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# New fuels and new combustion modes:
# A path to zero emissions / high efficiency mobility systems

## EXPERIMENTAL RESEARCH

Laboratorium für Aerothermochemie und Verbrennungssysteme
Aerothermochemistry and Combustion Systems Laboratory

### CHEMICAL ENERGY CARRIERS FOR COMBUSTION IN TRANSPORTATION

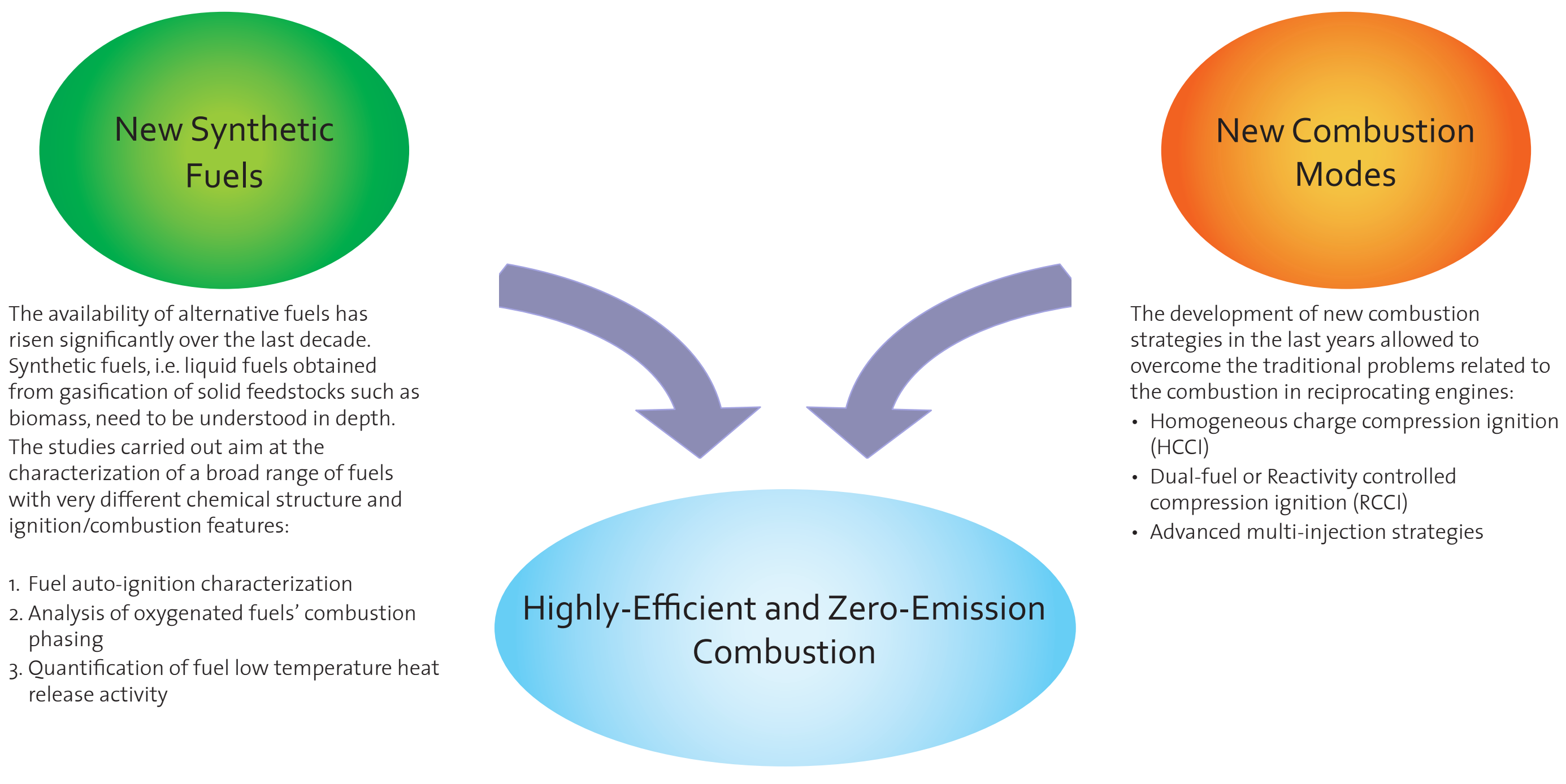
Despite the continuous development of new technologies the combustion process is still at the basis of most of the energy transformation processes employed in mobility systems.

The continuous study devoted by the research community to the understanding and improvement of the combustion process allowed to match from year to year the always more stringent emission standard regulating the Diesel and gasoline automotive engines.

Moreover, this effort brought light on future and promising paths to further develop the combustion systems and approach the target of highly-efficient/zero emission combustion in mobility systems. In particular:

- The employment of new synthetic fuels that feature specific characteristics
- The development of new combustion strategies

In order to make the best of these two concepts and of their combination, much more understanding is still needed. To pursue this goal at LAV we use different experimental equipments as well as advanced computational methods to understand the process from its fundamentals, until its apllication in real engines.



New Synthetic Fuels

New Combustion Modes

Highly-Efficient and Zero-Emission Combustion

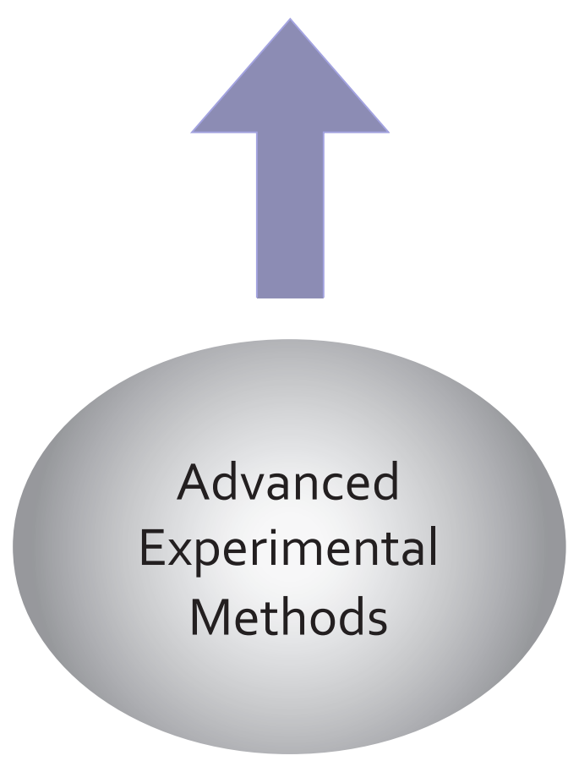
The availability of alternative fuels has risen significantly over the last decade. Synthetic fuels, i.e. liquid fuels obtained from gasification of solid feedstocks such as biomass, need to be understood in depth.

The studies carried out aim at the characterization of a broad range of fuels with very different chemical structure and ignition/combustion features:

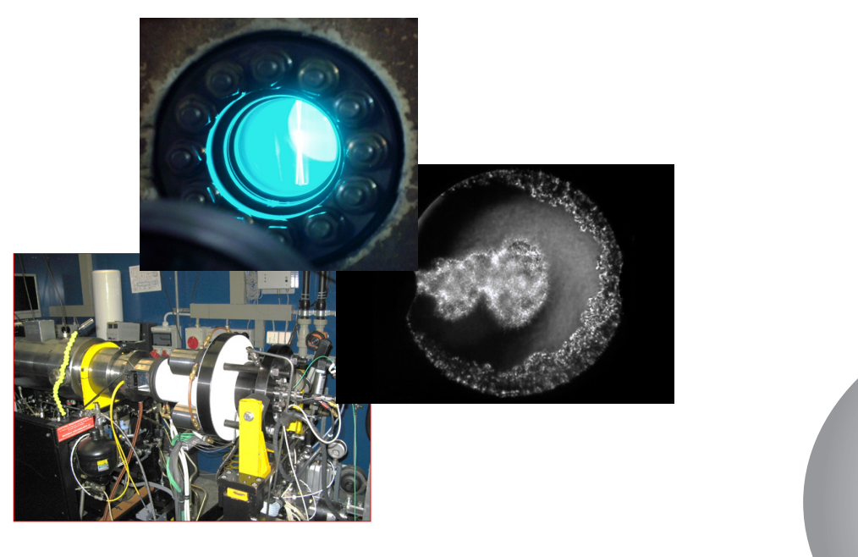
1. Fuel auto-ignition characterization
2. Analysis of oxygenated fuels' combustion phasing
3. Quantification of fuel low temperature heat release activity

The development of new combustion strategies in the last years allowed to overcome the traditional problems related to the combustion in reciprocating engines:

- Homogeneous charge compression ignition (HCCI)
- Dual-fuel or Reactivity controlled compression ignition (RCCI)
- Advanced multi-injection strategies



Advanced Experimental Methods



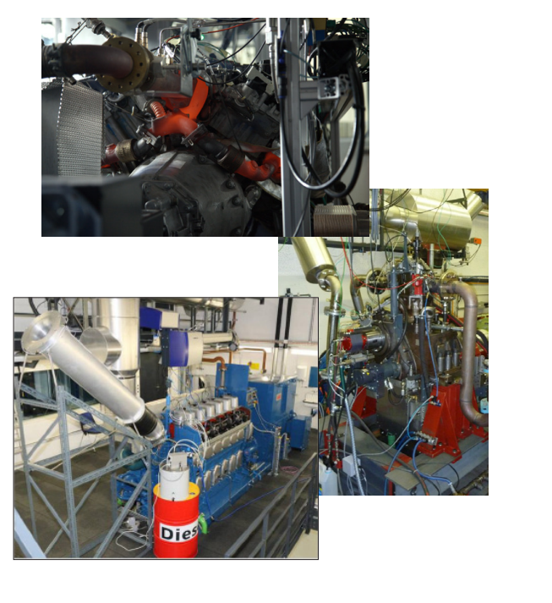
#### OPTICAL DIAGNOSTICS AT REAL ENGINE CONDITIONS

The application of optical diagnostics in a well-controlled environment enable a privileged access to the processes taking place during the combustion.

This fact result in:

- fundamental understanding of the phenomena
- Data to be used for the model validation

A rapid compression expansion machine and a constant volume high pressure vessel are, among other optically accessible facilities, are available in the department and they are intensively employed for the study of the combustion under a wide range of conditions.



#### HIGHLY INSTRUMENTED TEST ENGINE

The final goal of our research is the improvement of the combustion systems, and most of all in the reciprocating combustion engines.

The understanding gained in our research shall be then tested and combined with the complex reality of a real engine.

Engines of a wide range of size are instrumented with a wide number sensor, in order to monitor, as close as possible, the combustion process in the real scenario

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## FUEL MODELLING FOR HCCI APPLICATIONS

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### INTRODUCTION

The interest on the HCCI, especially in regard to Diesel-fuels occurred in the mid-90s. The capability of the process to be run with various fuels, in conjunction with the ability to produce synthetic fuels "tailored" to the needs of the HCCI process, renders the fuel itself an important parameter for the development of a controlling strategy. Towards this goal, the detailed knowledge of the auto-ignition behavior of practical and alternative fuels under different operating conditions is necessary.

An optically accessible Rapid Compression Expansion Machine (RCEM) has been used to investigate the homogeneous auto-ignition of different candidate fuels for Homogenous Charge Compression Ignition (HCCI) combustion.

An empirical, three-stage, Arrhenius-typeignition delay model, parameterized on shock tube data, was found to be applicable also in a transient, engine-relevant environment.

The pressure rise due to cool-flame heat release, which is crucial for the induction of main ignition, have been investigated with regard to operating parameters. Finally, a simplified cool-flame heat release model is proposed, that is mathematically independent from the three-stage ignition delay model.

### EXPERIMENTAL SETUP: THE RCEM

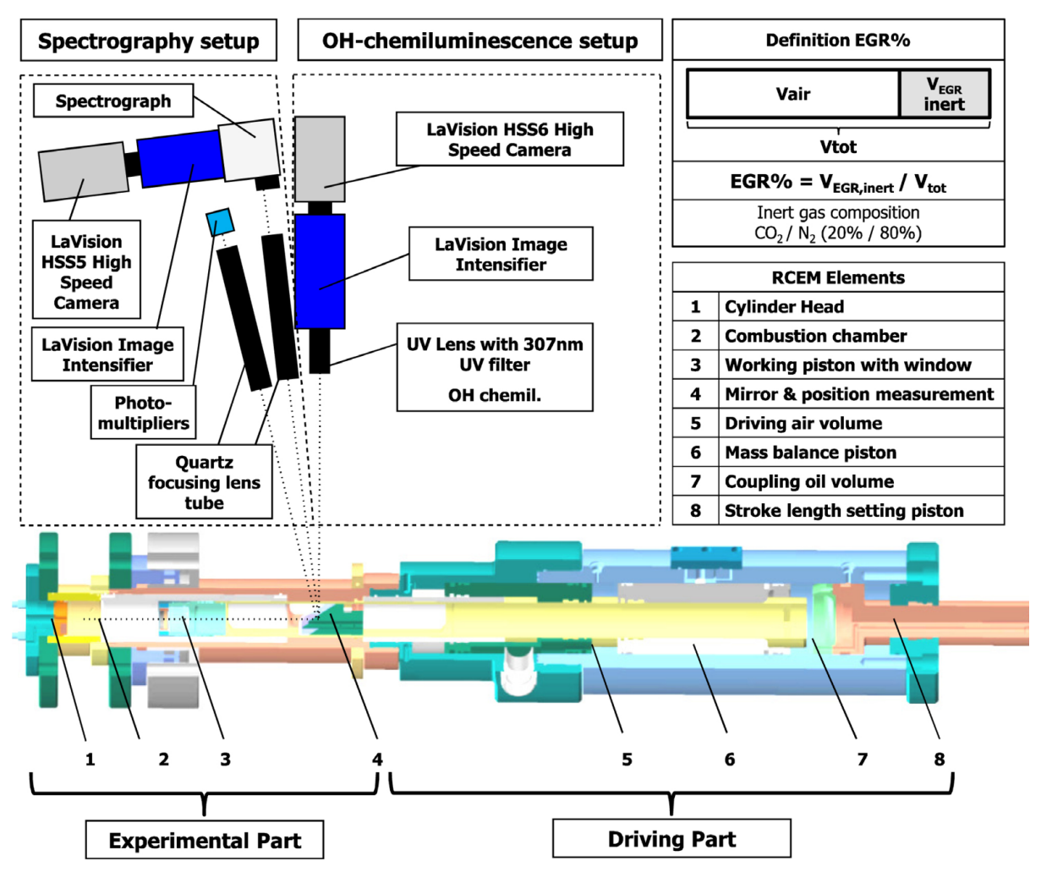

*Figure 1: Rapid compression expansion machine and optical setup.*

The RCEM is a highly flexible free-floating piston test rig (Figure 1). Excellent optical access is provided together with the independent setting of operating parameters, such as compression ratio, charge initial pressure and temperature. A transparent virtually flat piston was utilized in the current work. A fully heated combustion chamber provides a homogeneous, steady-state, pre-compression temperature distribution, which was assessed with dedicated experiments.

The fuel was delivered directly into the combustion chamber during the cylinder loading process, well before the compression start, ensuring the homogeneity of the mixture.

The ignition of the homogeneouse charge was observed for the different fuels varying different operating conditions:

- Equivalence ratio (from 0.30 to 0.85)
- EGR ratio (from 0% to 50%)
- Initial charge temperature (from 110°C to 160°C)

| Fuel | - | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
|---|---|---|---|---|---|---|
| Density [25 °C] | kg/m³ | 683 | 734.9 | 687.3 | 728.1 | [illegible] |
| Cetane Number | - | 56 | 48.2 | 47.3 | 33.4 | 33 |
| C/H-ratio | - | 0.44 | 0.47 | 0.44 | 0.46 | 0.44 |
| Lower Heating Value | MJ/kg | 44.57 | 44.23 | 44.5 | 44.37 | 44.4 |
| Composition* | | | | | | |
| Hexane - C6H14 | wt% | - | - | - | [illegible] | - |
| Heptane - C7H16 | wt% | 100 | [illegible] | 72 | [illegible] | 47 |
| Octane - C8H18 | wt% | - | 7.7/7.3 | 28 | 2.1/24.7 | 53 |
| Nonane - C9H20 | wt% | - | 20/0 | - | 1.5/0 | - |
| Decane - C10H22 | wt% | - | 3.2/0 | - | - | - |
| Cyclo-alkane | wt% | - | 46.7 | - | 29.3 | - |

### OPTICAL SETUP AND MEASUREMENTS

As shown in *Figure 1* many diagnostics were performed during the tests. The combustion event was studied measuring the pressure evolution within the chamber, but also analyzing the spectrum of the light emitted during the process through a high-speed spectrography and through differents photomultipliers filtering at different wave length.

Moreover, high-speed OH* chemiluminescence imaging (65 kfps) was performed in order to study together the temporal and spatial evolution of the ignition.

### FUEL IGNITION MODELING AND ANALYSIS

An empirical, three-stage, Arrhenius-type ignition delay model, parameterized on shock tube data, was found to be suitable for the evaluation of ignition delay in HCCI applications. It allows the computation of both LTR and HTR ignition delays. Through a knock-integral method the ignition delay was computed by integration on pressure/temperature trace.

A cool-flame heat release model allows for the evaluation of the cool-flame heat release profile as a function of the operating condition parameters, such as temperature, equivalence ratio and EGR rate.

The combined cool-flame heat release / 3-Arrhenius model has found to be capable of predicting accurately both first and second stage ignition delay.

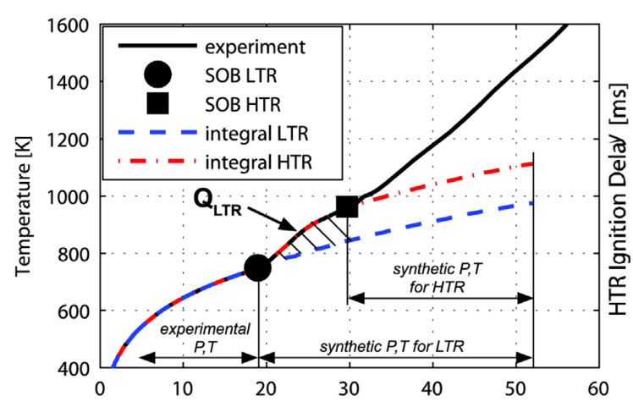

*Figure 2: Cool flame model results: the new synthetic pressure trace is obtained by the calculation of the heat release during the cool flames*

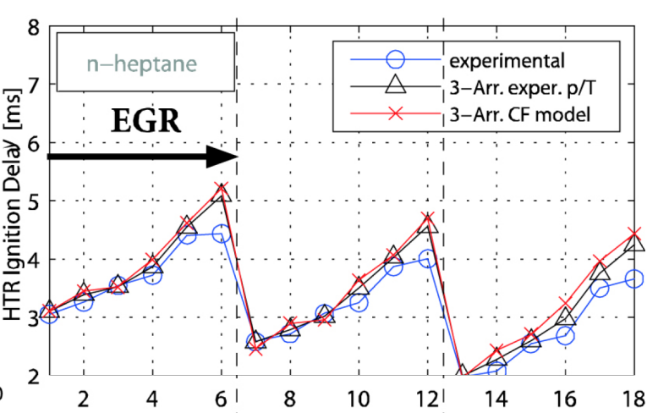

*Figure 3: Comparison between experimental and model predictions for n-heptane.*

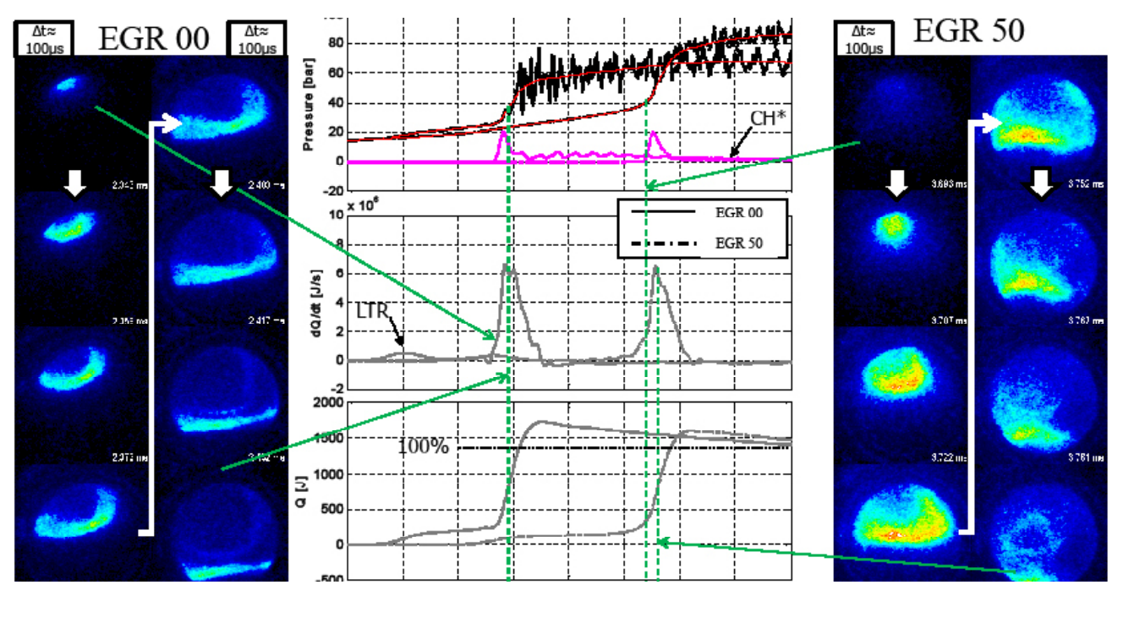

*Figure 4: OH high speed imaging at different test conditions and comparison to the pressure in the chamber and the calculated heat release.*

The high speed chemiluminescence images allowed to identify a propagating autoignition front that developes in a specific position and spread to the entire chamber.

Even though the velocity at which the ignition propagates through the chamber seems to be strictly related to the speed of sound in the media, the features of the flame front are affected by the test conditions (i.e. EGR rate).

### RELATED PUBBLICATIONS

[1] Mitakos, D. et al., „Ignition Delays of Different Homogeneous Fuel-air Mixtures in a Rapid Compression Expansion Machine and Comparison with a 3-Stage-ignition Model Parameterized on Shock Tube Data," SAE Int. J. Engines 6(4):1934-1952, 2013
[2] Mitakos, D., Blomberg, C., Wright, Y., Obrecht, P. et al., „Integration of a Cool-Flame Heat Release Rate Model into a 3-Stage Ignition Model for HCCI Applications and Different Fuels," SAE Technical Paper 2014-01-1268, 2014

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## CLEAN DIESEL COMBUSTION RESEARCH

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### INTRODUCTION

The increasing demand for mobility and transportation, as well as increasingly stringent emission regulations worldwide, have driven the development of internal combustion engines mainly towards the reduction of gaseous and particulate emissions, while enhancing the overall efficiency. For the specific application of combustion in diesel engines, the main focus has been on the reduction of exhaust NOx and particulate matter, while maintaining or even improving fuel economy.

A promising technology to contribute to further NOx reduction is closing the intake valve well before bottom dead centre, so called Miller valve timing. This approach partially shifts the compression work from the piston compression stroke to the charging system, allowing to reject this part of the generated compression heat via inter- and after-cooler. The result is a reduction of the charge air temperature before fuel injection and consequently a reduced cycle temperature, which significantly reduces the thermal NOx formation during and after combustion. To counterbalance the power output losses resulting from the early valve closure, high boost pressures are required. However, some recent investigations have shown a minimum in NOx emissions at certain in-cylinder temperatures followed by an increase of emissions with further reduction of charge temperature (increasing Miller degree). The same effect has been observed for continuous retardation of SOI, also leading to longer ignition delays. This behaviour is unexpected, as it goes against the steady trend of the adiabatic flame temperature, which has continuously been reported in literature to strongly correlate with NOx emissions in diesel engines.

### MTU-396 SINGLE CYLINDER RESEARCH ENGINE

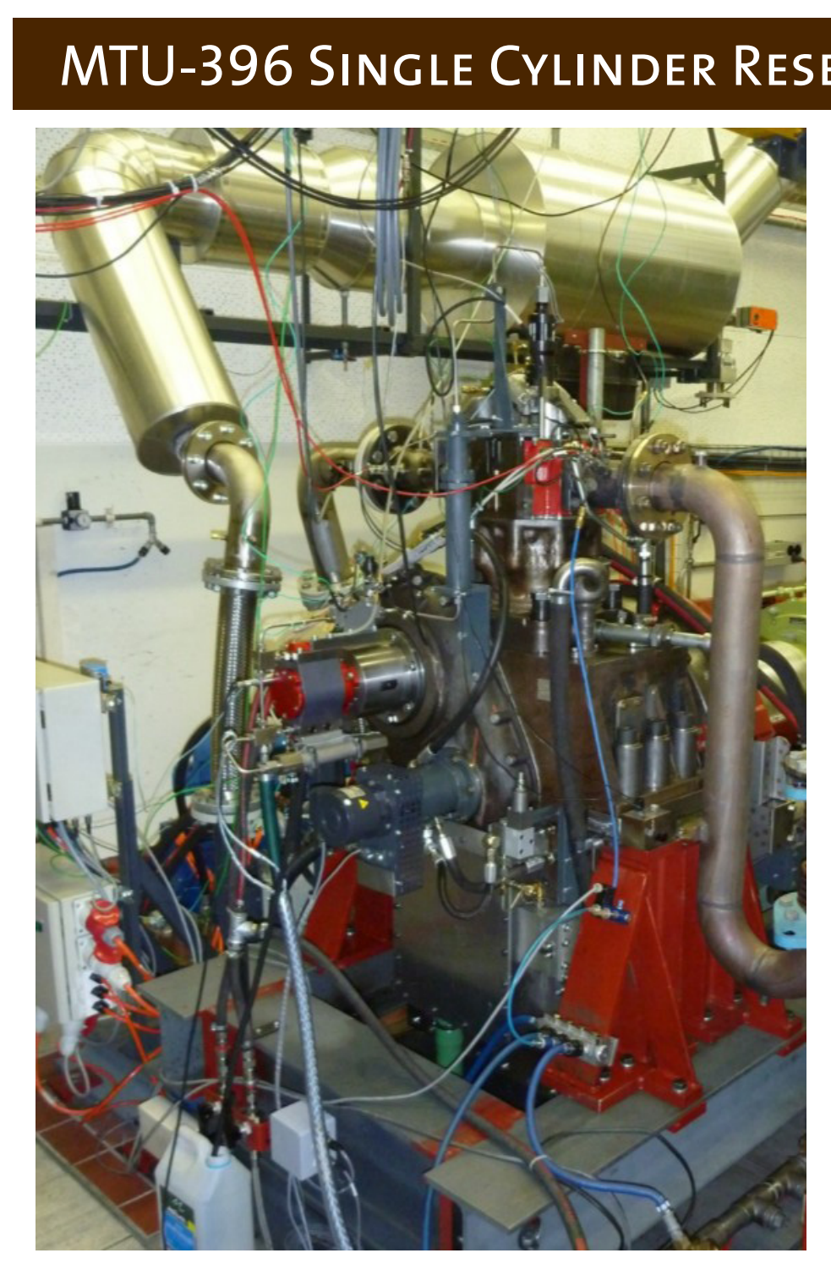

*Figure 1: MTU 396 engine testbench at LAV.*

The MTU-396 single cylinder engine at LAV is equipped with state of the art measurement equipment and offers the possibility to study the combustion process isolated from environmental influences. The intake pressure and temperature can be set to the desired boundary condition, the common rail injector is capable to handle pressures up to 1600 bar and the exhaust can be throttled to rise the pressure to the desired value. Together with the fully variable EGR, a wide range of experiments can be covered. Additionally the engine can be motored. A special feature of this test bench is the modified cylinder head, where one exhaust valve is replaced by a flexible access to the combustion chamber. This gives opportunities to use pyrometry or direct gas sampling techniques at this test bench.

| | |
|---|---|
| **Engine type** | 4-stroke, 3 valves, DI diesel engine, EGR |
| Intake | conditioning of $p_{IN}$ and $T_{IN}$ |
| Exhaust | variable setting for $p_{EX}$ |
| Bore x Stroke | 165 mm x 185 mm |
| Compression ratio | 13.77 |
| max. BMEP | 20 bar |
| max. cyl. pressure | 155 bar |
| max. inj. pressure | 1600 bar |
| Special feature | 3 valves cylinder head for modular access to combustion chamber |

*Table 1: Configuration of MTU 396 single cylinder engine.*

#### EXTREME MILLER TIMING

To study the effects of reduced charge air temperature on NOx emissions, the engine is equipped with early intake valve closure (see Fig. 2). It is apparent that in case of Miller timing the valve not only closes well before Bottom Dead Center (BDC), but also the maximum valve lift is drastically reduced compared to the Baseline case. The exhaust valve timing remained unchanged.

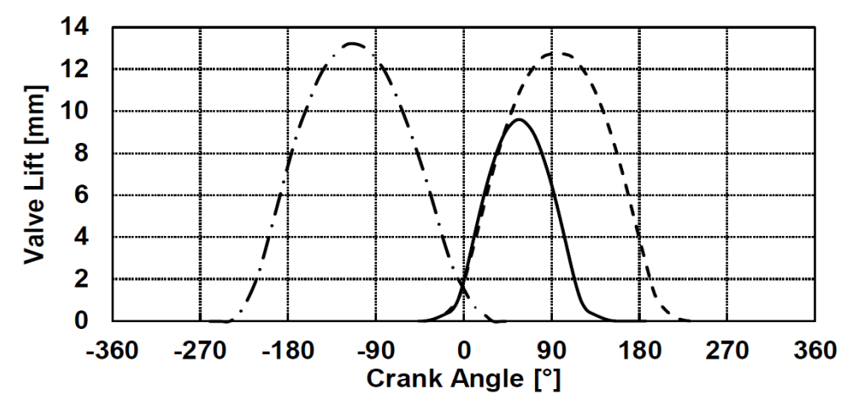

*Figure 2: Baseline and extreme Miller valve timing.*

### EXTENDING THE POTENTIAL OF MILLER TIMING TO REDUCE NOx EMISSIONS

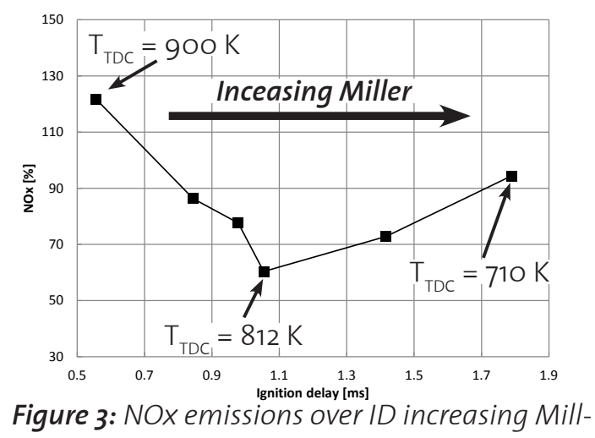

*Figure 3: NOx emissions over ID increasing Miller degree at constant SFC, injection pressure and air-to-fuel ratio [1].*

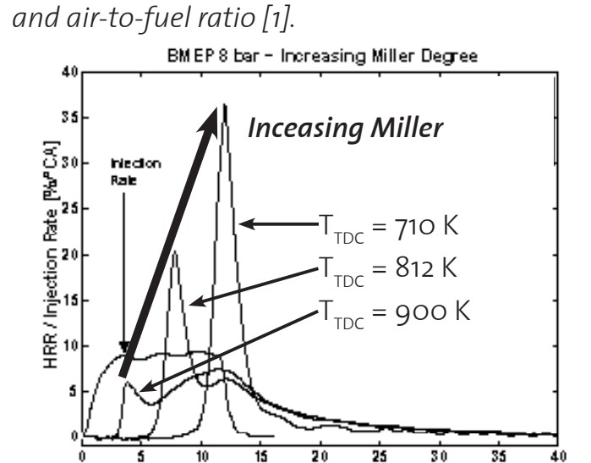

*Figure 4: Effect of increasing Miller degree at low load operating conditions on Heat Release Rate [1].*

Experiments on a heavy-duty, medium speed, single cylinder DI Diesel engine with a gradual reduction of TDC temperature (i.e. increasing Miller degree, prolongue ignition delays) have shown that the NOx-SFC trade-off is improved for moderate Miller degrees (see fig. 3). The NOx emission values are normalized, with 100% corresponding to IMO Tier II emission levels for a medium speed Diesel engine. However, similarly to reports from literature, at some point, the trend is reversed and NOx emissions increase with further temperature reduction. This has been observed for extreme Miller timing and cold intake conditions

The NOx emissions correlate with the relative amount of premixed combustion, which increased monotonically with increasing Miller degree (see fig. 4).

The application of pilot injection in combination with extreme Miller timing shows to counteract the observed trend reversal in NOx emissions encountered at very cold in-cylinder conditions. (see fig. 5). Reductions in NOx emissions of up to 60% have been attained when comparing emissions from cases with single and pilot injection at constant extreme Miller operating conditions.

It is shown that the use of Miller degree for NOx reduction can be extended to lower loads and more extreme Miller degrees with the introduction of pilot injections

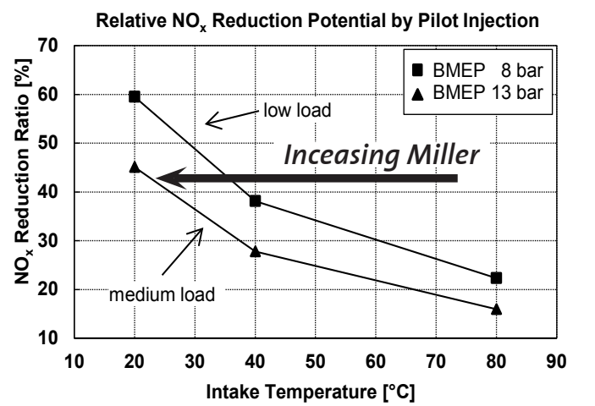

*Figure 5: Potetnial of NOx reduction by applying splitting the injection (Pilot+Main) for extreme Miller timing [1].*

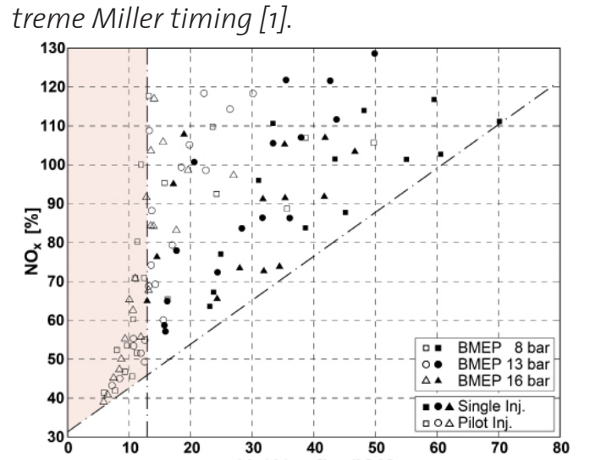

*Figure 5: NOx versus peak pressure rising rate at extreme Miller timing for constant global lambda, different loads and main SOI. [1].*

### REFERENCES

[1] Brückner, C., Kyrtatos, P., Boulouchos, K., "Extending the NOx Reduction Potential with Miller Valve Timing using Pilot Fuel Injection on a Heavy-Duty Diesel Engine," SAE Technical Paper 2014-01-2632, 2014.

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## DUAL FUEL IGNITION

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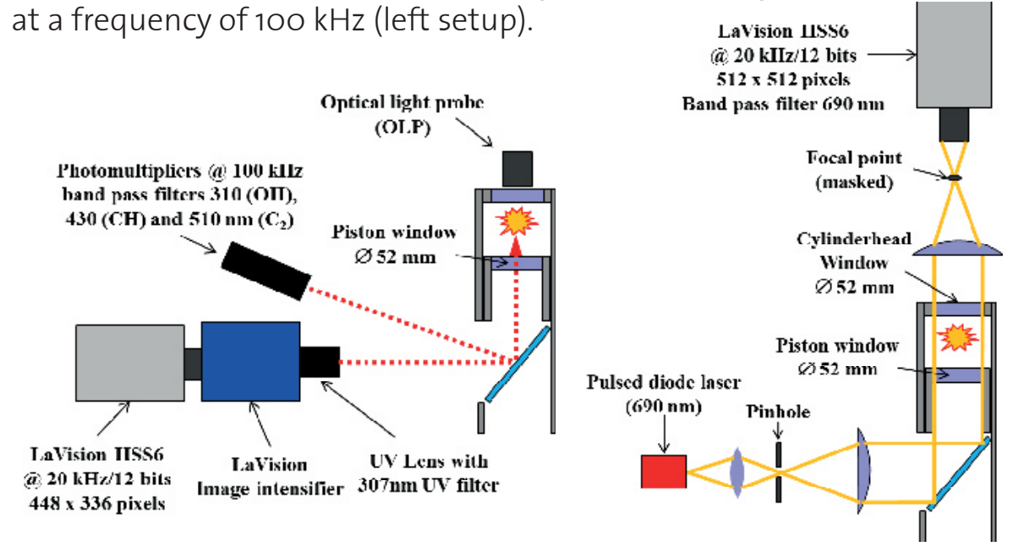
### PILOT IGNITION IN LEAN BURN GAS ENGINES

#### MOTIVATION

Natural gas as fuel for engines has gained significant importance in recent years due to its widespread availability and potential for emission reduction such as NOx and particulate matter. Additionally, methane as the main component of natural gas combines a high research octane number with a low C/H ratio, therefore allowing for simultaneous CO2 emission reduction and increase in engine thermal efficiency. Lower combustion temperatures due to lean burn operation, Miller/Atkinson valve timings and/or EGR lead to a lower knock tendency and hence allow for a higher compression ratio or boost pressure level. All these measures however lead to adverse conditions for the initiation of the combustion process and slower flame propagation which can lead to combustion instabilities, incomplete combustion or misfire. To overcome these effects, ignition systems which provide sufficient ignition energy, fast inflammation and stable combustion are required such as pilot ignition. While most studies found in literature focus on engine performance, fundamental experimental data is sparse [1].

#### OPTICAL DIAGNOSTICS

The optical accessibility through the piston window and the cylinder head window (d=52 mm) allows for different optical measurement systems. An intensified high speed camera (LaVision HSS6) equipped with a 307 nm band-pass filter recorded pictures of the OH chemiluminescence at a frequency of 20-30 kHz during ignition and combustion. An optical light probe (OLP) for multi-color pyrometry can be mounted additionally to the photomultiplier tubes recording the total UV light emitted by the energized OH, CH and C2 radicals at a frequency of 100 kHz (left setup).



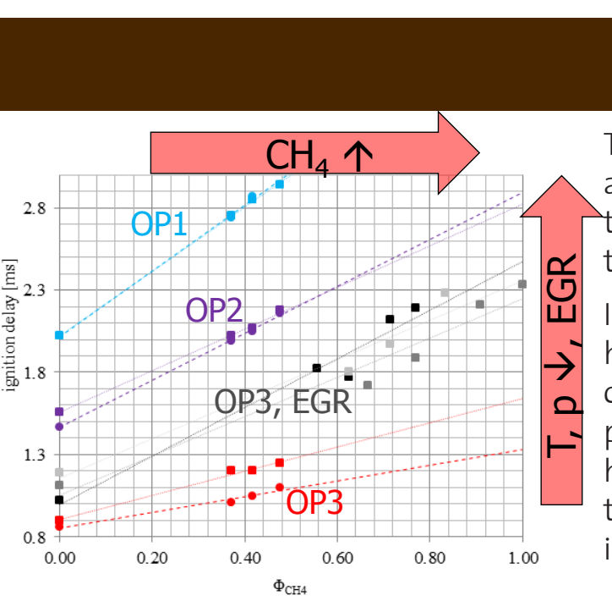
Also, reactive high speed schlieren imaging can be performed (right setup). A collimated light beam originating from a pulsed diode laser unit is sent through the combustion chamber for visualization of changes in refractive indices originating representing density gradiens arising from spray vapor phase evolution, ignition spots and premixed flame propagation.

#### "ENGINE" OPERATING CONDITIONS

Three p/T combinations were assessed, corresponding to engine operating conditions achieved with Miller/Atkinson valve timings (motored conditions) [1].

The conditions at the respective injection timings were chosen according to the engine experiments, leading to different p/T combinations at start of injection. A production grade solenoid actuated multistream injector with 6 nozzle orifices was used for the Diesel pilot. A combination of 20% CO2 and 80% N2 represents the EGR gas.

| | Diesel pilot | | |
|---|---|---|---|
| | OP1 | OP2 | OP3 |
| T [K] at SOI | 605 | 675 | 720 |
| p [bar] at SOI | 20.3 | 23.8 | 25 |
| $\Phi_{CH4}$ | 0-0.47 | 0-0.47 | 0-1.0 |
| EGR | 0%-20% | 0%-20% | 0%-30% |



The ignition delays increase with increasing amounts of methane, decreasing temperature and pressure and the presence of EGR in the ambient mixture.

Increasing methane equivalence ratios show a higher impact on the ignition delay for "cold" conditions than for higher temperatures and pressures, therefore suggesting that methane has an inhibiting effect on the low temperature reactions leading to high temperature ignition.

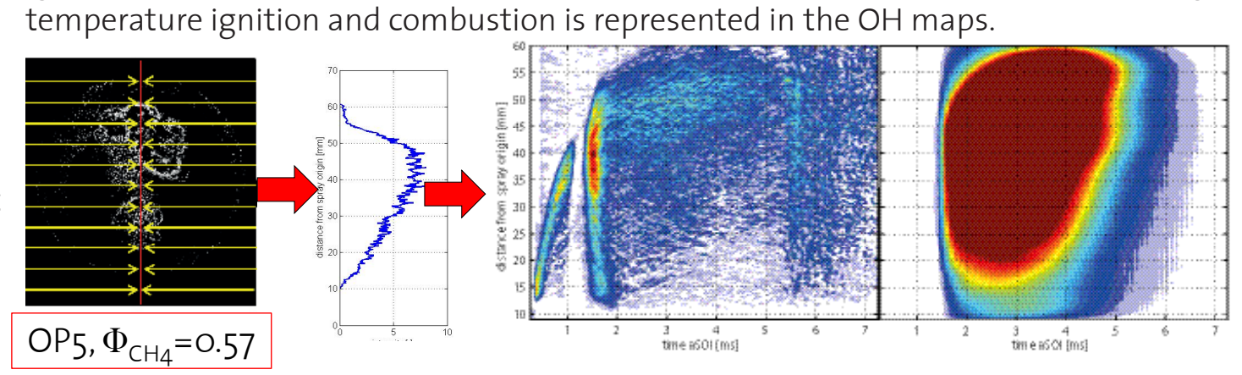
#### "FUNDAMENTAL" OPERATING CONDITIONS

To eliminate the effects of the multi-component diesel fuel, increase the observable domain and generate spray data, a new set of experiments with a modified setup and operating conditions was generated (OP4-OP6).

| | Diesel pilot multi-hole | | | n-heptane pilot single hole | | |
|---|---|---|---|---|---|---|
| | OP1 | OP2 | OP3 | OP4 | OP5 | OP6 |
| T [K] at SOI | 605 | 675 | 720 | 732 | 776 | 823 |
| p [bar] at SOI | 20.3 | 23.8 | 25 | 17.8 | | |
| $\Phi_{CH4}$ | 0-0.47 | 0-0.47 | 0-1.0 | 0-0.66 | 0-1.0 | 0-0.6 |
| EGR | 0%-20% | 0%-20% | 0%-30% | 0% | 0%-20% | 0% |

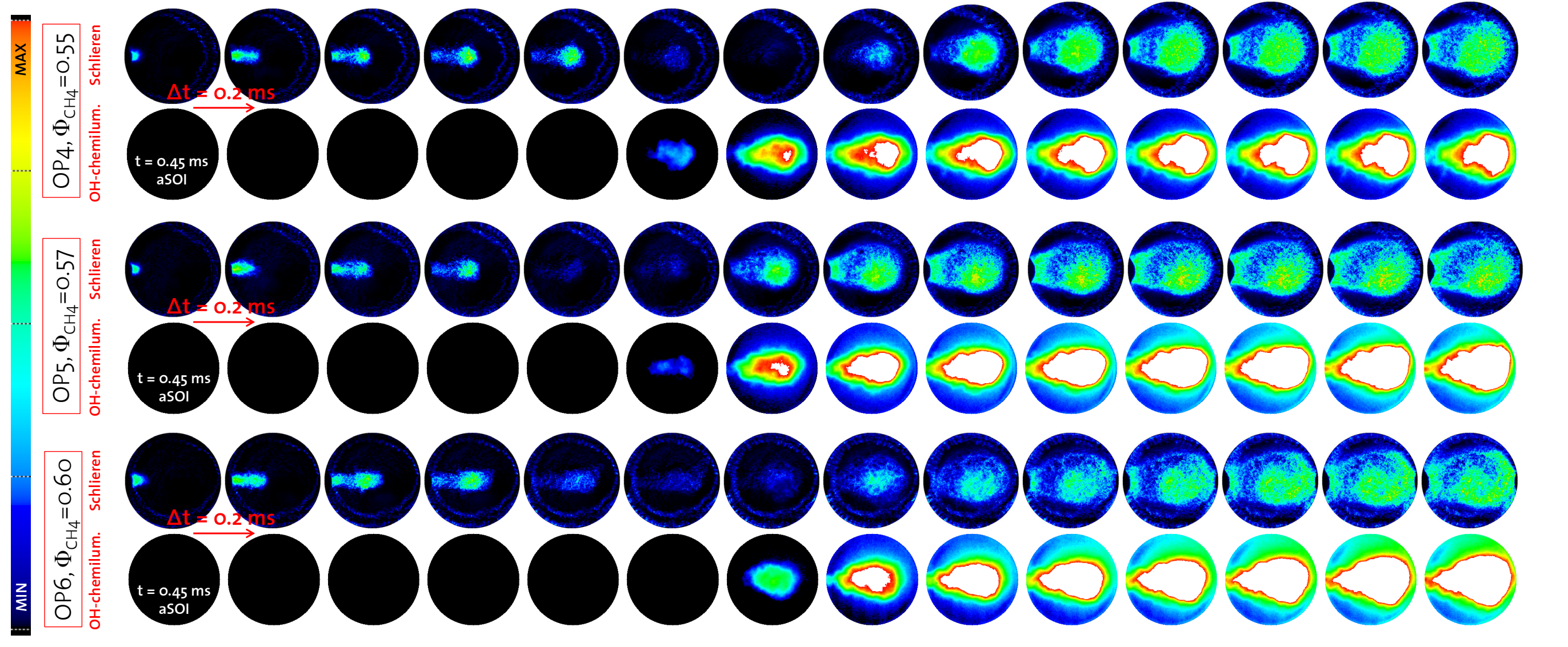
Pilot injection was realized by a single hole injector using n-heptane as the pilot fuel and EGR was chosen to consist of 100% N2. A modified cylinderhead design allows the application of the Schlieren technique to visualize the gaseous and liquid phase of the pilot spray and the additional determination of the premixed flame front.

From both 2D imaging methods (OH chemiluminescence and schlieren), maps of the intensity distribution along the spray axis over time can be generated. Two distinct phases in the schlieren maps are observed, representing pilot vapor phase penetration and combustion. In between, the schlieren signal weakens due to low temperature ignition (density of vapor very close to ambient caused by small temperature rise. High temperature ignition and combustion is represented in the OH maps.



OP5, $\Phi_{CH4}$=0.57

#### "FUNDAMENTAL" EXPERIMENTAL RESULTS



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[2] Schlatter et al., „Experimental Study of Ignition and Combustion Characteristics of a Diesel Pilot Spray in a Lean Premixed Methane/Air Charge using a Rapid Compression Expansion Machine ", SAE technical paper 2012-01-0825, 2012

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