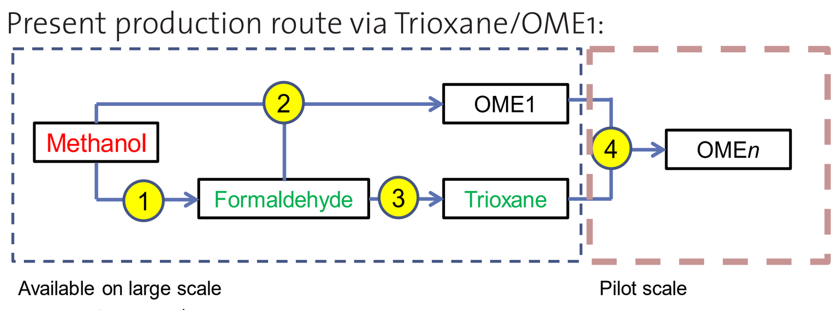


Figure 4: OME production route

Details of Process 4:
Process available (BASF / TU Kaiserslautern)
Product chain length adjustable freely

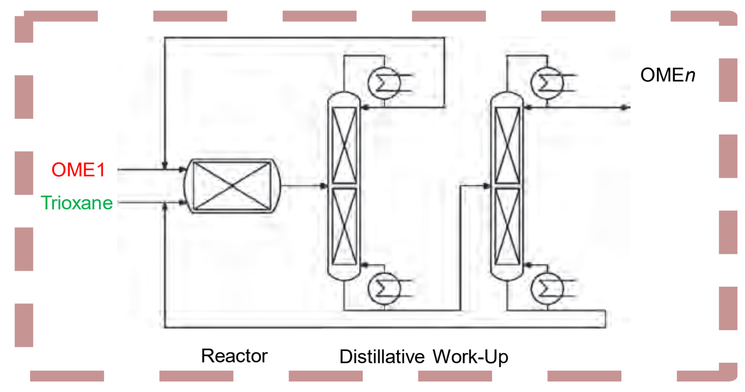


Figure 5: OME production step 4 in detail

J. Burger et al., "Production process for diesel fuel components poly(oxymethylene) dimethyl ethers from methane-based products by hierarchical optimization with varying model depth", Chem. Eng. Res. Des. 91, 2648-2662, 2013.

Production Costs of OME:

Strongly dependent on methanol price
Example: OME3-5 via Trioxane/OME1 route

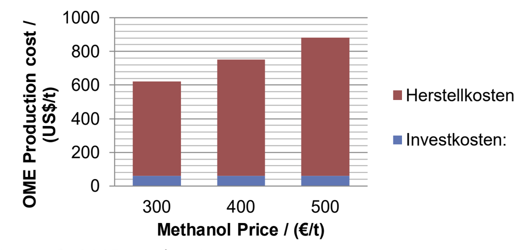
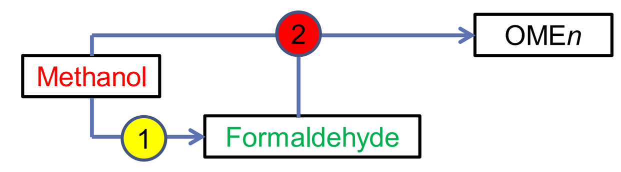


Figure 6: OME production costs

N. Schmitz et al., "From methanol to the oxygenated diesel fuel poly(oxymethylene) dimethyl ether: an assessment of the production costs", Fuel (submitted), 2016.

Future Production of OME

Numerous research activities. Two examples:
Direct route via Methanol/Formaldehyde. Step 2 under research:



Usage of DME. Step 2 under research:

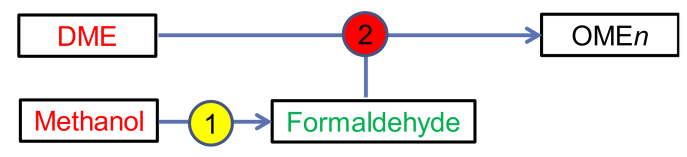


Figure 7: OME production; future production steps

Dual Fuel Engines With OME

Comparison of OME and Diesel

Figure 8 compares the heat release rates of an operating condition at 1600 rpm and 8 bar brake mean effective pressure (BMEP) with either Diesel or OME as pilot fuel with similar injection settings (This means: similar fuel mass but different energy share). The global stoichiometry is one for both pilot fuels. At this load, the percentage of pilot fuel is already very low, thus, lower energy content of OME only minor influence the stoichiometry of the premixed natural gas. However, the impact of the pilot fuel on the combustion is very high. The ignition delay is lower due to the higher cetane number and the natural gas combustion is faster. The latter effect can be attributed to the higher temperature, since the combustion is closer to top dead center. Furthermore, the stoichiometry of the natural gas is closer to 1 which increases the flame speed.

Figure 9 shows a lower load condition at only 5 bar. The comparison shows a the operation condition with the minimum possible amount of pilot fuel. In the Diesel case, this is 37% of the total energy share. In the case with OME it is only 7%. Especially for cases with low load, the dilution of the pilot spray has an important effect on the ignition delay. The energy share of OME is significantly lower, due to a lower ignition delay. This can be attributed to the combination a higher cetane number and the lower heating value, which reduces the effect of dilution. The combustion behaviour of OME under engine like conditions can be found in:

S. Iannuzzi, C. Barro, K. Boulouchos, J. Burger, Combustion behavior and soot formation/oxidation of oxygenated fuels in a cylindrical constant volume chamber, Fuel, Volume 167, 1 March 2016, Pages 49-59

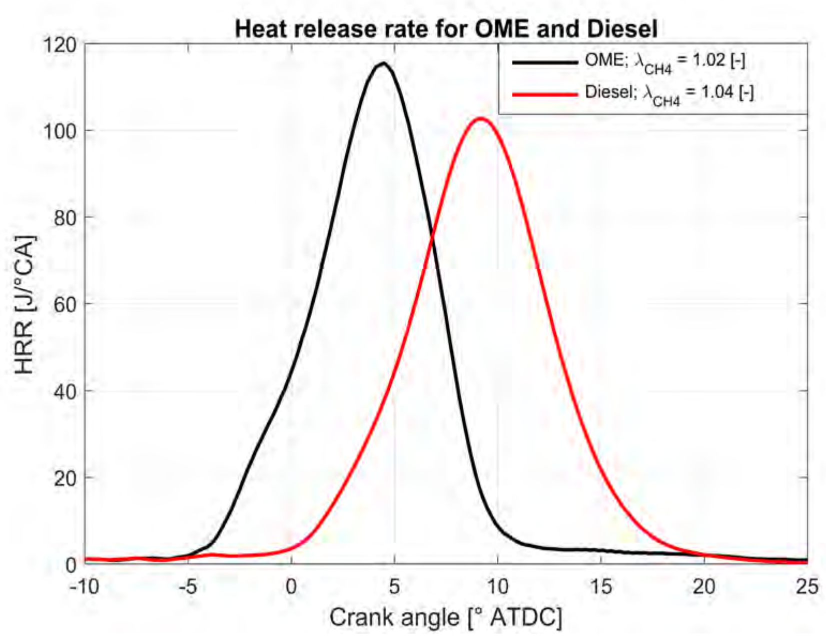


Figure 8: Heat release rates of natural gas combustion, ignited with OME (black) and Diesel (red) with similar injection settings.

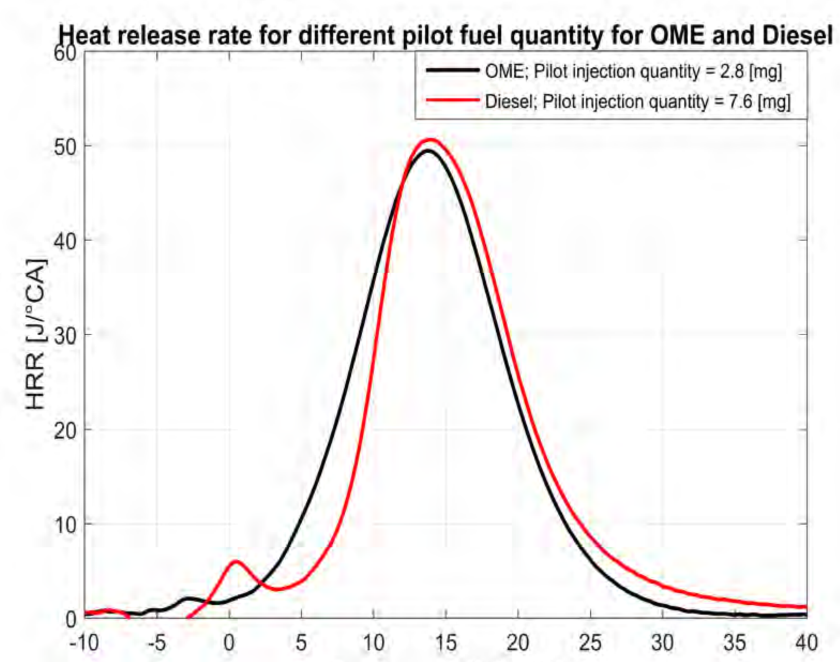


Figure 9: Heat release rates of natural gas combustion, ignited with OME (black) and Diesel (red) using the minimum possible amount of pilot fuel for similar combustion behavior.

Particulate Matter (PM) and Particulate Number (PN) Emissions

In the lower load operating condition, as depicted in figure 3, the share of pilot fuel can be up to 50%. The large amount of pilot fuel causes two major effects. The mixture of natural gas needs to be very lean (slow flame speed) and the core of the auto-ignition zone is fuel rich. The latter one cause high PM emissions. The figures 10 and 11 show a comparison between 4 different engine settings at 4 bar BMEP with high EGR ratios, according to table 1.

OP 1: 1500 rpm, 4 bar BMEP, 35% EGR, Swirl no
OP 2: 1500 rpm, 4 bar BMEP, 35% EGR, Swirl yes
OP 3: 2000 rpm, 4 bar BMEP, 40% EGR, Swirl no, DOI 700 μs
OP 4: 2000 rpm, 4 bar BMEP, 40% EGR, Swirl no, DOI 600 μs

Table 1: Operation condition characteristics

PM has been recorded using an AVL Micro Soot Sensor, the spectral particulate number distribution has been recorded with a Cambustion DMS 500. Figure 10 shows, that measures like swirl addition or reduction of the pilot injection duration help to reduce PM emissions, but the level remains high. Furthermore, the figures, 10 and 11 show that, both, PM and PN are orders of magnitudes lower using OME instead of Diesel as a pilot fuel. This is attributed to the oxygen content of OME, inhibiting soot formation. Using OME, only OP1 shows detectable PN level. However, the size range indicates that the recorded particles are most likely of volatile nature. OME shows a huge potential to reduce PM/PN emissions during low load operation of dual fuel engines.

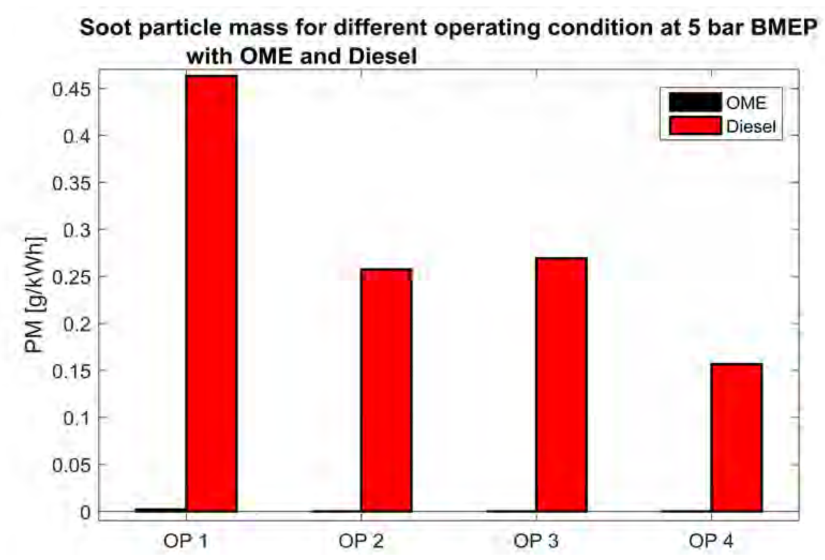


Figure 10: Comparison of PM emissions of OME (black) and Diesel (red)

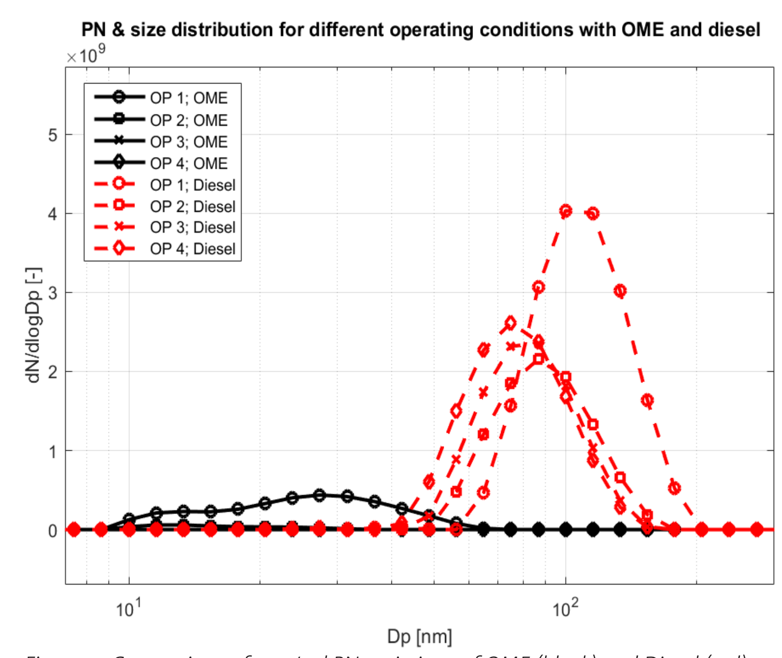


Figure 11: Comparison of spectral PN emissions of OME (black) and Diesel (red)

Conclusion and Outlook

A dual fuel engine has been operated with natural gas, premixed as main, and Diesel as well as OME as pilot fuel. The used OME blend contains OME 2, OME 3 and OME 4. This particular blend has an approximatley 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 operations with OME as pilot fuel show shorter ignition delays and a faster combustion in comparison to similar operating conditions with Diesel. Using Diesel, the operation in the lower load range requires a high share of pilot fuel. This has a negative effect on the CO_2 as well as on soot emissions. Due to the shorter ignition delay, the operation with OME allows a higher share of main fuel. Moreover, the oxygen content of the fuel inhibits formation of soot almost completely. Therefore, the exhaust emissions of the operating conditions with OME do not show PM or PN.

Involved Partners

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

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Introduction

Injector geometries of large marine two-stroke diesel engines differ extensively from typically used configurations in diesel engines. The injector orifices are asymmetrically arranged as all the bores face a similar direction. Due to this geometric setup, the orifices are also distributed eccentric with respect to the central bore of the injector. Experiments have shown that sprays from such orifices propagate non-symmetrical to the nominal axis of the orifice [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 orifice 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/m^3, 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. Figure 4 & 5 show the SCC test rig in Winterthur and a schematic, respectively [1].

Ballistic imaging

Definition of ballistic imaging

Ballistic imaging is a laser-based optical measurement technique to resolve structures in highly scattering media as for example dense sprays. The technique is shadowgraphy based as it is a line-of-sight method that eliminates multiply scattered light from the detector. The techniques aim is to reveal details of something surrounded by light scattering particles (e.g. fog, mist, smoke, etc.) which are disturbing the view [5].

Working principle

As ballistic imaging is a time-gated method, a very fast shutter (an optical Kerr effect (OKE), based on CS_2) is used in front of the camera to discard the photons that are unwanted in the images. In a typical setup described in [5], a high frequency mode-locked laser which creates 50 to 150 fs pulses is used together with an amplifier as light source as depicted in Figure 1. The beam is then split into two beams, one for triggering the OKE (switching beam) and one for the illumination of the spray (imaging beam). The imaging beam uses a delay arm to set the temporal overlap of the two beams. This allows exact triggering of the OKE gate.

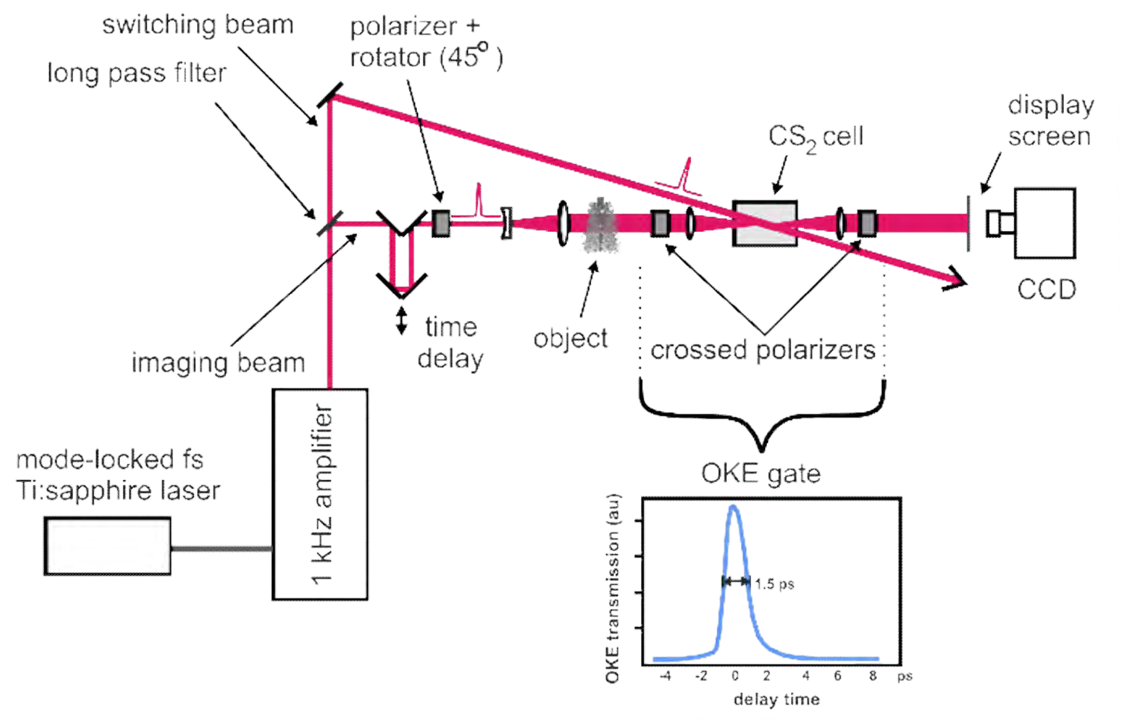

Figure 1: Optical arrangement for optical Kerr effect time-gated ballistic imaging [5].

After a system relayed the imaging beam through the OKE gate, a far-field microscope or similar is used to capture the photons with a camera.
Figure 2 a) depicts a dense spray acquired with the shadowgraphy illumination technique and Figure 2 b) shows a typical ballistic image of the same spray but of an enclosed region.

The image shown in Figure 2 b) has very good contrast between surrounding air and spray within the cloud of drops surrounding the spray (visible in Figure 2 a)). This makes this optical measurement technique very valuable for evaluating the primary and secondary breakup of a spray, as voids, ligaments and surface properties can be analysed using single or multiple image ballistic imaging. Additionally, the spray shown in Figure 2 b) gets more visibly through towards the bottom of the image. This powerful measurement technique can therefore be used for liquid core investigations of sprays as well (depending on the optical density of the spray) [5].

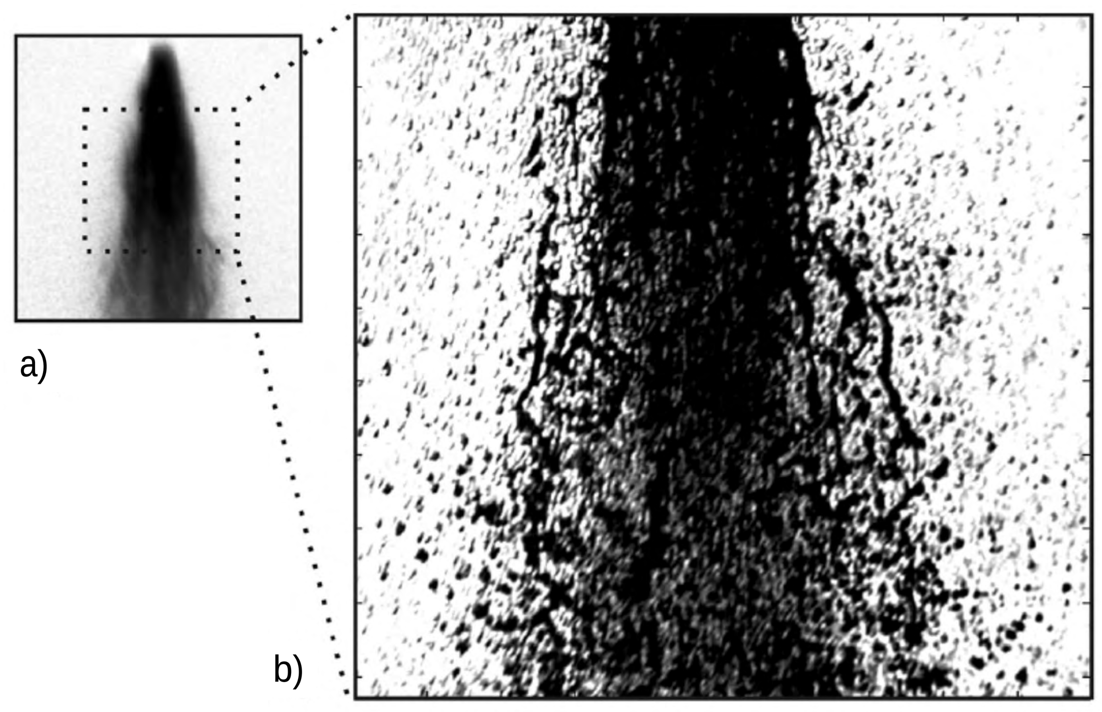

Figure 2: A laser shadowgram (a) and a ballistic image (b) of the same spray [5].

In-nozzle flow

The experience with transparent nozzles for in-nozzle flow investigations of Chalmers University of Technology will be used to build a series of Winterthur Gas & Diesel Ltd. internal matched geometries.

The transparent nozzles are made of acrylic as it has almost an identical refractive index as diesel, the fluid of interest. This physical property is needed to eliminate optical refractions from the cylindric shaped orifice. Unfortunately, the plastic prohibits high temperatures due to stability reasons. Therefore, the in-nozzle flow investigations using high-speed shadowgraphy imaging will be performed with realistic back-pressures but at ambient temperatures. It is assumed that gas density is dominant compared to gas temperature in the primary breakup region of the spray.

Figure 3 a) depicts a sketch with a sectional view of the transparent nozzle used in a first set of tests. The orifice has a diameter of 0.75 mm which is a standard orifice size for large marine two-stroke diesel engines. The image shown in figure 3 b) shows a shadowgraphy image of the orifice as illustrated with the dashed rectangular field of view in figure 3 a). The used rail pressure was 500 bar and the back-pressure was atmospheric. The diesel flow enters the sac bore of the transparent nozzle from the right side. Dark areas indicate areas where the light is refracted and therefore the gaseous phase of the diesel, 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 dark as well. In the lower part of the image one can see the spray emerging from the orifice. The strong cavitation in the orifice can be explained with the sharp edge nozzle and short orifice design which is not realistic for commercial nozzles. However, it already indicates asymmetric behaviour, as the cavitation on the right wall is more developed as on the left wall, which is the main objective to investigate in this project.

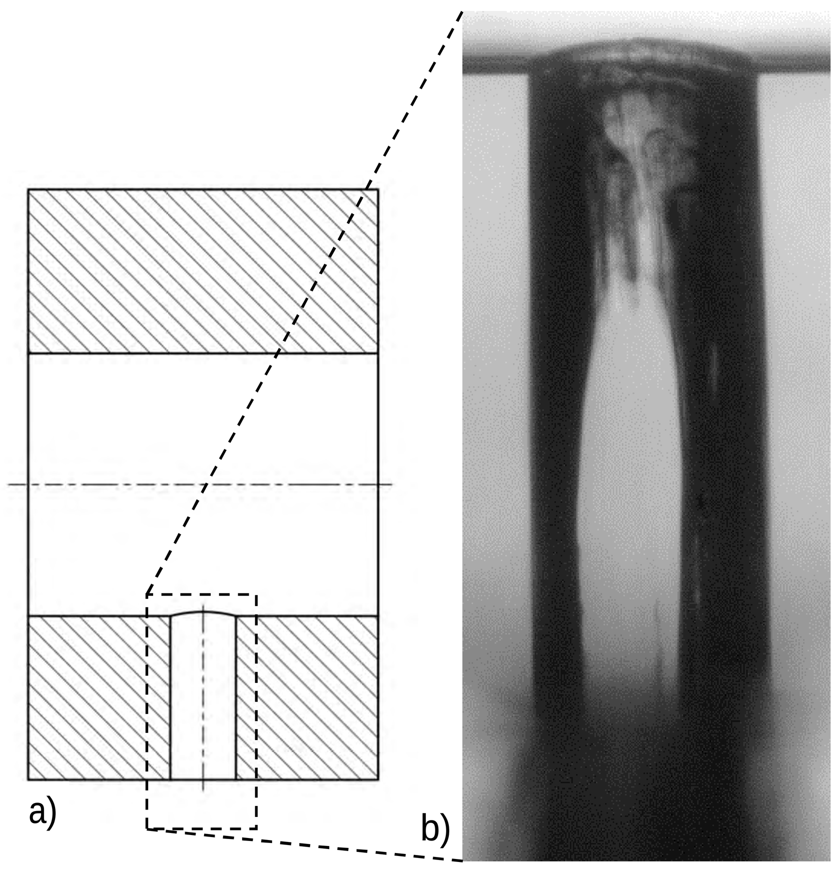

Figure 3: Sectional view of transparent nozzle with field of view around the orifice (a). Image of in-nozzle flow at 500 bar rail pressure where dark areas indicate diesel in the gaseous state (b).

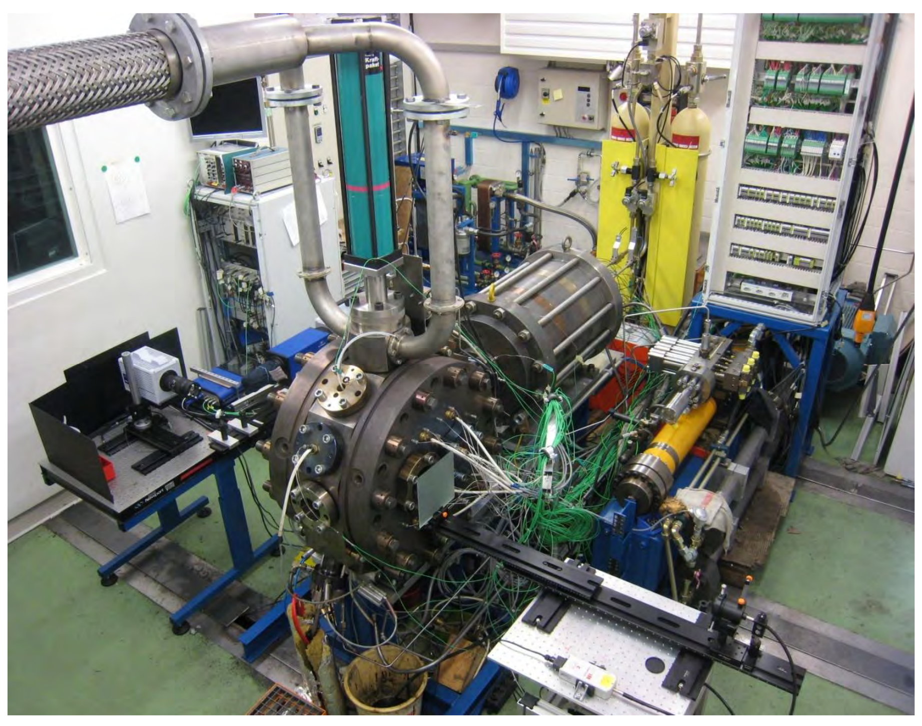

Figure 4: High-temperature, high-pressure Spray Combustion Chamber (SCC) at Winterthur Gas & Diesel Ltd. [1].

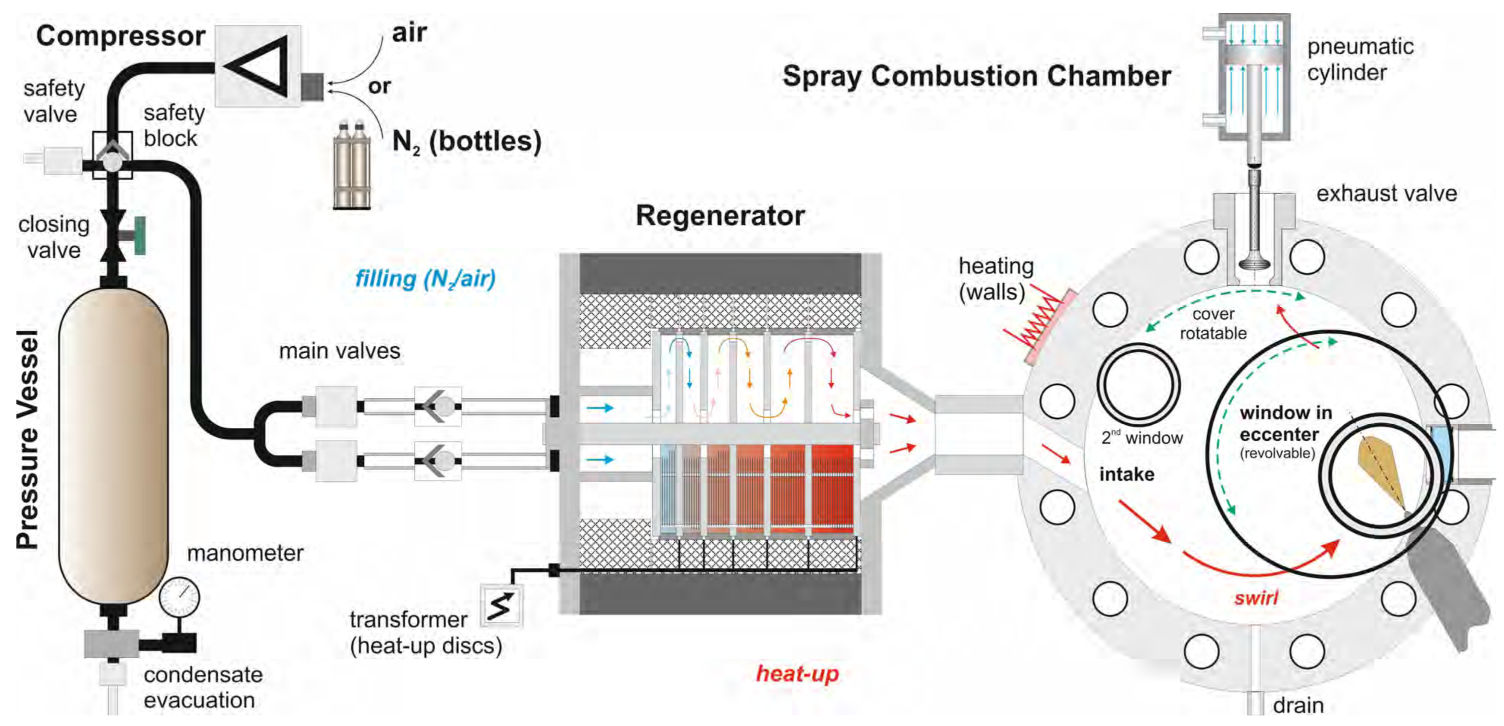

Figure 5: Schematic of Spray Combustion Chamber (SCC) with pressure vessel, regenerator and spray combustion chamber. Maximal pressure: 20 MPa, maximal temperature: 950 K [1].

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CERC
Combustion Engine Research Center

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

BFE OFEN UFE SFOE

Project INFLOSCOM,
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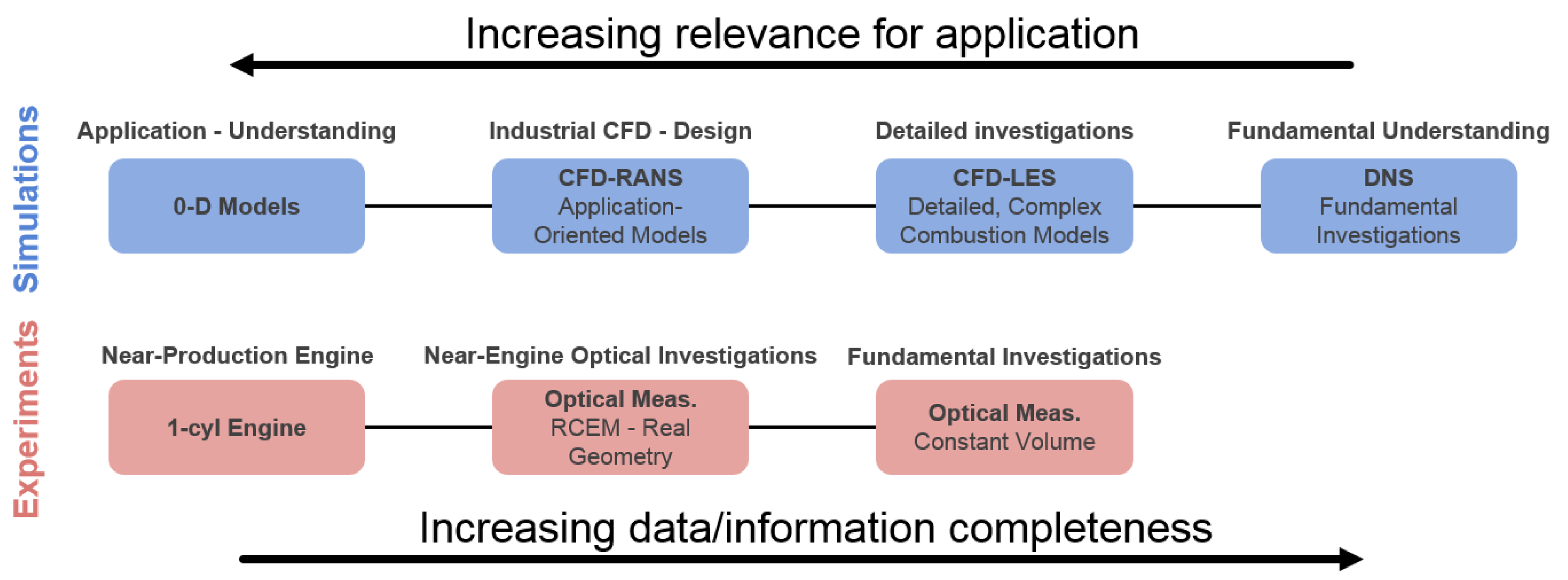
Aerothermochemistry and Combustion Systems Laboratory

Gas Prechamber Combustion Modeling

Lean-burn gas engines aiming at low NO_x emissions and high efficiency require large ignition energy and distributed ignition sources in order to ignite and consume the lean premixed main charge, aiming to maximize efficiency and reduce unburned hydrocarbon emissions. A widely used technology in these engines is prechamber ignition systems, where the ignition source is located in a separate small volume, connected to the main chamber via small orifices. Research in the field of prechamber combustion has been extensive in the past years, with work done both in experimental and numerical investigations. In the design of prechamber ignition systems, commercial as well as research computational fluid dynamics codes are often used. Nevertheless, detailed understanding of heat transfer and turbulent jet ignition and combustion phenomena are still not well understood. The development of combustion and heat transfer models to be applied in such codes is often hampered by unavailability of reliable and detailed data. Recent advances in numerical modeling and increases in computational power and availability have allowed the use of direct numerical simulations (DNS) for the retrieval of reliable and detailed data for the improvement of physical and chemical process understanding of such complex phenomena. This work presents a hierarchical approach for combustion research and model development, with particular focus on prechamber combustion. This approach combines experimental and numerical work ranging from optical diagnostics in generic setups to metal engine measurements and from generic DNS calculations and real-geometry 3D-CFD, to phenomenological 0D models.



Introduction

Natural gas (NG) can be used in existing internal combustion engines, but due to its favorable characteristics – namely high resistance to self-ignition (knock) – it can be utilized best in high-compression-ratio, high-efficiency, lean-burn engines. Lean-burn gas engines possess the advantage of lower fuel consumption, and as a result also emit lower CO_2 emissions compared to stoichiometric engines. Nevertheless, they suffer from increased cycle-to-cycle variations and unburned hydro-carbon emissions. Prechambers are used to increase the ignition energy and stabilize combustion under increasingly lean conditions by creating optimal conditions near the spark plug for the early flame development and distributed ignition points in the main combustion chamber. This increases combustion speed and reduces unburned hydrocarbon emissions.

1-cyl Engine Experiments

Single-cylinder research engine experiments are performed to evaluate different prechamber designs in terms of combustion characteristics, performance, as well as emissions (mainly NO_x and CH_4 slip). The main aim of the investigations is to extend the operating range of the engine to higher loads and leaner mixtures, in order to reach very low engine-out NOx values.

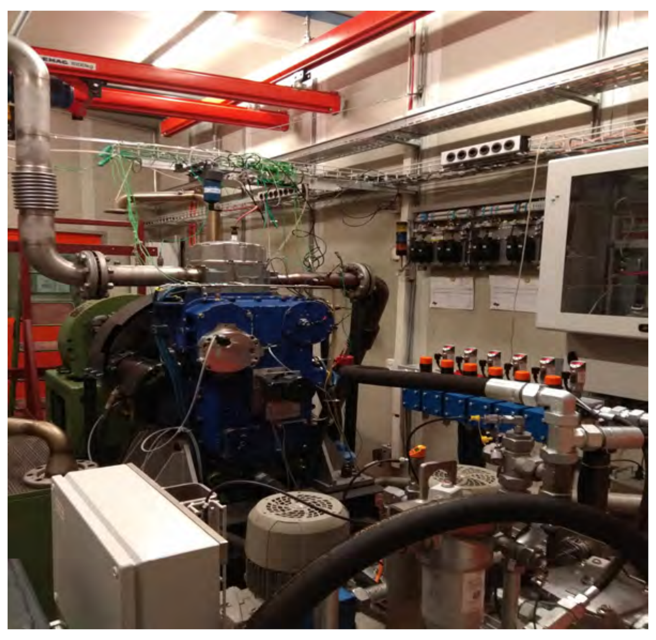


Fig.1: View of the single cylinder research engine test facility

Optical Investigations

Optical data is obtained from prechamber combustion systems under near-engine conditions, in order to provide validation data for the simulations and increase the understanding of in-prechamber and main chamber combustion processes. Optical data from within the prechamber will be obtained using an optically accessible generic, single-hole prechamber designed and manufactured within LAV.

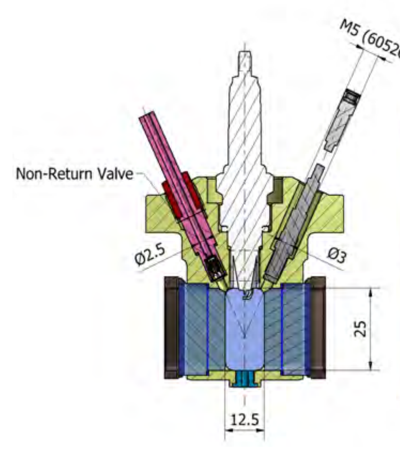


Fig.2: Optically accessible generic PC design

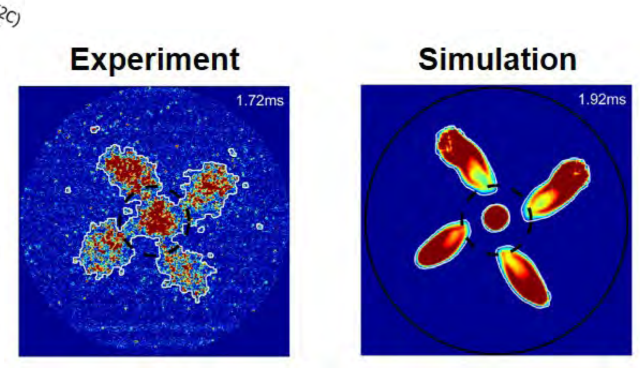


Fig.3: Comparison of the measured OH* chemiluminescence signal

Reactive DNS

Reactive Direct Numerical Simulations are used for the in-depth understanding of the early flame propagation within the prechamber, the flame stability at the prechamber exit, the resulting combustion in the main chamber and the influence of the walls on the turbulent flame.

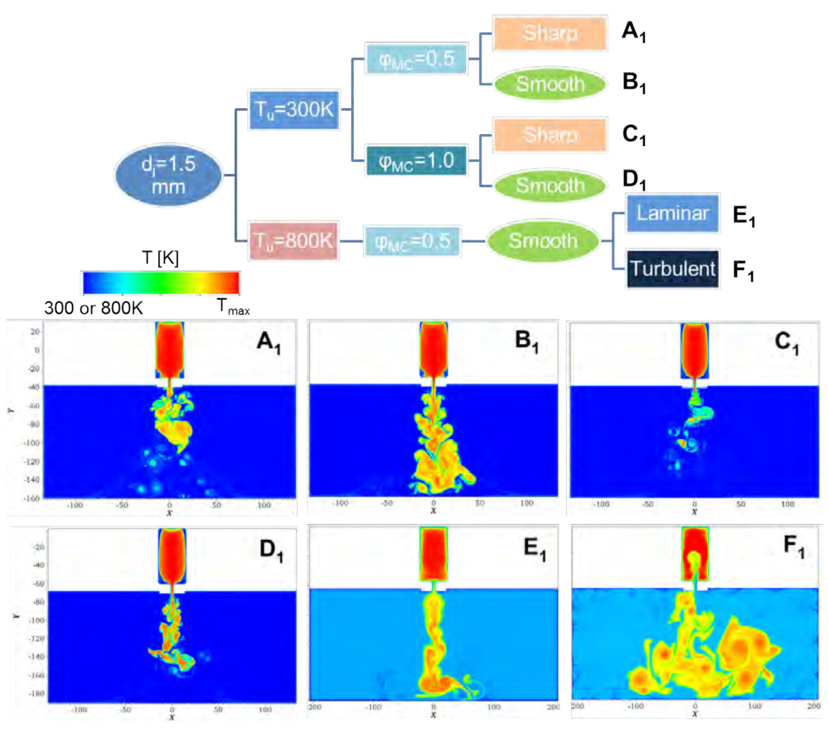


Fig.4: Effect of unburned mixture temperature T_u (same in both chambers), equivalence ratio in the main chamber phi_{MC}, nozzle geometry (sharp vs. smooth corners) and turbulence ($u'_{PC}=1.5S_L$, $l_t=0.5d_t$, $u'_{MC}=3S_L$, $ll=4d_t$) on the temperature distribution.

3D CFD & 0D Models

The experimental and DNS simulation results will be used to provide an in-depth understanding of the combustion processes within the prechamber, as well as after the jet exist into the main chamber. This data will be used to develop detailed 3D CFD combustion models, to be used in the future for prechamber design and overall engine design optimization. In addition, the data will be used for the development of phenomenological models for prechamber engine design and optimization in wide operating ranges.

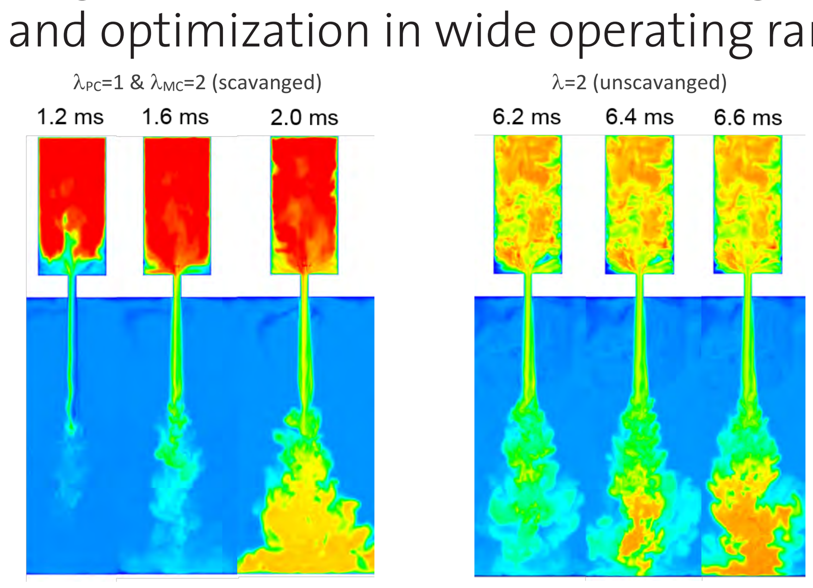


Fig.5: Prechamber jet ignition in the optically accessible prechamber geometry for two different prechamber mixtures and a constant main chamber mixture

Expected Impact

The knowledge generated within these projects is expected to contribute significantly to the future design and development of internal combustion engines using prechamber combustion systems. Such engines will allow the widespread use of natural gas as a fuel, which in itself will lead to a 20% reduction of greenhouse gas (GHG) emissions compared to other traditional fossil fuels. In addition, the increase in efficiency due to expansion of the lean limit operating window, the increase in power density as well as the increases in compression ratio will result in a further reduction of fuel consumption and GHG emissions. The optimal design of prechambers should also allow the minimization of the CH4 slip, a potent GHG. Finally, future use of alternative fuels from power-to-gas processes in prechamber gas engines will allow the complete removal of GHG emissions using gas engines.

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Publications:
1. S. Benekos et al., 2016, Direct Numerical Simulation and experimental validation of ignition/early flame propagation and flame-wall interactions in future gas engines, Intermediate report, June 2016
2. P. Kyrtatos et al., 2017, Advanced Methods for Gas-Prechamber Combustion Research and Model Development, 16th Conference „The Working Process of the Internal Combustion Engine", Graz
3. G. Xu et al. 2017, Experimental and Numerical Investigation of the Engine Operational Conditions' Influences on a Small Un-Scavenged Pre-Chamber's Behavior, SAE Int. J. Engines 10(5):2017

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High-Pressure Gas Injection

LAV Laboratorium für Aerothermochemie und Verbrennungssysteme
Aerothermochemistry and Combustion Systems Laboratory

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Introduction and Motivation

The overarching drive for reducing greenhouse emissions in the transportation and electricity sectors and also the introduction of increasingly stringent emissions legislation for internal combustion engines (ICEs) demand the formulation of novel combustion strategies. In this context, natural gas, whose primary constituent is methane (CH_4), has gained importance as a fuel whose combustion releases substantially lower CO2 emissions than conventional gasoline and diesel fuels for the same power output and has the potential to lead to further reduction of NO_x, unburnt hydrocarbon (HC) and soot emissions. Diffusion controlled combustion of natural gas can be adapted from standard diesel combustion technologies; however, very high injection pressures must be applied to overcome the typical end-of-compression cylinder pressure in an engine and high pressure ratios must be employed to counteract the lower density of the gaseous fuel. Due to the high injection pressures, real-gas effects become important; and because of the high-pressure ratio, the injected fuel will be at under-expanded conditions, thus leading to the formation of complex flow structures such as Mach disks and barrel shocks upon expansion of the gaseous jet in the main chamber. Owing to the complexity of the phenomena involved, the scope of this project is to study the fundamentals of high-pressure methane injection in terms of jet aerodynamics, mixture formation and their coupling to reaction kinetics up to ignition.

Experimental Approach

The Constant Volume Chamber (CVC) reproduces the conditions at the top-dead-center of an internal combustion engine; the air temperature and pressure can be adjusted to simulate different loads and compression ratios. It is equipped with a large frontal window (φ = 90mm) and four smaller side windows (φ = 42mm) that allow the application of different optical techniques simultaneously.

In order to study the evolution of the jet at different injection pressures and ambient conditions, the schlieren technique has been applied to quantify the tip penetration and spreading angle of the jet. Figure 1 shows the CVC with the injector mounted on the side and the mirror inside the chamber in order to use the largest window for visualization. For the experimental campaigns, different injection pressures ranging from 150bar up to 300bar have been studied as well as various chamber pressures to achieve pressure ratios (Injection/Chamber) in the range of 5 to 25.

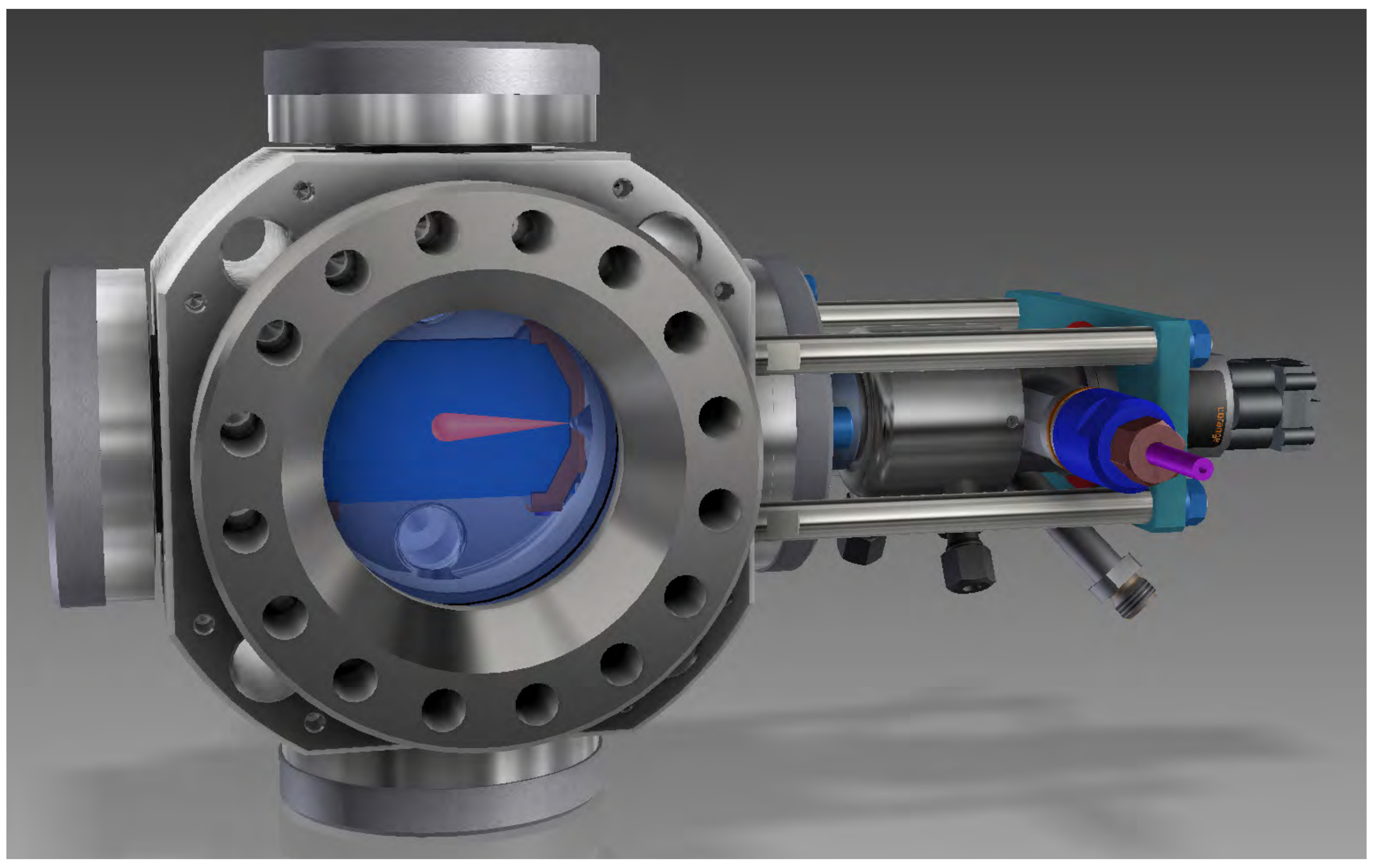

Figure 1: Schematic of the CVC with the injetor mounted on the side and the mirror inside de combustion chamber for double-pass schlieren visualization though the front window

Figures 1 and 2 depict a few of the conditions that have been studied. Figure 1 compares different pressure ratios at a constant injection pressure and it can be seen that the higher pressure ratio (i.e. lower chamber pressure) the faster the tip of the jet penetrates [1]. On the other hand, Figure 2 depicts different injection pressures at a constant pressure ratio and it shows that the evolution of the jet tip is very similar for most of the cases [1].

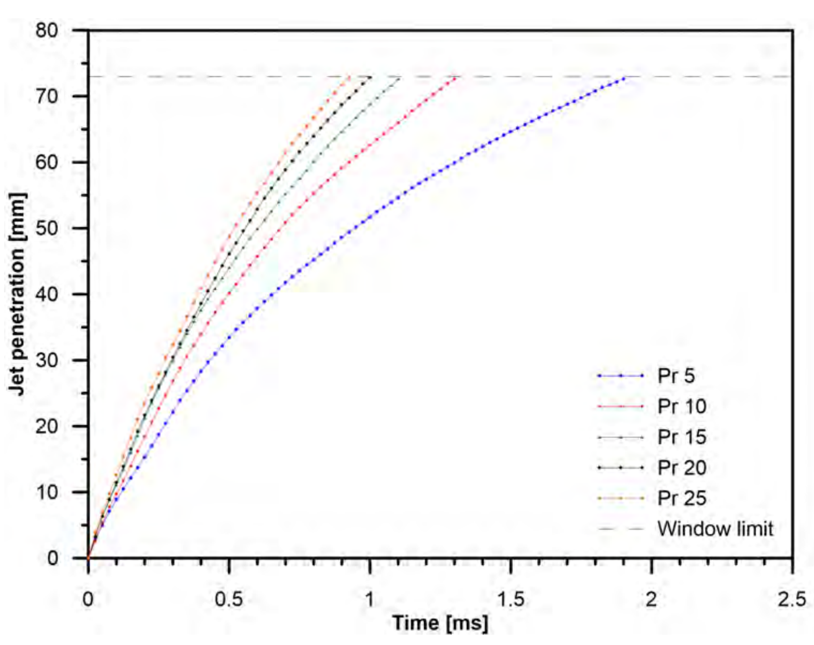

Figure 2: Comparison of tip penetration for different pressure ratios, at 300bar of injection pressure

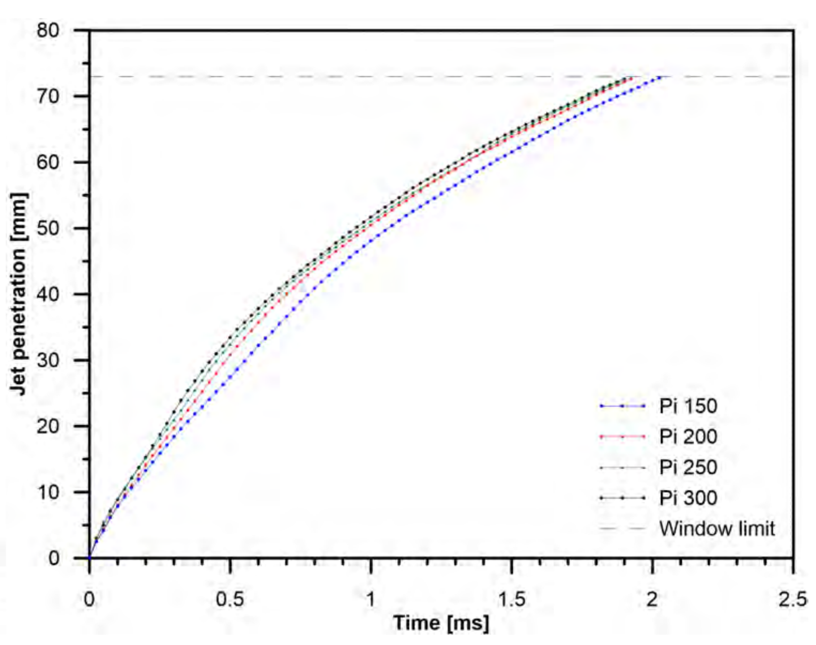

Figure 2: Comparison of tip penetration for different injection pressures, at a pressure ratio of 5

Modelling Framework

Simulations of the transient methane jets executed in a two-stage process in a RANS framework:

First, a fully detailed simulation of the injection process is conducted. This accounts for needle dynamics, nozzle flow and resolution of possible shocks in the near-nozzle area of the main chamber. Very fine resolution and correspondingly small time-steps are employed. Real-gas effects are accounted for by using a cubic real-gas equation of state (EoS)[2], by extending enthalpy to incorporate an enthalpy departure term[2], by modelling mixture viscosity and conductivity with Chung's models[3] for dense fluids and by employing real-gas mixing rules.

Second, a simulation of flow in the CVC is carried out. The detailed simulation is used to extract time-varying boundary conditions at the nozzle outlet, which now serves as the inlet of the domain[4]. A coarser mesh of typical RANS resolution for engines (~0.2mm) is employed, which can accommodate considerably larger time-steps while still respecting CFL criterion. Refinement is required in the near-nozzle area to enable the prescription of detailed flow profiles. Real-gas EoS is still employed, but enthalpy, conductivity and viscosity are tabulated as polynomial functions of temperature for fixed pressure. This approach leads to a massive reduction in computational cost and simulation turnaround time, while preserving the accuracy in mixture formation of the detailed simulations, as shown in Figure 3.

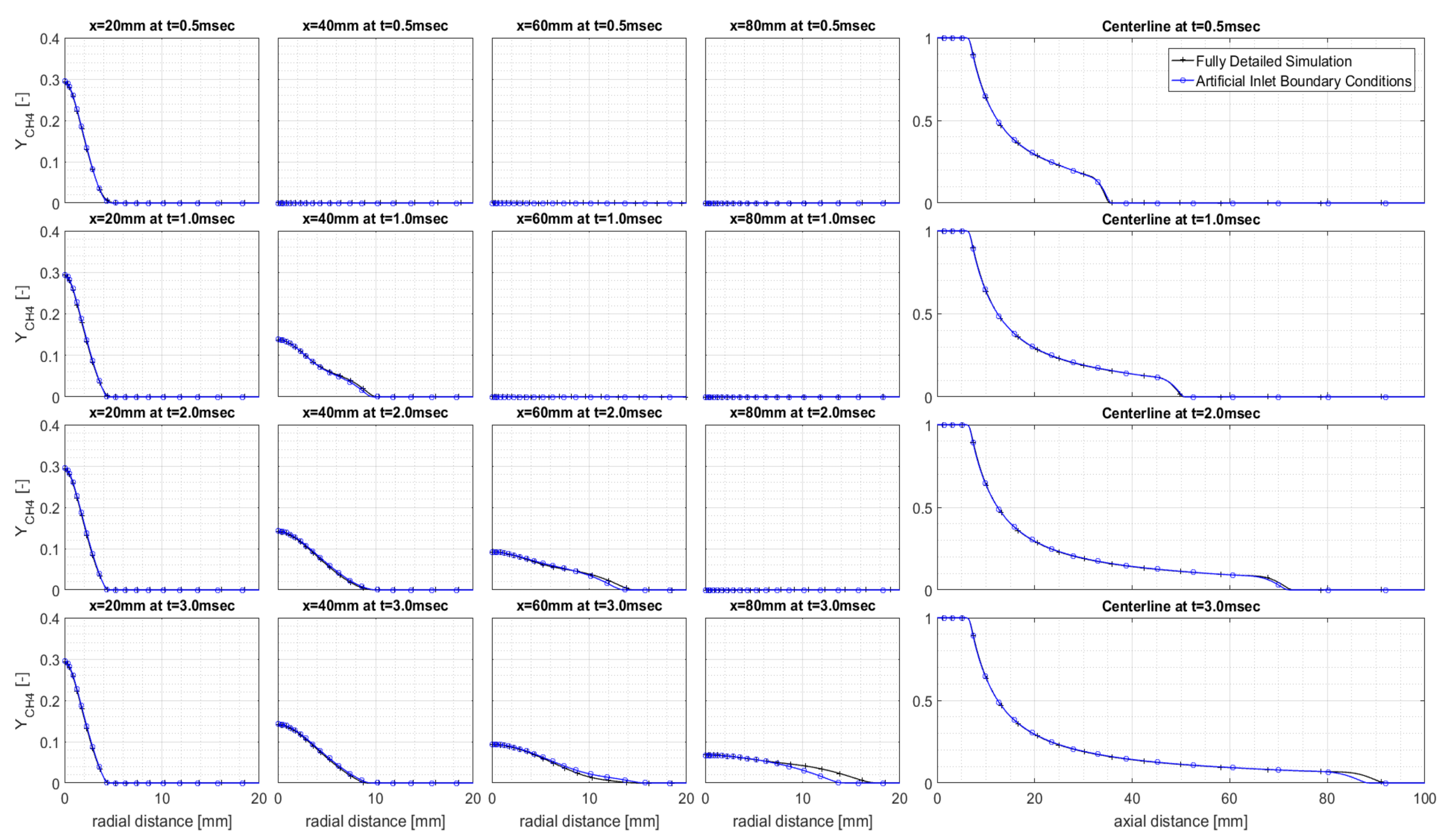

Figure 3: Comparison of methane mass fraction distribution across four different axial positions and along the jet centerline at four different times during an injection event of 3ms at an injection pressure of 250bar and a pressure ratio of 2.5

Collaborations

Universität der Bundeswehr München — M. Banholzer, Prof. M. Pfitzner

L'orange YOUR POWERFUL INJECTION — I. Berger, Dr. M. Willmann

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FVV

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Combustion Fundamentals

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Aerothermochemistry and Combustion Systems Laboratory

Empa
Materials Science and Technology

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Hydrogen Enriched Methane Combustion

Introduction and Motivation

Energy storage is a key challenge for the integration of renewable energies in future energy supply due to their production volatility and high discrepancy between installed power and average production which leads to fluctuating excess production. In the RENERG2 (RENewable enERgies in future enerGy supply) project, power-to-gas is considered in order to convert energy flows (electricity) into energy carriers (hydrogen). The hydrogen can be used for hydrogen / methane blends in mobility as well as by means of decentralized power co-generation.

For the gas-to-power path, a variety of fuels (H_2/CH_4 admixtures), highly dynamic operation, many start and stop cycles and a high conversion efficiency are required for the energy converter. The classical IC-engine is well suited for this profile. However, such engines are well known for their cyclic fluctuations related to the early stage of the combustion process [1]. A question to be addressed in this project is: Which correlations exist between the properties of the fresh gas phase, the electric characteristics of the ignition spark, and the macroscopically observable behaviour of the engine?

In order to address these questions, a combined experimental and numerical approach is pursued. Experimental data allow the validation and calibration of numerical models, which in turn provide highly resolved information in space and time of quantities which are not experimentally accessible.

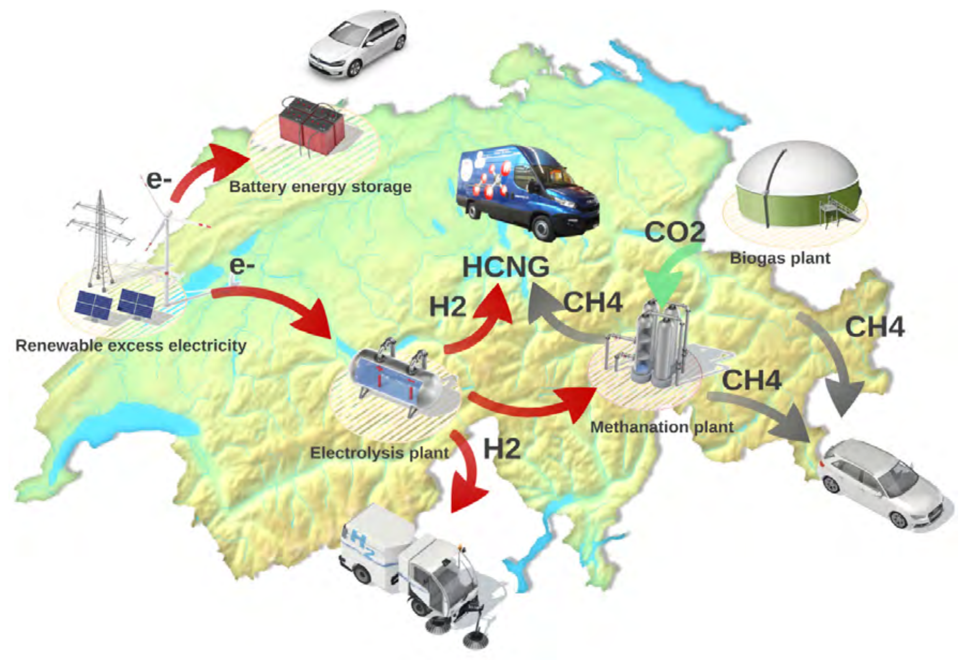
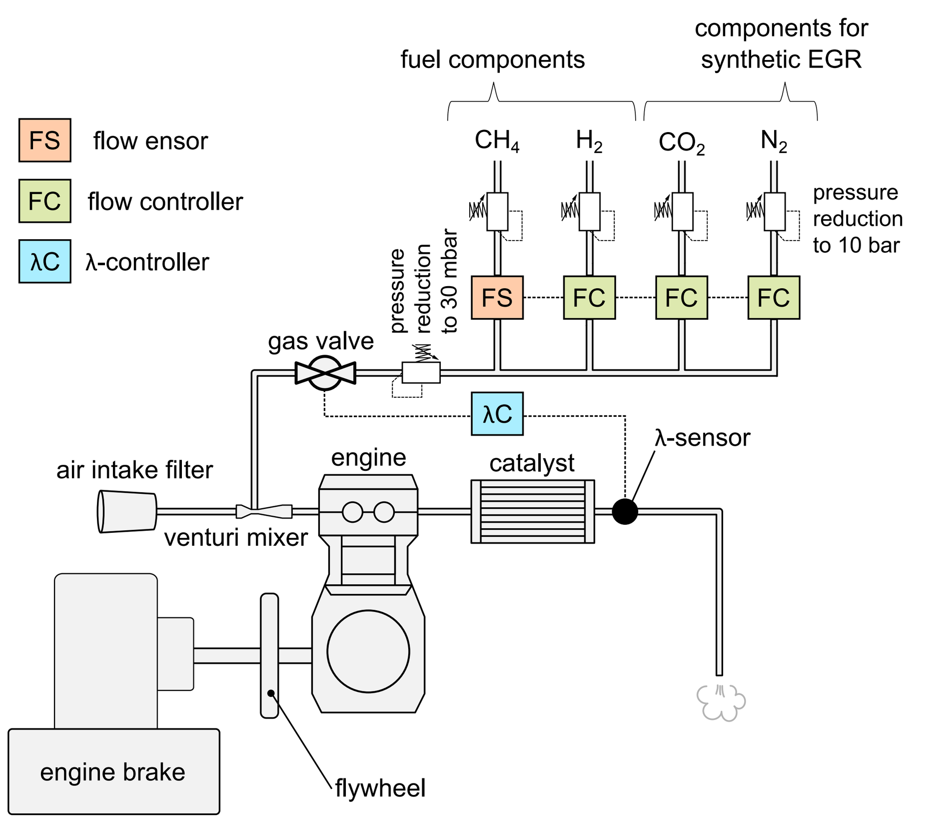


Figure 1: Schematic conversion path for the integration of renewable excess electricity in the mobility sector via gaseous energy carriers.

Engine Measurements

A single cylinder engine test bench (see Fig. 2) was installed for the generation of multi cycle data sets of hydrogen admixture combustion in stoichiometric and lean burn mode as well as with varying synthetic EGR rates. In order to have full flexibility in terms of added hydrogen- and synthetic EGR rates a device was installed where the intake gas can be composed of CH4, H2, CO2 and N2 freely according to the desired intake conditions. A gas valve in combination with a venturi mixer allows for a lambda adjustment independent of the gas composition. A wide band lambda sensor delivers the necessary control signal to the lambda controller.



Test Bench Key Features	
Displacement	250 ccm
H2-content	0-50%
Synthetic EGR rate	0-25%
Lambda	1.0-1.8
Rotational speed	1'000-10'000 rpm
Data logging	Engine torque Rotational speed Mass flows Exhaust gas analysis Fluid temperatures Pressure indication

Figure 2 Schematic of the installed single cylinder test bench

Numerical Modeling

One-dimensional simulations of laminar flames, based on detailed chemical mechanisms, allow to study properties of the flame and its response to hydrogen addition, as exemplarly indicated in Fig. 3. Tabulation of characteristic flame parameters serve as a sound basis for three-dimensional reactive CFD simulations.

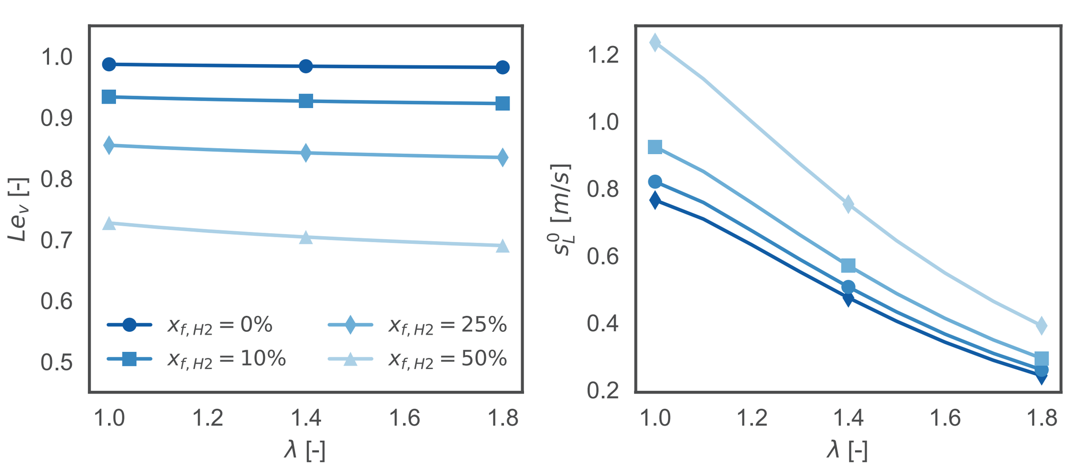


Figure 3: Effective Lewis-Number volume based (left) and laminar flame speed (right) for different hydrogen content in the fuel

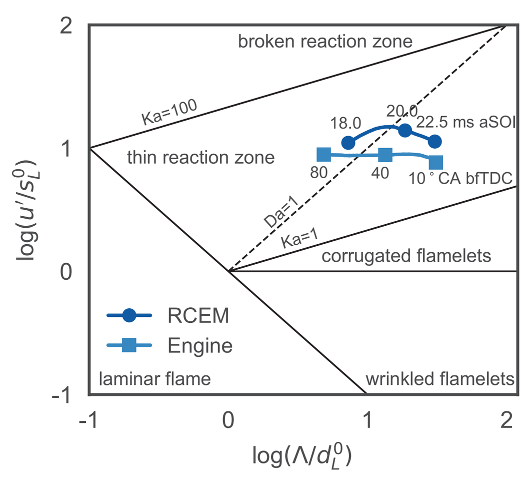


Figure 4: RCEM and engine in the Borghi diagram

The operating conditions of the engine and the RCEM have been derived in order to achieve comparability in the Borghi Diagram at ignition timing (Fig. 4). There, characteristic velocity- and length scales are compared based on properties of the laminar flame and the turbulent flow field.

Three-dimenional Large Eddy Simulations of the combustion process enables the study of cyclic phenomena, such as the typically observed cycle-to-cylce variations. These fluctuations are caused by the interaction of the propagating flame with the turbulent flow field. Here, combustion is modeled by the G-Equation, using a turbulent flame speed closure which is coupled to tabulated laminar flames. This approach allows to consider the thermo-chemical effects of the hydrogen addition.

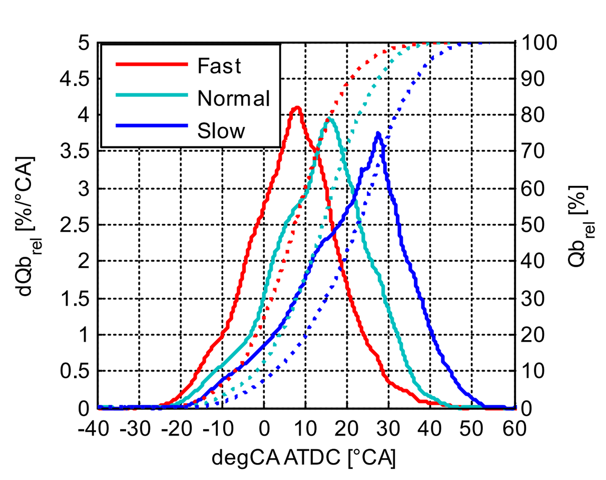


Figure 5: Simulated heat release rate for 3 characteristic cycles [2]

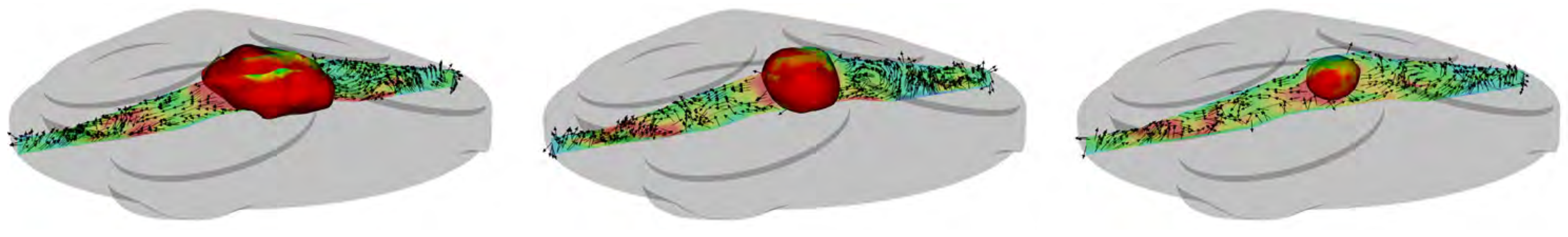


Figure 5: Turbulent flame front 16°CA after ingnition for a fast (left) average (centre) and slow (right) burning cycle inside the single cylinder engine [2]

Optical Diagnostics

A Rapid Compression and Expansion Machine (RCEM) simulates the compression and expansion stroke of a single engine's cycle. Optical accessibility inside the combustion chamber is granted through a quartz glass in the piston and through lateral windows in the cylinder head (see Fig. 6, left), what allows the study of the charge motion and its interaction with the the plasma channel and the early flame formation.

A novel turbulence generation mechanism was applied by a high pressure air injection at the beginning of the compression stroke to achieve turbulence intensity levels similar to an engine by varying the injection pressure ratio (PR) [3]. Particle Image Velocimetry (PIV) is a widely-used technique in order to measure velocities in a two-dimensional plane at a specific time. High-speed PIV measurements (10 kHz) allow to study the temporal evolution of the in-cylinder flow field and derive characteristic numbers such as velocity magnitude and turbulent velocity fluctuations (see Fig. 6, middle). Schlieren imaging and OH*-chemiluminescence were used to track the early flame kernel formation and flame propagation during the combustion process as indicated in Fig. 6 on the right. Moreover, the electrical discharge characteristics was recorded together with high speed plasma channel lumnoisty imaging to track plasma channel deflection and re-strike events.

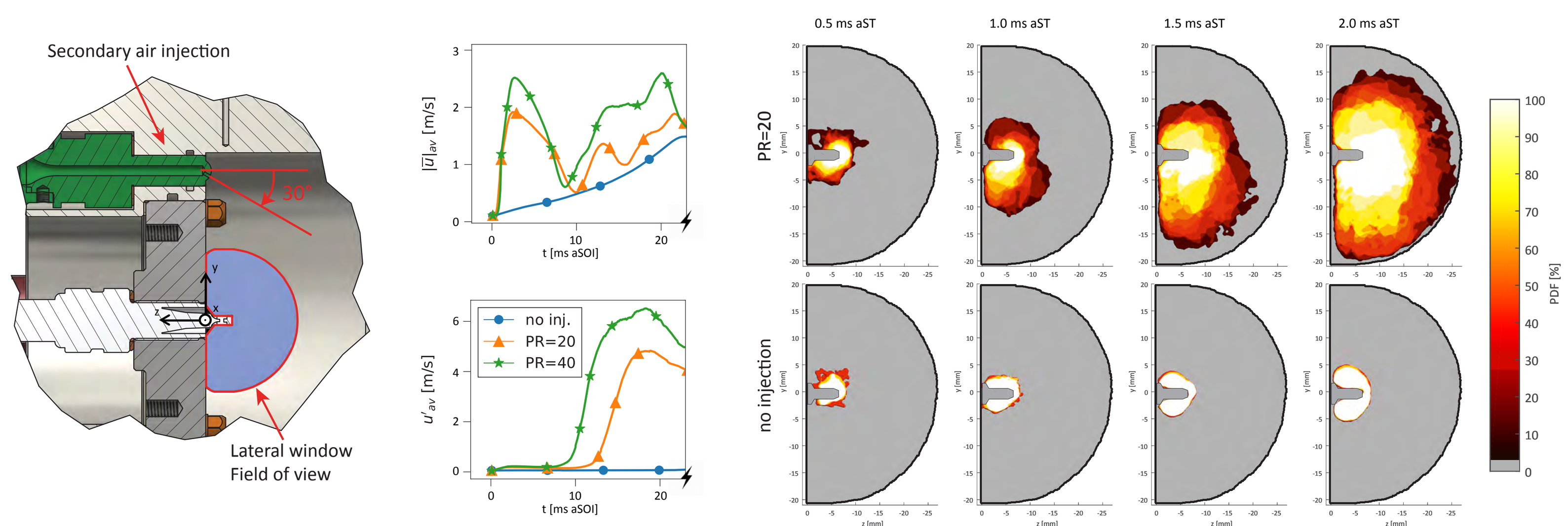


Figure 6: Field of view via lateral windows (left), spatially averaged velocity magnitude and turbulent fluctuation speed around the spark plug location (middle) and impact of secondary air injection on the early flame kernel evoluation for premixed methane combustion based on OH chemilumninescence (right)*

Different hydrogen enrichment ratios (10, 25 and 50 vol%) in methane were experimentally investigated under „quasi laminar" and turbulent flow conditions in the RCEM at fixed ignition conditions of 10 bar and 650 K at lean air-fuel ratios. Thermodynamic analysis based on in-cylinder pressure indication was compared to optical data (see Fig. 7) and serves as a basis for numerical simulations.

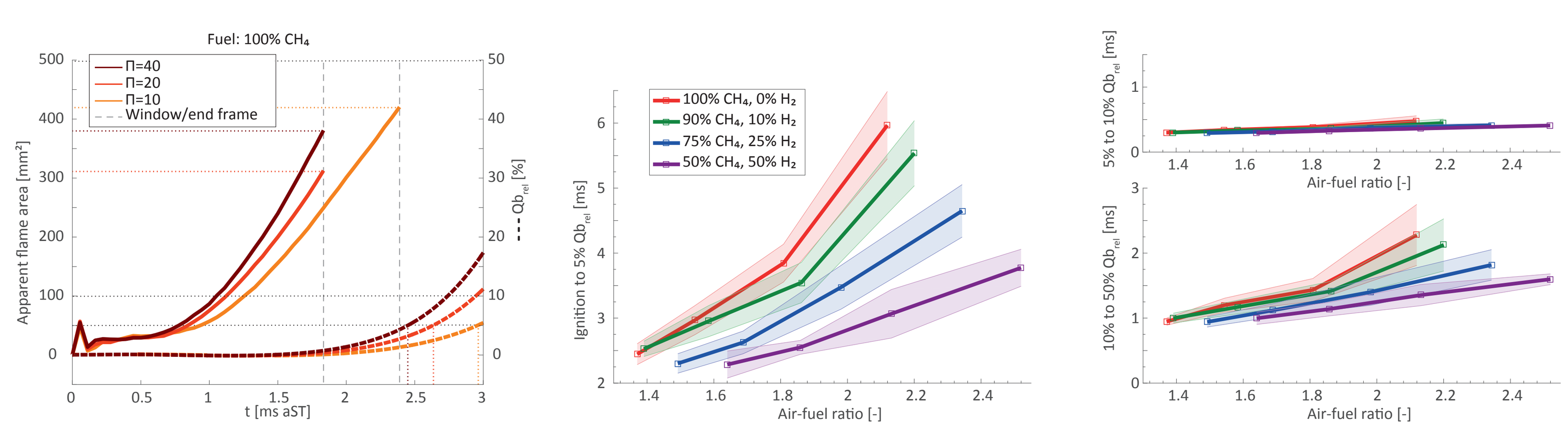


Figure 7: Apparent flame area and experimental heat release rate after spark timing for different turbulence levels (left). Characteristic fuel conversion durations for different hydrogen enrichment ratios (right).

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A New Method for Accurate Droplet Density Estimation in Droplet-Laden Turbulent Flows

Abstract

A method, originally proposed for the estimation of probability densities [1], is adapted for the estimation of droplet densities in turbulent flows. Compared to Voronoi analysis [2], which is typically applied, this new method, referred to as smooth distribution element tree (DET) method, leads to more accurate density estimates that enable the identification of physical effects more clearly. The latter is illustrated in the context of preferential sweeping of heavy droplets settling in turbulent air.

Motivation

The droplet number density and mass loading distribution are relevant quantities for the investigation of droplet-laden turbulent flows. On one hand, the droplet number density enables a better understanding of the physical effects that determine behaviors like preferential concentration [3] or settling enhancement [4]. On the other hand, the mass loading distribution is a characteristic quantity at the heart of Eulerian-Eulerian flow descriptions applied in certain flow simulations [5].

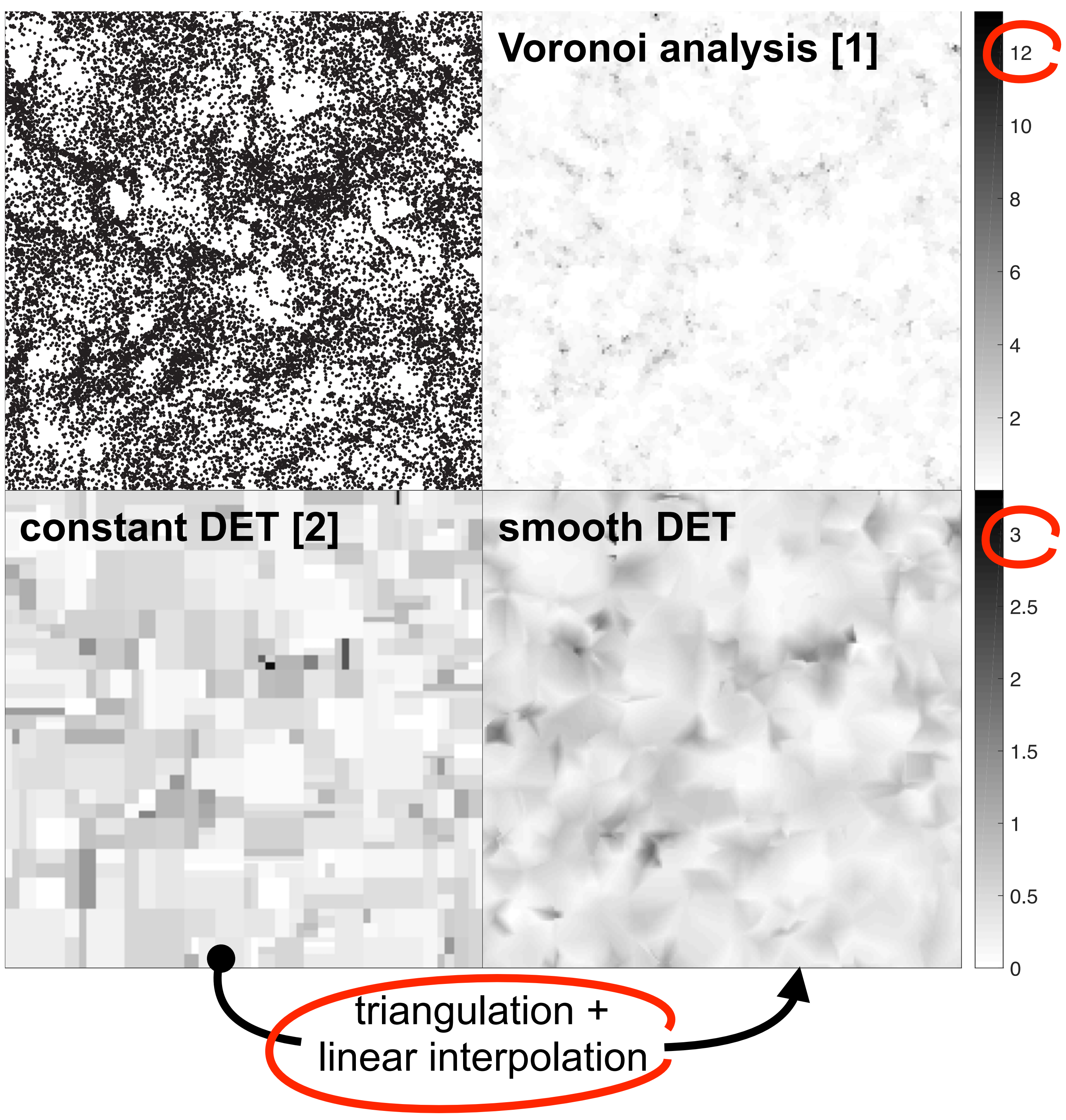
DNS Setup

forced turbulent carrier flow: air at atmospheric conditions in periodic box, $R_\lambda = 42.4$

droplets: water, mass load'g 35%, $\rho_p/\rho_f = 839$, $St_\eta = 1.2$

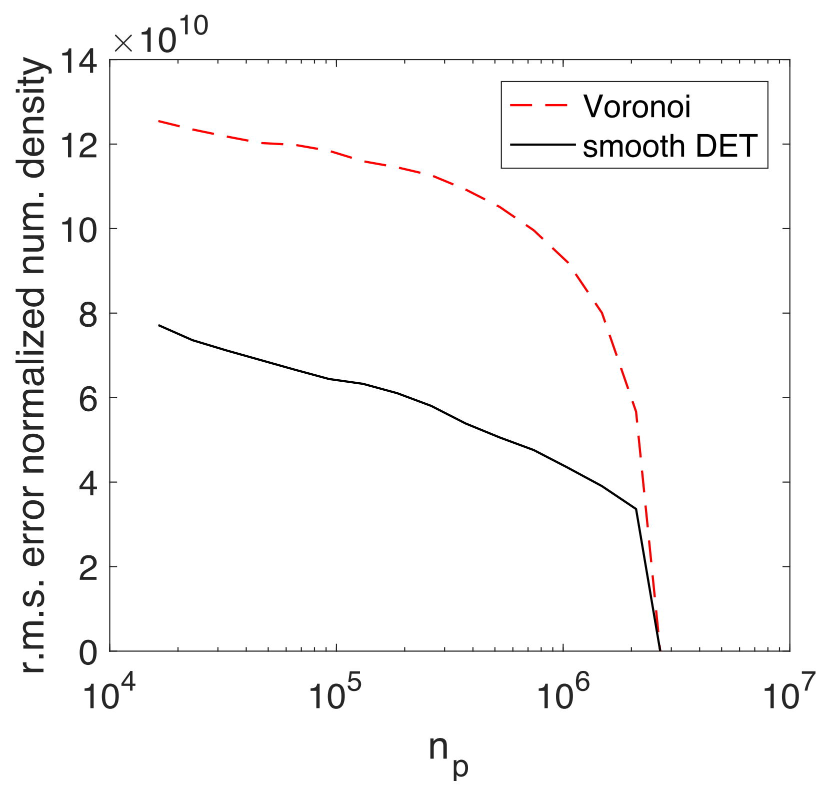
gravity: Rouse number $R = U_t/u_\eta = 0.912$

Droplets and mass-loading estimates in vertical cross-section of turbulent flow:



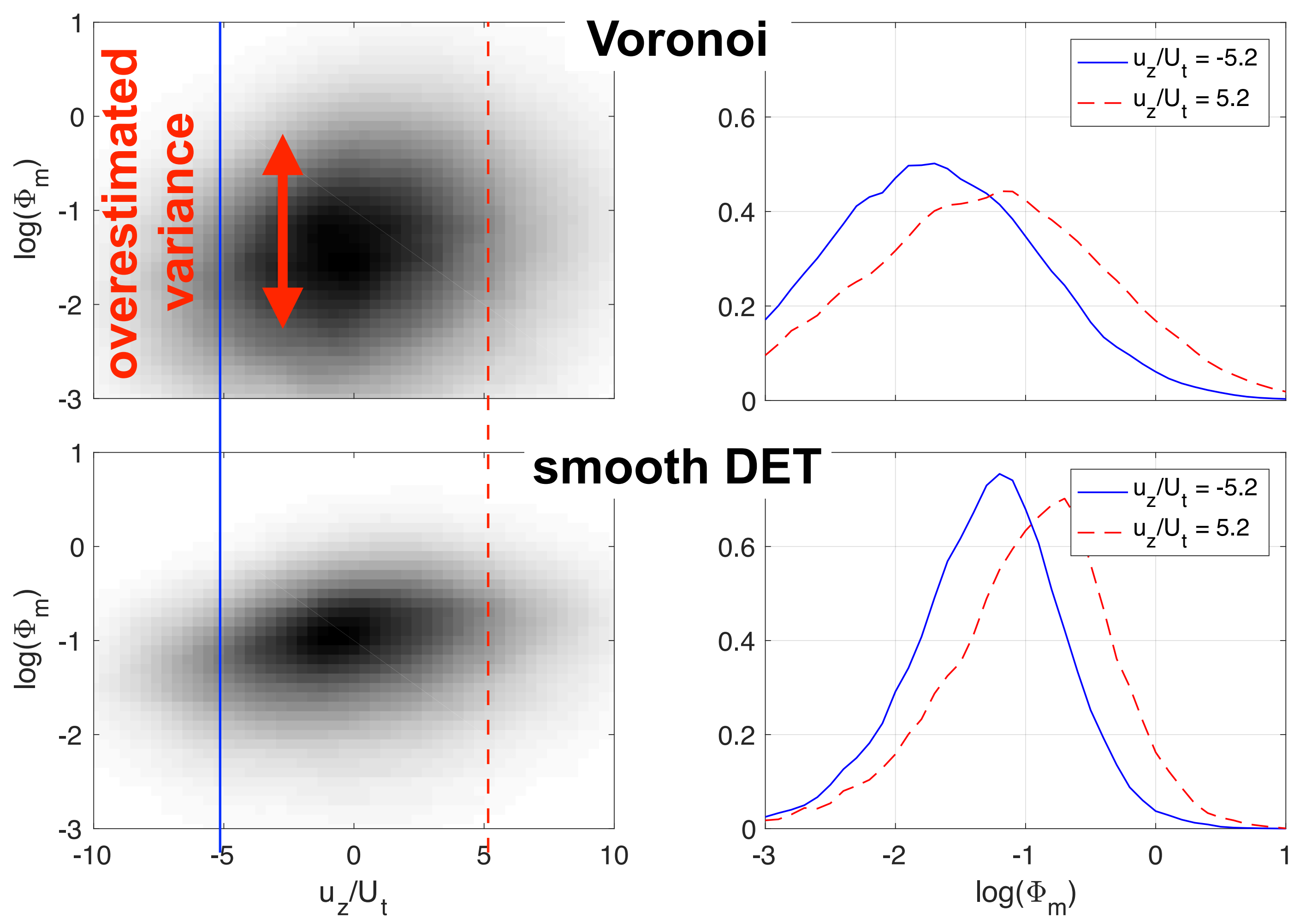
Accuracy of Density Estimators

To evaluate the accuracy of the density estimators, a one-way coupled DNS was considered and the r.m.s. error convergence in the normalized number density from ensembles with increasing droplet counts n_p relative to a largest ensemble with 2.68×10^6 droplets was evaluated:



Investigation of Preferential Sweeping

Joint PDFs of the log-mass-loading and the Eulerian fluid velocity in the direction of gravity u_z were inspected:



Droplets accumulate (larger loading) in settling fluid (- - -), whereas rising fluid carries smaller loading (——). This effect is a manifestation of preferential sweeping and is represented more clearly by the smooth DET estimator.

References

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