The Year 2016
at the Institute for Combustion Engines
Dear Readers,

Throughout the year, all employees of the Institute for Combustion Engines once more dedicated their work to the research of important scientific projects and the organization of great events. With this review of the year 2016, we invite you to have a look at our work. Please do not hesitate to contact us for further information.

Yours,

Stefan Pischinger, Head of the Institute for Combustion Engines
At the Institute for Combustion Engines (VKA) under the direction of Prof. Dr.-Ing. (USA) Stefan Pischinger, we conduct research on all topics concerning the vehicle powertrain. Our core focus is still the research on conventional combustion engine development like the implementation of innovative engine designs, fundamental research on more efficient combustion processes also in combination with alternative fuels or the improvement of the engine mechanics and aftertreatment systems. Additional research areas including virtual engine development, hybrid powertrains, electromobility as well as fuel cells and mechatronics for combustion engines have strongly grown in the last years and will also play an essential role in the future of our Institute. At any time our research is closely associated with the ongoing development of intelligent methods for test procedures and engine calibration. The Institute for Combustion Engines employs more than 260 scientific, technical and administrative employees as well as student assistants.
The Institute for Combustion Engines (VKA)

263 Employees in total

1 Head of the Institute
Professor Dr.-Ing. (USA) Stefan Pischinger

81 Scientific Employees
Combustion Development
Optical Diagnostics
Exhaust Gas Aftertreatment
Mechanics / Design / Acoustics
Hybrid Systems & Electromobility
Mechatronics / Fuel Cells / Connectivity

69 Student Assistants
Research & Administration

3 Chief Engineers
Research, Operations & Cluster of Excellence TMFB

1 Junior Professor
Mechatronic Systems for Combustion Engines

108 Technical & Administrative Employees
Mechanical Workshops
Test Cell Operation
Electrical / Electronical Workshops
Administration
Secretary
IT

6 Completed Dissertations

179 Completed Master and Bachelor Theses
Since the beginning of 2012, the Fuel Design Center (FDC) is located in Schinkelstraße 8 in Aachen, which is the core area of RWTH Aachen University. The improvement of the institutional structures of the Cluster of Excellence “Tailor-Made Fuels from Biomass” as well as the requirement to create a sustainable, jointly used research center was essential for the founding of FDC. With its structure and orientation, the FDC can be assigned to the profile areas “Mobility & Transport Engineering” (MTE), “Energy, Chemical & Process Engineering (ECPE)” and “Molecular Science & Engineering” (MSE).

The FDC offers more than 1000 m² of laboratory area, among others facilities for detailed investigations of novel fuels under real combustion conditions. In addition to the expansion of the already existing chemistry laboratory, for example a high pressure chamber to visualize injection processes, two single cylinder research engines for thermodynamical examinations and two optical engines were installed.

The “Rapid Compression Machine” (RCM) and the shock tube are operated by the junior research group “Physico-Chemical Fundamentals Of Combustion” (PCFC) under direction of Junior Professor Alexander Heufer. In addition to the employees of PCFC, the research group “Model-Based Fuel Design” (MBFD) of Junior Professor Kai Leonhard is located at FDC, as it offers more than 600 m² of office area. The FDC does not only house these two junior professorships founded by the Cluster of Excellence: the Cluster office and the speaker of the Cluster are also located at the FDC.

Furthermore, the program coordinators of the “Competence Center Power to Fuel” (P2F) and the “Center for Automotive Catalytic Systems Aachen” (ACA) work at FDC. Both project houses are closely related to the topics of the Cluster of Excellence TMFB.

Hence, the FDC offers facilities for interdisciplinary and transdisciplinary work groups as well as guest scientists. Therefore, it essentially contributes to a continuation of the Cluster of Excellence “Tailor-Made Fuels from Biomass” as well as to a structural development of RWTH Aachen University. Of course, the FDC shall be continuously operated as competence center after the end of the second funding line.

Facilities

High Pressure Chamber (HPC):
- Investigation of Diesel injection, mixing and ignition processes
- Thermodynamic conditions up to 1000 K and 140 bar, simultaneous recording of Shadowgraphy and OH*-chemiluminescence

Single Cylinder Research Engines:
- Investigation of spark ignition and compression ignition coupled to special measurement techniques such as infrared spectroscopy and particulate matter sizer
- Peak firing pressures up to 250 bar, combustion chamber with access for optical measurement devices

Optical Engines:
- Investigation of mixture and emission formation
- Diesel-engine geometrically almost identical to the thermodynamic single cylinder Diesel research engine including w-type piston bowl and exhaust gas recirculation
The Cluster of Excellence “Tailor-Made Fuels from Biomass” is funded by the Excellence Initiative by the German Federal and State Governments to promote science and research at German Universities.

Rapid Compression Machine (RCM):
- Measurement of chemical ignition delay time (typical range 2 - 200 ms)
- End of compression pressures higher than 100 bar possible (pressure peaks up to 1000 bar allowed)

Shock Tube (ST):
- Measurement of chemical ignition delay time (typical range 0.1 - 4 ms)
- End of compression pressures higher than 50 bar possible (pressure peaks up to 500 bar allowed)

Gas-Chromatography and Mass Spectroscopy
- Measurement of stable species during ignition process
- Coupled to RCM and ST via rapid sampling system (planned)

ASG AFIDA
- Correlation to EN ISO 5165 (CN determination)
- Sample size 40 ml
- 20 min. per fuel
- Optional: exhaust gas sampling
- Automation possible
- Free parameter selection

Steady State
Mixture Formation

Ignition Tendency and
Combustion Kinetics

Transient Mixture Formation
and Emission Formation

Combustion Characteristics
under Real Operating
Conditions

The Institute for Combustion Engines (VKA)
The “Center for Mobile Propulsion” is an ultra-modern high-quality research center at RWTH Aachen University. Under the direction of Professor Stefan Pischinger from the Institute for Combustion Engines, 16 institutes jointly investigate modern, electrified powertrains for mobile applications in an interdisciplinary approach. The CMP provides a worldwide unique infrastructure. Its spectrum ranges from numerous component test benches, for example for combustion engines, electric motors, traction batteries and transmissions, to complete powertrain test benches to highly modern HiL-test bench environments. Moreover, the CMP offers a sophisticated real-time network which enables the virtual coupling of individual component test benches via an EtherCat connection. By this, researchers can examine interactions of single components for dynamic cases of applications, consider the effects of different powertrain topologies and integrate necessary control strategies of the overall system already in an early project phase. The CMP’s modular set-up supports a consequent research of individual components and control concepts, which can be developed further independently without disregarding the overall system.

Furthermore, the graduate school "Integrated Energy Supply Modules for Roadbound E-Mobility" funded by the German Research Foundation DFG is operating at the CMP. In total, 25 researchers work within the graduate school and explore research topics around the mobile powertrain.
Emission Chassis Dynamometer

In order to strengthen strategically the profile areas “Mobility and Transport Engineering” as well as “Energy, Chemical and Process Engineering” of RWTH Aachen University, the chassis dynamometer of the Institute for Combustion Engines was rebuilt in 2014. This was intended to accommodate the scientific and legal requirements for research infrastructure in the development process of modern passenger car powertrain concepts. Since February 2015, the new emission chassis dynamometer is in operation.

At the moment 4-wheel drive vehicles account for a constant share of 7% of the registered vehicles. However, new powertrain concepts (e.g. hybrid vehicles) will lead to an increasing share and to a greater diversification of possible powertrain concepts.

Consequently, there are powertrain concepts which cannot be investigated with a conventional single axle test bench. In order to meet the future technical requirements, the old single axle dynamometer was replaced by a brand new 4-wheel drive chassis dynamometer. This 4-wheel drive dynamometer consists of two driven and independently operable axles. The front axle is installed fix, while the rear axle is arranged slidable/variable and a wheelbase between 1,800 mm and 4,400 mm can be realized.

The new 4-wheel chassis dynamometer provides a unique research facility, which features an outstanding and trend-setting combination of properties for both R&D tasks and certification tasks.

All the requirements of the different national and international legislations, i.e. for Europe EG70/220 and EG 80/1268, 715/2007 ECE R83, for the USA 40 CFR 86, 1065, for Japan LEV 2000, article 31, Trias 60-4, Trias 5-9, attachment 42, are met with VKA’s new 4-wheel dynamometer. Therefore the new chassis dynamometer allows test cycles for either conventional, 4-wheel drive, hybrid and electric vehicles (e.g. SOC tests) as well as for motorcycles. Besides, vehicle testing with different alternative fuels (ethanol, methanol, LPG and CNG) is possible. Up to a vehicle speed of 250 km/h full load tests, performance measurements and freely configurable test cycles can be realized. By relocating the vaporizer of the modernized test bench, it is possible to test vehicles up to a height of 2.96 m (i.e. MB Sprinter).

Technical Data of the New 4-Wheel Drive Chassis Dynamometer

Max. testing velocity: 250 km/h
Max. power (front axle): 220 kW (short-time overload up to 330 kW)
Max. power (rear axle): 220 kW (short-time overload up to 330 kW)
Max. power (4WD): 440 kW (short-time overload up to 660 kW)
Max. traction force (front axle): 6,400 N
Max. traction force (rear axle): 6,400 N
Max. traction force (4WD): 12,800 N
Mass simulation: 150 kg up to 4,536 kg
Diameter: 48° (1,219,2 mm)
Wheelbase: 1,800 mm to 4,400 mm
Max. axle load: 2,500 kg
Dynamometer width: 700 mm
Inner distance: 900 mm
Outer distance: 2,300 mm

The Institute for Combustion Engines (VKA)
Aldenhoven Testing Center (ATC)

Aldenhoven Testing Center (ATC) is a state-of-the-art interdisciplinary testing center for mobility. It is operated by ATC – Aldenhoven Testing Center of RWTH Aachen University GmbH, a joint venture of Düren county and RWTH Aachen University. ATC was built between 2009 and 2013 on the grounds of the former coal mine Emil Mayrisch in Aldenhoven, Germany, and thus represents an example for successful structural change. All aspects of future challenges and possibilities towards modern mobility can be developed and tested at ATC. The installation was financed by capital of RWTH Aachen University as well as public funding of the State of North Rhine-Westphalia and the European Union (European Regional Development Fund). Besides seven track elements, automotiveGATE enhances ATC as a test and development environment for the future European global navigation satellite system Galileo. All tracks and facilities can be rented out by interested institutions for their research, development and testing towards mobility. Further extensions, in particular for research and development of connected and autonomous driving are currently planned or built.

Further information is available on www.atc-aldenhoven.de.

Galileo

ATC is covered by six terrestrial stations, so called pseudolites, which provide a simulated signal of the currently installed Galileo satellite system. This allows development and testing of application systems already now.

The receiver data can be visualized online or recorded for offline analyses. Recorded data can be played back. For the usage of the system, dedicated Galileo receivers are required. GPS and EGNOS signals as well as augmentation data of the local reference station can be received and used furthermore.
Test Track Elements

Seven test track elements of different kinds provide outstanding conditions for research, development and validation of single systems up to full vehicles. Worldwide exclusive is the coverage with a simulated signal of the European Galileo positioning system. In addition, workshop, office and conference facilities are available while working on site.

Hill Section
The hill sections offer different slopes of 5 %, 12 % and 30 %. The 12 % track can be flooded, allowing hill starts with low friction (µ-low). The gross axle weight can be up to 10 t.

Vehicle Dynamics Area
The vehicle dynamics area is a flat, 210 m diameter circular surface that can be used by passenger cars and trucks. The regular acceleration lane is 400 m long.

Rough Road
To conduct evaluations of ride comfort, five different road surfaces are available on the east straight of the oval circuit: plate bumps, saw tooth profiles, Belgian block as well as two different rough asphalts.

Handling Track
The handling track with various curve radii allows the testing of driveability and chassis in extreme situations. It is 800 m long and 6 m wide with adjacent run-off areas. A 1 g dip allows a dedicated vertical acceleration of the vehicle.

Research Intersection
The research intersection is highly variable for individual test cases concerning the lane setup as well as the positions and configuration of artificial buildings. Connection points for sensors are in short distance to each other.

Oval Circuit
The oval circuit is the central element of the testing center. It provides a total length of approximately 2 km and comprises 3 lanes. Depending on the lane and the curve radius, a lateral force free driving up to 117 km/h is possible. The straights are each 400 m long. Even trucks can use the oval circuit - the gross axle weight can be up to 10 t.

Braking Test Track
The braking test track with different friction linings allows tests to analyze the braking performance of a vehicle. The measuring part of the braking test track has a length of 150 m and comprises an asphalt and a tiles lane. Both lanes can be flooded, allowing µ-split tests.
New in 2016
Changes in the Board of Management

With the end of the year 2015, the former chief engineer Thomas Huth left the Institute for Combustion Engines to address himself to a new task in industry. The Institute for Combustion Engines would like to thank him for his effort as chief engineer and wishes him all the best for his future employment.

The position of chief engineer is taken over by Peter Dittmann. In addition, he is Program Manager of the Project House "Center for Automotive Catalytic Systems Aachen" (ACA) at RWTH Aachen University since 2014. Mr. Dittmann studied Mechanical Engineering at Otto von Guericke University Magdeburg. After finishing his studies in 2011, he worked as research assistant at the Institute for Combustion Engines (VKA) of RWTH Aachen University. In July 2016, he was appointed as chief engineer at the Institute for Combustion Engines.

Moreover, the Board of Management was enforced by Benedikt Heuser. He studied Business Administration and Engineering with a specialization in Mechanical Engineering at RWTH Aachen University. After finishing his studies in 2012, he worked as research assistant at the Institute for Combustion Engines. Since 2015, Mr. Heuser is Chief Operating Officer (COO) of the Cluster of Excellence "Tailor-Made Fuels from Biomass" at RWTH Aachen University.

Conferment of Doctorate

We congratulate our employees on the conferment of their doctorate. We wish them all the best for their future career.

Björn Michael Franzke
Numerical Investigation of the Exhaust-side Gas Processes and the Gas Temperature Measurement of Turbocharged Gasoline Engines
("Numerische Untersuchung des Auslassvorgangs und der Abgastemperaturmessung an turboaufgeladenen Ottomotoren")

Thomas Huth
Influence of an Automatic Transmission with an On-Demand Clutch Actuator and a Model Predictive Control on Vehicle Power Train Efficiency
("Einfluss einer modellprädiktiven Regelung und einer bedarfsgerechten Betätigung eines Automatikgetriebes auf den Antriebsstrangwirkungsgrad")

Dominik Lückmann
Interaction of Double-Entry Turbines with the Internal Combustion Engine
("Interaktion zweiflutiger Turbinen mit dem Verbrennungsmotor")

Jan-Simon Remco Pfluger
Potential of Real-Time Cylinder Pressure Analysis by Using Field Programmable Gate Arrays
("Untersuchung des Optimierungspotentials der Echtzeit-Zylinderdruckauswertung durch Einsatz eines FPGA")

Johannes Christian Ruschhaupt
Systematic Gear Set Synthesis of Layshaft Transmissions
("Systematische Radsatzsynthese von Vorgelegegetrieben")

Christoph Szasz
New Simulation Methodology for the Thermomechanical Analysis of Cast Iron Cylinder Heads
("Neue Simulationsmethodik zur Thermomechanik-Berechnung von Zylinderköpfen aus Gusseisen")
Recent News of Aldenhoven Testing Center (ATC)

Research Intersection Opened

In 2016, the Aldenhoven Testing Center (ATC) was able to extend its facilities: A research intersection complements the testing possibilities.

The research intersection is highly variable for individual test cases. This concerns the lane setup with up to 5 lanes in parallel as well as the positions and configuration of the artificial buildings, which can be created with movable concrete brick elements. Connection points for sensors are in short distance to each other. Positions for traffic lights, traffic signs and street lighting are very flexible.

The research intersection will be extended to a full urban traffic scenario by late 2018. Moreover, further extension of the Car-2-Car and Car-2-X infrastructure is planned for the near future.

1st Aldenhoven Testing Center Business Day and Open Day at “campus aldenhoven”

On May 13th, 2016, the 1st ATC Business Day took place. It especially addressed small and medium-sized enterprises which were able to inform themselves about the various testing possibilities on site. After a welcome reception, the chief executive officers presented the track elements which could be visited afterwards. The ATC Business day will be offered once a year in the future.

In 2016, an Open Day at the surrounding “campus aldenhoven” was connected with the 1st ATC Business Day. During this Open Day, around 100 oldtimers of the 23rd Oldtimer Classics, organized by Düren Motorsport Club, stopped off at the Aldenhoven Testing Center. Moreover, visitors could explore the test track walking or by bike and enjoy entertainment for all age groups. The program was completed by an exhibition from different institutes and companies from the automotive sector.
Welcome to Our New Employees in the Year 2016

Ferenc Aubeck
Research Associate
Hybrid & E-Mobility

Philipp Band
Workshop

Sandra Claassen
Organization and Event Management

Isabelle Hoppe
Research Associate
Gasoline Engines - Thermodynamics

Hermann Kolbe
Research Associate
Software and Testing Solutions

Sung-Yong Lee
Research Associate
Diesel Engines Passenger Cars

Stefan Dohlen
Facility Management

Markus Eisenbarth
Research Associate
Hybrid & E-Mobility

Stefania Esposito
Research Associate
Thermodynamic Simulation & TC Development

Felix Meyer
Workshop

Denis Pendovski
Research Associate
Diesel Engines Passenger Cars

Marcel Picard
Research Associate
Operations - Diesel Engines

Konstantin Etzold
Research Associate
Hybrid & E-Mobility

Felix Falke
Research Associate
Thermodynamic Simulation & TC Development

Christian Granrath
Research Associate
Embedded Software Systems

Hendrik Ruppert
Research Associate
Powertrain and Vehicle NVH

Stefan Sterlepper
Research Associate
Gasoline Engines - Calibration

Günter Wesch
Laboratories
Research at the Institute for Combustion Engines
Engine-in-the-Loop: Closed-Loop Test Bench Control with Real-Time Simulation

The complexity of automobile powertrains grows continuously. At the same time, development time and budget are limited. Shifting development tasks to earlier phases (frontloading) increases the efficiency by utilizing test benches instead of prototype vehicles (road-to-rig approach). Early system verification of powertrain components requires a closed-loop coupling to real-time simulation models, comparable to Hardware-in-the-Loop testing (HiL). Especially engine test benches embedded in realistic simulations (Engine-in-the-Loop, Road-to-Rig) seem to be a promising approach to reducing development efforts.

The accuracy of Engine-in-the-Loop (EiL) tests heavily depends on the used simulation models, parameter calibration and the implementation in the test bench. Time and costs needed for a simulation increase rapidly with a growing level of detail. An economic balance between the simulation’s quality and the necessary efforts needs to be identified. Co-simulation approaches like FMI allow for modular model exchange and reduce the development effort in pure Model-in-the-Loop (MiL) environments. In contrast to an ordinary test bench, the effort to couple real-time simulation with a test bench is also higher. Although EiL has great potential, the increased integration work might outweigh its benefits. The international research project Advanced Co-Simulation Open System Architecture (ACOSAR) emphasizes the issue of great efforts to set up real-time simulation and engine test bench. In one of ACOSAR’s usecases, VKA, dSPACE GmbH and ESI ITI GmbH show the seamless transition from a purely simulated vehicle in a Model-in-the-Loop co-simulation to a heterogeneous testing scenario with an engine test bench linked to real-time models. Both MiL and EiL are calibrated by extensive vehicle measurements on test track, chassis dynamometer and conventional engine test bench.

Based on the vehicle measurements, it is possible to create and parametrize a detailed simulation of the vehicle dynamics. During model development the co-simulation approach is utilized. Co-simulation allows the use of different simulation tools for each sub-system and the execution together within a complete system simulation run by a master simulation tool. With this approach models from domain-specific simulation tools can be integrated in a modular way. In the present work, the sub systems comprise a GT-POWER combustion engine model, a SimulationX transmission model and a dSPACE ASM vehicle dynamics model. The interfaces for offline simulations have to be designed according to the requirements of the intended coupling between real-time simulation and a test bench. The most relevant coupling signals are shown in figure 2. The automated driver in the vehicle simulation starts the engine and generates a desired accelerator pedal position signal. Within the combustion engine model, the pedal position is converted to an effective crankshaft torque and sent to the input shaft of the transmission. Depending on the current state of the transmission, the drive shaft torques are transmitted to the vehicle model and the engine speed is fed back to the engine model. The shaft torques cause the vehicle to move resulting in four different wheel speeds which are sent back to the transmission.
This derived signal structure is used for a seamless transfer from a pure simulation to the transient control of a real engine. All presented signals are preserved, only the GT-POWER engine model is substituted by a real combustion engine on a test bench. In order to run the test bench and the combustion engine, the simulation models are extended with an interface and a simulation of the residual bus.

Figure 3 illustrates the technical structure of the test setup. The models are executed in real-time on a HIL simulator system communicating with the test bench automation system via an EtherCAT fieldbus. Vehicle model and transmission model match their simulation counterparts and run with the same step size (500 µs).

In addition to the EtherCAT communication between the test bench and HIL simulator, a residual CAN bus simulation of the vehicle created by the HIL simulator is connected to the engine control unit. The engine torque demand depends on other vehicle sub-systems, such as the TCU and brake system, which are emulated by the residual bus simulation. The residual bus is generated by an additional model and integrated into the HIL simulator application. All necessary information including brake status, vehicle speed and torque interventions of the transmission are already available and delivered from the detailed vehicle and controller models to the engine control unit by CAN. Besides the driver model’s torque request, other major influences of the engine torque demand are transmission torque interventions during gear changes.

Engine-in-the-Loop enables not only the closed-loop control of the combustion engine, but also a nearly infinite variety of test setups and drive cycles. For example, the user can easily change vehicle parameters like vehicle mass etc. and can directly evaluate the dependency on the real fuel consumption and emissions. NEDC, WLTP and RDE are either driven by the automated driver or a human driver is able to control the EiL with a real steering wheel and accelerator pedal. This flexibility reduces costs and gives the possibility to evaluate different vehicle setups in a very early phase of the development process.

This work is funded by Deutsche Forschungsgemeinschaft (DFG).

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Progress in the Definition and Investigation of Novel Biofuels for Optimized Combustion Engines

Vision and Background of the Project

Since 2007, the Cluster of Excellence “Tailor-Made Fuels from Biomass” (TMFB) has been working on a solution for one of the major challenges that our society is facing today: a rising energy demand and the limited availability of fossil energy resources. For this purpose, researchers from the fields of chemistry, biology, process engineering and mechanical engineering have joined forces in this Cluster of Excellence to develop new alternative fuels from biomass which will not be competing with the food chain. The vision of the cluster is to establish innovative and sustainable processes for the conversion of whole plants into fuels which are tailor-made for novel low-temperature combustion engine processes with high efficiency and low pollutant emissions, paving the way to the 3rd generation of biofuels.

VKA’s Role and Contribution

A tailor-made fuel as aimed for in the cluster of excellence is characterized as a well-defined blend of distinct molecular components with optimized physicochemical properties for future combustion systems, which can be produced by sustainable and economical production processes. Therefore, the effect of the molecular structure on the mixture formation, the combustion and the emission formation needs to be investigated in detail. All aspects are addressed in the research work that is carried out at VKA:

• Spray propagation, mixture formation, ignition and emission formation in a high-pressure chamber
• Mixture formation and emission formation in an optical accessible fired Diesel engine
• Fuel consumption and emission reduction potential of tailor-made fuels in thermodynamic single cylinder engines, both Diesel and gasoline
• Characterization and development of adapted exhaust gas aftertreatment catalysts
• Development of characteristic fuel numbers to describe the engine combustion performance of newly derived biogenic fuels.

The experiments applied in the TMFB activities at VKA shall be explained using the tailor-made fuel 1-octanol (figure 1) as an example. This fuel was derived in the Fuel Design Process, an interdisciplinary methodology that has been developed with complementary groups in the Cluster of Excellence: here, based on pre-defined boundary conditions, new fuel candidates are derived using a model-based, data driven approach.

By setting specific boundary conditions such as the ignition tendency or the boiling behavior, only fuel candidates fulfilling these desired properties are considered. For Diesel type combustion it is well known that a fast mixture formation and high oxygen content enable a significant soot reduction. For this reason a new fuel was aimed for that features increased oxygen content, a moderate self-ignition tendency as well as a low boiling point. The mid-chain alcoholic fuel candidate 1-octanol, which can even be produced in a 2-step synthesis from biomass-based furfural and acetone, perfectly meets the stated requirements and therefore was investigated at VKA.

Pure 1-octanol was already investigated extensively using a single cylinder engine and a high soot reduction potential was observed. However, a complete substitution of fossil fuels by 1-octanol in the near future will not be possible. Furthermore, pure 1-octanol is not compliant with the current EN590 legislation mainly due to its high viscosity and low Cetane number. Therefore, using 1-octanol as blend component is a possible way to utilize its beneficial features. By blending 1-octanol into EN590 Diesel fuel it is possible to take advantage of the soot reduction potential of the biofuel, while simultaneously not sacrifice the limits stated in the EN590. Fuels with 1-octanol contents of 20 % v/v (O20) and 50 % v/v (O50) were investigated. However, only with O20 all critical points of the standard are fulfilled with the Cetane number being at the lower end.

During the single cylinder investigations the O20 blend allowed for a soot reduction of over 60 % compared to Diesel fuel without sacrificing any other emissions. Increasing the 1-octanol content to 50 % the soot emissions decrease further and are 85 % lower than Diesel due to the higher oxygen content and reduced aromatic content. However, since the Cetane number of O50 is considerably lower than that of Diesel fuel, the combustion noise increases due to higher pre-mixing.

Since the results found at the single cylinder engine were very promising, in succession tests have been performed with a series production passenger car as well.

For the vehicle investigations a Mercedes A-Class 220 CDI (W176) was used which is compliant to the current EU-6b legislation without DeNOx system. The vehicle was investigated with Diesel fuel and both blends on a dynamometer during the New European Driving Cycle (NEDC). The results shown are the averaged values from three cold-started NEDC runs.

The results shown are the averaged values from three cold-started NEDC runs.
The engine-out emissions of Diesel and the two blends are displayed in figure 2. It is obvious that the soot emissions decrease strongly with increasing 1-octanol content. They are reduced by more than 85 % for the O50 blend compared to Diesel. This behavior could already be seen during the single cylinder investigations. Furthermore, the NOx emissions decrease slightly with increasing 1-octanol share. One possible explanation could be the 60 % higher enthalpy of vaporization of 1-octanol compared to Diesel. The increased cooling effect of the blends would lead to lower cylinder peak temperatures and therefore reducing the NOx formation. This could also be an explanation for the slightly increased HC and CO emissions.

The engine-out CO2 emissions during NEDC are reduced by up to 4 g for the blends, mainly due to the lower C/H ratio of the fuel. A small fraction of the lower CO2 emissions can also be attributed to the higher amount of unburned hydrocarbons and CO.

With respect to the tail-pipe-emissions (see figure 3), it is obvious that the particulate numbers are reduced by more than 85 % with higher 1-octanol share compared to Diesel fuel. On the downside, however, the longer ignition delay of 1-octanol causes CO-emissions, which are slightly above the limit given by the EU-6b legislation. With engine measures such as higher compression ratio, adjusted fuel injection timings etc., this drawback could easily be overcome.

This work was performed as part of the Cluster of Excellence “Tailor-Made Fuels from Biomass” which is funded by the Excellence Initiative by the German Federal and State Governments to promote science and research at German Universities.
Range Extender Module

The capability of electrical storage with respect to capacity and charging time will not be sufficient in the medium term to offer the accustomed and appreciated flexibility and range of traditional combustion engine driven vehicles. Furthermore, materials required for batteries are globally proportionally rare (in particular lithium). Therefore, it is necessary to extend pure electric drivetrains with a combustion engine module in the near future. Two ways are possible for this: Either the mechanical power of a combustion engine is directly coupled into the drivetrain or a generator with minimized conversion loss is used.

The operation of range extenders offers new degrees of freedom compared to conventional drivetrains. A challenge for range extenders is the excitation of the vehicle body and the noise emissions. Range extender operation should not be noticed by the driver. The focus of research lies not only on noise excitation through the combustion itself, but notably also on new approaches on an air and exhaust system. The unfavorable geometric boundary conditions compared to conventional powertrains exacerbate the problem of charge exchange noise of small range extender engines. Three dimensional and one dimensional simulation of the combustion process and gas exchange enable the determination of the excitation spectrum already in the context of the basic research. A noise level calculation of the generator dependent on speed and load attached to the cooperation of the researchers in matter of the acoustic behavior provide a basis for researching an optimal range extender module.

Different operation regimes for combustion engines in range extender modules have an influence on the pollutant emissions. A detailed modeling of the influence of different technology packages on the exhaust emissions for the complete range of possible operating points allow for a good understanding of the technologies required for a range extender combustion engine. All factors influencing the pollutant emissions have to be taken into account, i.e. the coolant temperature.

Other Research Topics

The research training group covers a lot of different research topics in the field of electromobility. In the field of batteries, the focus is to extend the lifetime of Li-Air batteries. This kind of batteries offers a power density which is in a different order of magnitude than todays’ Li-Ion batteries. This battery technology could increase the driving range of electric vehicles dramatically. Another research topic is power electronics. Novel concepts for DC-DC converters enable the use of low voltage batteries for electric vehicles. An electric vehicle without high-voltage battery requires less isolation effort and it would be cheaper than a vehicle with a high voltage battery.

The increased diversity of drivetrain topologies is a challenge for test bench operation. To increase the flexibility of test benches, research on the real time networking of test benches is conducted in this research training group.

In the field of thermal management the use of the waste heat of the electric drive components is investigated. The heat flux coming from the electric components is significantly lower than the flux from a combustion engine. This requires new heating concepts for electric vehicles.

3rd mobilEM Colloquium

In October 2016, the third mobilEM colloquium took place in the Center for Mobile Propulsion (CMP). Posters and presentations by doctoral candidates delivered insight into current research topics and progress of their work. Presentations by the professors Sauer, De Doncker, Harneyer and Kneer as well as external speakers from the University of Ulm, Bosch, FEV and Hanon Systems enriched the colloquium with expert knowledge.
The “Competence Center Power to Fuel” (P2F) of RWTH Aachen University unites technical specialists for fluctuating renewable energy, electrochemistry, catalysts, synthesis, process engineering, fuel design, combustion engines and life cycle assessment (LCA). Each conversion step from well to wheel is covered by a RWTH professorship and demonstrates its interdisciplinary approach. Because of that, P2F can provide consulting and engineering services to the industry from one hand and acts as a main contact during applications for public funded projects.

The objective of P2F is the identification of synthetic fuels for combustion engines made from renewable electricity under the condition that this is a global process chain optimum beginning from electrolysis and ending at combustion engine. These synthetic fuels are also called e-fuels. On the one hand these e-fuels shall increase engine efficiency and reduce pollutant emissions. On the other hand the production process chain is examined and optimized under consideration of fluctuating renewable energy. In addition, new production approaches are under investigation. All results of these subprocesses converge in the LCA. One particularly promising approach is to produce oxymethylene ethers (OME) from renewable electricity. OME offers the potential to realize a near to zero emission fuel as an alternative for Diesel engines.

In collaboration with Forschungszentrum Jülich and Dechema, RWTH Aachen University has been awarded the contract for the project “Power-to-X” at the German Kopernikus announcement of the German Federal Ministry of Education and Research (BMBF). A total of 62 facilities from industry and science are involved in the project. The aim is to investigate large-scale technical requirements to convert excess electrical energy into fuels and raw materials for the chemical industry. P2F developed the subproject outline “Oxymethylene Ethers: Fuels and Plastics Based on Carbon Dioxide and Hydrogen”. The research topics and project partners are shown in figure 1. The VKA examines mixture formation, executes single cylinder testing and exhaust gas aftertreatment.

The dimethoxymethane (DMM) or OME1 screening of Diesel blends show that even low amounts of OME1 reduce soot drastically and pure OME1 is completely soot free. At 50 % volume fraction the soot-nitric oxide trade-off is nearly eliminated, see figure 2. A 35 % v/v OME1 and 65 % v/v Diesel blend is most promising due to the drastic soot reduction and Cetane number within EN590 limits.

Furthermore, the P2F consortium could be expanded by our new partner, the Institute of Energy and Climate Research (IEK-1) of Forschungszentrum Jülich. IEK-1 is directed by Prof. Dr. Olivier Guillon.

Further information is available here: www.p2f.rwth-aachen.de.
Recent Progress in the Center for Automotive Catalytic Systems Aachen (ACA)

The Catalytic NOX Aftertreatment and its Perspectives

In February 2014, the Center for Automotive Catalytic Systems Aachen (ACA) was founded at RWTH Aachen University. The Project House was initiated by Prof. Pischinger (VKA) to enable interdisciplinary research in the field of catalytic exhaust gas aftertreatment. It was funded by resources of the Institutional Strategy II as part of the Exploratory Research Space (ERS) of RWTH Aachen University.

Currently, ACA unites institutes of the departments of mechanical engineering, physics and chemistry; these are: Institute of Inorganic Chemistry (IAC), Institute for Technical and Macromolecular Chemistry (ITMC), Institute for Combustion Technology (ITV), Institute for Combustion Engines (VKA), Institute of Heat and Mass Transfer (WSA), the Materials Synthesis and Processing group of the Institute of Energy and Climate Research (IEK-1, FZ-Jülich) as well as The Central Facility for Electron Microscopy (GFE). The high grade of interdisciplinarity allows integrated regard of catalytic processes from molecular level up to the macroscopic total system. Thereby, all aspects of the exhaust gas catalysis, from material synthesis to analysis to system integration, can be researched on a multidisciplinary level and holistically optimized.

The necessity of such a holistic consideration becomes clear while regarding the global challenges of the 21st century. Particularly global warming as well as increasing shortage of natural resources should be pointed out. Furthermore, future emission legislation for combustion engines put high requirements on engine and exhaust gas aftertreatment concept through strict pollutant limits and demanding test cycles as well as through CO2 fleet limits respectively combustion engine efficiency targets.

Regardless of engine or vehicle type, the reduction of nitrogen oxide (NO) from lean burn combustion is one key issue for current and future aftertreatment systems. The particular challenge for these exhaust gases is the temporal coexistence of nitrogen oxide (NO and NO2) and excess oxygen (O2). Therefore a reducing agent is necessary to reduce nitrogen oxide to nitrogen. To solve this issue two systems are established in current applications. The SCR system (Selective Catalytic Reduction) uses ammonia as reducing agent. This ammonia is generated from an aqueous urea solution which is injected into the exhaust system. Using a NSC (NOX-Storage-Catalyst) instead the nitrogen oxide is stored for a certain period of time. To reduce this stored nitrogen oxides a short period of rich engine operation is used (combustion under lack of oxygen). Under this conditions the exhaust gas contains nearly no oxygen and higher concentrations of carbon monoxide and unburned hydrocarbons as well as hydrogen. These products of incomplete combustion can be used as reducing agent.

The NOx aftertreatment is one of the main topics of research in the ACA, whereat both systems, SCR and NSC, have to be considered due to that they each provide specific advantages for future challenges. While NOX-Storage-Catalysts reach good efficiencies at low and medium exhaust temperatures, the SCR has nowadays the ability to reach efficiencies greater than 98 % in medium and high temperatures. To reach future challenges it is not only favorable but necessary to combine advantages of both technologies. Within this research some promising commercial systems have been chosen first to investigate the state of the art and to set a reference for further developments. For these investigations the interaction of catalytic material, catalyst performance and system performance in vehicle use is of particular interest.

The performed investigations adapt the real use requirements like temperature and event specific dynamics to a laboratory gas bench that is able to dose all relevant exhaust components with the demanded dynamic (figure 1).

![Figure 1: VKA's 2nd generation Laboratory Gas Bench (LGB)](image)

With this approach small catalyst samples can be investigated regarding storage and desorption under realistic conditions.
In an investigation on the LGB two commercial LNT samples have been compared with regard to their storage and regeneration performance. Therefore two gas mixtures for a lean and a rich condition have been defined based on measurements from the engine test bench. With these gas mixtures a cycling experiment with 5 lean-rich events like it is shown in figure 2 was performed after a preconditioning phase. Out of the experimental data we could determine the storage behavior of the empty system in the first event as well as the storage and regeneration efficiency in a stabilized state in the last cycle.

The zoom in plot on one regeneration (rich) phase as shown on the right in figure 2 provides detailed information on the regeneration process. Based on this we can evaluate the regeneration paths of NO\textsubscript{x} to either the desired N\textsubscript{2}, the undesired N\textsubscript{2}O or the NH\textsubscript{3} which can be desired in combined applications with an NH\textsubscript{3} SCR system. Furthermore we can evaluate the reduction agents that slip through. With these information it is possible to calculate the reduction efficiency and find optimization potential for the material design and system layout.

Combining these performance investigations with a detailed chemical characterization of the samples we could provide a holistic view on the relation between material design, coating structure and catalytic performance.

A first conclusion of ACA’s current work is the awareness that significant improvements in automotive catalysis require a new holistic approach of development across all systems. The establishment of an interdisciplinary team in the project house sets the foundation therefore.

Based on the investigation of the current systems in combination with new materials developed in the perovskite, spinell and zeolithe area and detailed modelling of catalytic reactions ACA designs a new DeNO\textsubscript{x} concept. This concept is expected to show superior performance to the common systems enabled by an intelligent combination of NO\textsubscript{x} storage and SCR functionalities in a combined catalyst.

Using a NSC (NO\textsubscript{x}-Storage-Catalyst) the nitrogen oxide is stored for a certain period of time. To reduce this stored nitrogen oxides a short period of rich engine operation is used (combustion under lack of oxygen). Under this conditions the exhaust gas contains nearly no oxygen and higher concentrations of carbon monoxide and unburned hydrocarbons as well as hydrogen. These products of incomplete combustion can be used as reducing agent. While the reactions of carbon monoxide and hydrogen are well known, the unburned hydrocarbons form a group of various speciations. In former investigations propylene was used as reference substance for this group. Goal of this research work is to investigate different hydrocarbons and defined mixtures.

Since summer 2015, the institutes in the Center for Automotive Catalytic Systems Aachen (ACA) cooperate in a research project with Ford Forschungszentrum Aachen. With regard to the current challenges for DeNO\textsubscript{x} systems due to new regulations for driving cycles and emission limits the aim of this project is to investigate the influence of hydrocarbons on NO\textsubscript{x}-Storage-Catalysts.

**Figure 1: Current challenges and project goal**

<table>
<thead>
<tr>
<th>Challenges</th>
<th>EU6 and post EU6 Legislation</th>
<th>CO\textsubscript{2} targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDE</td>
<td>wide range of driving conditions</td>
<td>increased NO\textsubscript{x} conversion</td>
</tr>
<tr>
<td></td>
<td>reduction in regulated and secondary emissions during regeneration</td>
<td>high efficiency under all conditions</td>
</tr>
</tbody>
</table>

Figure 2: left: LNT cycle experiment
right: Regeneration performance of N-substrates with HC-slip in rich event

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At Ford, engine test bench experiments were used to examine the hydrocarbons that are relevant in rich engine operation. The hydrocarbons that have been defined for the investigations are propylene (C_3H_6), acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6), toluene (C_6H_5CH_3) and n-decane (C_{10}H_{22}).

The project is divided into 5 work packages. In work package 1, the NO\textsubscript{x}-Storage-Catalyst (NSC) is being investigated in bench testing. The hydrocarbons that have been defined for the investigations are propylene (C_3H_6) as reference as well as acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6), toluene (C_6H_5CH_3) and n-decane (C_{10}H_{22}).

In work package 2, the NO\textsubscript{x}, HC and carbon monoxide (CO) conversion of the NSC is being investigated on a laboratory gas test bench. This allows to freely define the temperature and composition of the exhaust gas upstream of the catalyst and thus to investigate the catalyst's performance under different conditions. In work package 2, we try to use a first principle approach for understanding and ultimately ranking the propensity of the different hydrocarbons (HC) used in the conversion of automotive exhaust gases using a catalyst. In work package 3, our aim is to investigate the gas composition inside the catalyst. To do this, we use a flow channel with both an access for gas suction using capillaries and an optical access. The scope of work package 4 is to investigate the extent of coking and the impact of conditions, HC species, HC concentration, temperature as well as duration of rich condition. Detailed investigations on the catalyst's material properties were performed in work package 5.

The scope of work package 1, which was performed at the Institute for Combustion Engines, is to investigate the impact of different hydrocarbons contained in the exhaust gas of a specific Diesel engine – as provided by Ford – on the NO\textsubscript{x}, HC and carbon monoxide (CO) conversion of the NSC. With each of the species a set of experiments was performed with 10 % water (H_2O), 10 % carbon dioxide (CO_2) and nitrogen (N_2) as balance:

Light-off experiments, in which the conversion is investigated as a function of temperature in the range of 100 – 500 °C, are performed with four different gas compositions. Two compositions are representing rich conditions with the HC only and with additionally CO and hydrogen (H_2). Furthermore, two compositions with 12 % O_2 are representing lean conditions, one with nitrogen monoxide (NO) and one with additionally CO.

Lean-rich-cycles have been investigated to simulate engine like operation of the NSC, where the lean phases used the gas composition with NO and CO. For each of the described rich composition separate cycles were performed. The switching from lean to rich occurred at an NO concentration downstream the catalyst of 50 % of the dose value. Additionally, one rich light off and on set of lean-rich-cycles with CO and H_2 are performed with a mix of different HCs consisting.

In a last measuring campaign the oxygen storage capacity of the catalyst was determined in dry conditions.

In figure 2 the gas composition during the rich event at 250 °C (top) and 350 °C (bottom) with CO and H_2 are shown as exemplary results. In the graphs the HC concentrations measured by FTIR are shown, for better comparison normalized to the respective concentration upstream the catalyst (dosed values). For the HC mix the measurements are taken from the flame ionization detector (FID) and normalized to the C_3-equivalent of the dosed HC. It is remarkable that for all HC species except for ethane (C_2H_6) the time trace shows a relatively slow increase, while for ethane the concentration rises rapidly after the beginning of the rich event. At 350 °C most of the HC are completely converted, except for ethane and n-decane.

![Figure 2: HC's in rich event at 250°C and 350°C](image)

The detailed performance evaluation at VKA’s Laboratory Gas Bench (LGB) provides an extensive knowledge about the catalyst behavior and the input for the simulation tasks. In combination of all experimental and simulation data an optimization of catalyst composition and operation shall be achievable.

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Ford RWTH Alliance Dual Scroll

Turbocharging in combination with direct injection and variable valve timing represents the major technology trend in modern gasoline engine concepts for achieving high specific power output with low fuel consumption at the same time. These are base requirements for downsizing and downspeeding, when the engine operates at higher specific loads due to smaller displacement (downsizing) or due to gear ratios forcing the engine to run at lower engine speeds (downspeeding). Beside high specific power output, the low-end-torque performance and the fast acceleration during transients are major key attributes for driving quality providing driver satisfaction and the acceptance for downsized engines.

For 4-cylinder engines this trade-off between high specific power output on the one hand and compelling low-end-torque performance on the other hand can be addressed by separating the cylinders’ exhaust blow-down events. These performance requirements can either be accomplished through different technological strategies (e.g. scroll separation in exhaust manifold or turbine; variable exhaust valve event length) or by increasing the firing distance (3-cylinder grouping in 6-cylinder engines / 3-cylinder engines). Double entry turbines group the cylinders in such a manner that the blow-down gases of subsequent firing cylinders are separated. This leads to lower residual gases and thus an improved knock sensitivity. Double entry turbines are an attractive alternative to complex and expensive charging systems like bi-turbo concepts in e.g. six-cylinder engines for achieving lower residual gases and thus an improved knock sensitivity. Double entry turbines can only be utilized to its full extend by increasing the separation level of twin scroll and dual scroll turbines in single admission is shown in the scroll interaction map (figure 2). A larger separation implies that the pressure in the scroll which shows a lower mass flow rate is less influenced by the inlet conditions in the other scroll. This can lead to a reduction of EGR and pumping losses.

One of the main targets of the presented research project was the derivation of a matching process for double entry turbines. It has been shown that the scroll separation of double entry turbines can only be utilized to its full extend by the engine if the exhaust valve opening event is adapted accordingly. In order to define the exhaust valve lift and event length, a multi-point optimization has to be performed. Figure 3 gives an overview of the derived matching process.

Currently twin scroll turbines represent a well-established design of double entry turbines, whereas dual scroll turbines for passenger cars are still in a prototype and pre-series development phase. A major difference between the two can be highlighted in figure 1. The scroll separation of twin scroll turbines is achieved by a dividing wall which is located in the turbine volute. The mass flow of each scroll is able to access the turbine wheel over its full circumference. In contrast dual scroll turbines have two individual volutes which each access only 180 degree of the wheel. Due to the smaller geometrical interaction area, the dual scroll has a higher separation.

The separation level of twin scroll and dual scroll turbines in single admission is shown in the scroll interaction map (figure 2). A larger separation implies that the pressure in the scroll which shows a lower mass flow rate is less influenced by the inlet conditions in the other scroll. This can lead to a reduction of EGR and pumping losses.

Figure 1: Schematic differentiation of the twin scroll and dual scroll turbine housing designs

Figure 2: Comparison of the scroll separation capabilities of twin scroll and dual scroll turbines within the scroll interaction map

Figure 3: Overview of multi-point matching process for double entry turbines
In a first step, a variation of the exhaust valve event length and turbine size is performed in rated power as well as low-end-torque (LET) operating regions. Target values for the rated power operating point need to be set by means of power output, pumping losses, residual fractions inside the cylinder as well as fuel consumption. In the LET region, the engine speed is varied in addition to the turbine and valve train.

There are several combination of turbine size and exhaust valve event which enable the target power. In a final step, the combinations of exhaust valve event length and turbine size, which satisfy or exceed the set targets at rated power, are evaluated and marked inside the two dimensional diagram. Overlaying the resulting surface with the results at LET reveals the point optimum LET operating point.

In order to quantify a possible benefit of the dual scroll turbine design on the engine’s LET performance, the matching was conducted for the two turbine types on a 2.0l four cylinder gasoline engine with direct injection. Table 1 summarizes the main outcome in form of performance parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Twin scroll turbine</th>
<th>Dual scroll turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>LET Speed</td>
<td>1520 1/min</td>
<td>1565 1/min</td>
</tr>
<tr>
<td>Exhaust event length</td>
<td>223 °CA</td>
<td>235 °CA</td>
</tr>
<tr>
<td>(1 mm reference)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine wheel diameter</td>
<td>45.4 mm</td>
<td>42.8 mm</td>
</tr>
</tbody>
</table>

Both turbines are able to satisfy the effective power and pumping losses targets at rated power while the twin scroll turbine allows a slightly earlier LET.

As the wheel of the dual scroll turbine can be designed with a smaller diameter, the current investigations are focused on a transient comparison of the two turbine types. For that purpose, the rotor inertia will be scaled based on VKA’s turbocharger inertia data base and load steps at low engine speeds (n_{max} = 1500 1/min) are carried out. The results will help to confirm the suggestion that the dual scroll turbine will lead to a quicker boost build up.

### Table 1: Overview of matching results for a 2.0l four cylinder gasoline engine

Gasoline engine powertrain development for 2025 and beyond is focused on finding optimal cost solutions by balancing electrification and combustion engine efficiency measures. At the same time, engine and vehicle platform strategies dictate the requirements for the highest specific power levels, with OEMs targeting 200 kW/l and beyond. Besides Miller cycle, cooled exhaust gas recirculation, and variable compression ratio, the injection of water has recently gained increased attention as a promising technology for significant CO2 reduction.

Water injection has attracted increasing interest over the last few years as a way of addressing the following three topics: increases in efficiency, emission reduction by reducing enrichment demand, and performance enhancement. BMW has brought a first small series production vehicle to the market with the M4 GTS, which enables performance enhancement by the injection of water into the intake manifold.

Investigations performed by FEV and VKA over the course of the last two years provide deep insight into the fuel consumption reduction potential of an aggressive engine concept featuring direct water injection combined with the above-mentioned technologies. Such an approach has ideal synergies with the variable compression ratio (VCR). VCR can compensate for higher knock limitations with a lower compression ratio if water injection cannot be used due to a lack of water or at low ambient temperatures. At the same time, a high compression ratio of 14.7 can be maintained up to the highest loads if water injection is possible. This enables the highest partial load operation benefits while preserving low fuel consumption at loads above the ‘sweet spot’ level.

### Water Injection – High Power and High Efficiency Combined

In a first step, investigations were performed on a 400 cm³ single cylinder engine. Here, fuel and water were injected via separate direct injectors. The direct water injection allowed for a high IMEP of more than 22 bar, which is quite contrary to recent trends with the application of the Miller cycle with increased geometric compression ratios and reduced peak torque levels.

A minimum indicated specific fuel consumption (ISFC) of 197 g/kWh was reached with a combination of water injection, the Miller cycle, and cooled EGR. At the same time, fuel consumption below ISFC = 205 g/kWh is achieved in wide areas of the engine map, especially towards lower engine speeds and high loads.
Drive Cycle Simulation

A 4-cylinder engine with a displacement of 1.6 l and a state-of-the-art friction level was selected for subsequent drive cycle simulations in order to understand not only the fuel consumption reduction potential, but also the water consumption for such a concept. The variable compression ratio by way of a 2-stage VCR system, like FEV’s 2-stage con rod, is already considered to be the baseline technology, which features a compression ratio combination of 13 and 9.5. The water injection concept assumes a compression ratio of 14.7 and 10.7. This is considered to be a good compromise — achieving the maximum benefits of water injection while maintaining an acceptable low compression ratio for the cases in which water injection cannot be used. The high efficiency of the water injection concept at high engine load levels allows the application of a shift strategy with a higher degree of downspeeding.

Future Investigations

Further improvement of this direct water injection concept is expected with optimized spray targeting for the water injector. At the same time, the trade-off between fuel and water consumption will be assessed in more detail in further simulations. Moreover, future investigations with advanced ignition systems will depict the additional benefits that can be gained from this combination of technologies.
Alternative Commercial Vehicle Powertrains for Trucks and Buses

“Clean Energy Efficient On-Road Transportation” – ANFAHRT

Within the framework of the project “ANFAHRT”, the Institute for Combustion Engines (VKA) cooperates with Institute for Technical Combustion (ITV) from RWTH Aachen University and Faculty of Energy Technology, Faculty of Aerospace Engineering as well as Faculty of Electrical Engineering and Information Technology from FH Aachen to develop innovative alternative drive systems for commercial vehicles. The research scope extends from the basic topic of the components and their interactions within the powertrain systems to the vehicle behavior and the fleet operation. Results from three VKA work packages are further discussed.

System Optimization of Hybrid Commercial Vehicle Powertrains Based on Design of Experiments

Powertrain components are often designed for a large variety of applications and usage profiles. To specify the powertrain there are different approaches to define component sizes in terms of power, torque or energy capacity. Usually this sizing is determined by fulfilling requirements like energy consumption, maximum velocity, acceleration time or gradability. Also emission legislation has to be fulfilled. Hybrid vehicles, especially hybrid commercial vehicles, are often designed and bought by the fleet operator for their commercial profitability in terms of total cost of ownership (TCO). Most beneficial for the proposed dedicated component definition is the well-defined usage profile of e.g. a medium duty distribution vehicle or a heavy duty long haul truck. Therefore a longitudinal simulation model of a hybrid truck was developed. The powertrain components are scalable by a physical and empirical description of component behavior. This behavior is based on key parameters like maximum power output, peak torque request or desired energy content. The hybrid system control strategy is an equivalent consumption minimization strategy which not only minimizes the energy consumption, but also emissions. One of the base powertrains investigated is shown in figure 1. It shows a parallel positioning of the traction components in a P2 topology. Another layout which is investigated is a series hybrid. To fulfill the need for the profitability analysis not only the components and their behavior are modeled, but also the component costs are calculated within the simulation environment. A cost distribution of the high voltage parts of an example traction system is displayed in figure 2. It shows that the high power Li-ion battery is the most expensive part. With these component costs and the consumables consumption a ΔTCO analysis can be conducted. The base vehicle for comparison is a Diesel powered truck. To determine the component sizing in terms of minimal TCO after a predefined time a design optimization tool is used. As method for the multi-objective optimization problem design of experiments (DOE) was chosen. With this approach the component sizing can be optimized at the same time as the operating strategy parameters. One example was conducted with a 40 t long haul truck on a typical motorway driving cycle from Aachen to Cologne and back. The hybrid system is designed as an add-on and therefore the internal combustion engine, transmission and the aftertreatment are not changed. This vehicle is expected to be operated for 130000 km per year. The optimal size which was defined by the design optimization tool is a 60 kW electric machine and a 5 kWh high power Li-ion battery. In comparison to the conventional truck the TCO-optimized system has initial higher Δ-costs of 19 % after one year. This is caused by the additional electric traction system components, but already includes the benefit of the reduced fuel consumption. After three years the system is profitable due to 6 % of fuel consumption reduction in this specific cycle. A cost benefit of 6 % can be reached after 10 years of operation.

Future studies shall also consider the scaling of the internal combustion engine and exhaust gas aftertreatment system.

Speed Profile Optimization under Speed Limit in Time and Spatial Domain

Among various aspects for electric vehicle control optimization, driving speed profile optimization is a key factor for reducing energy consumption yet not increasing the overall travel time. Optimized vehicle speed can either be supplied to the driver in form of speed advisory, or, more in advance, to the ACC system as input to realize autonomous driving.

As common approach, two dimensional "drive tube" which only considers either the speed limit over distance are widely utilized for driving speed determination. However, the dimension of time, which is also vitally important for timely dependent events such as traffic light status, traffic jam forming-up, etc. are not able to be considered together with the other two dimensions.
With the support of V2X information and on board sensors, dynamic speed limitation in three dimensions (distance, time and velocity) can be generated in real time. Speed limit considers not only static speed limits which can be easily acquired from map data, but also dynamic speed limits generated by, e.g. traffic light, traffic jam, construction sites, etc.

The dynamic speed limit can be utilized as one layer of input to the vehicle controller, together with other layers of inputs such as predicted route including elevation information and temperature information from map data, etc., to generate an optimized speed profile in the optimization layer. The optimization is conducted with the algorithm "Dynamic Programming", which is well proofed in the field of automotive energy management, yet is re-defined for the new application with the dynamic 3-D speed limit.

To validate the concept, a test drive along a selected inner city drive was conducted with an electric vehicle as baseline. Afterwards, optimized speed profile was offline calculated with the similar boundary conditions. As can be seen in figure 3, both the baseline profile and the optimized profile were shown under the same 3-D speed limits. Both speed profiles were reproduced with the same vehicle on the test track. As shown in figure 4, energy consumption from the real world measurement showed 7.3% energy consumption reduction while keeping the same travel time.

As next step, the algorithm will be improved for real time implementation and further test cases and more realistic traffic conditions will be considered.

Considering the Ageing of Lithium-Ion Battery in the Operation Strategy for Hybrid Commercial Vehicles

Hybridization of the drivetrain has drawn more and more attention due to its potential of fuel saving and emission reduction in not only the passenger car sector but also commercial vehicle sector. The lithium ion battery system, as the state-of-the-art electrical energy storage system, is the key component for the hybridization. However, the performance of lithium ion batteries degrades over time due to a number of internal side reactions, the fatigue of the electrode materials as well as other mechanisms. Macroscopically, the aging of a battery can be characterized by the capacity fade and the internal resistance increase. By the end of its lifetime, the battery system can no longer satisfy the vehicle’s requirement due to the inadequate energy or power capability. The longevity is extremely important for large-scale battery systems, for example, those potentially integrated into plug-in hybrid (PHEV) commercial vehicles, where the replacement cost is high and a consistent driving performance throughout its lifetime needs to be guaranteed.

The degradation of a battery has been widely investigated. Although some aging mechanisms are still not fully understood, it is found that rate of aging is influenced by how the battery is used and stored. Several factors such as high charge and discharge rate, deep depth-of-discharge, an extreme state of charge (SOC), extreme temperature, etc. are generally acknowledged to accelerate the battery degradation. In vehicles, these factors are influenced by the onboard operation strategy, in which usually the usable SOC range and the engine turn-on thresholds are defined. However, imposing restrictions on the operation strategy to prolong battery lifetime, will most probably have a negative impact on the vehicles’ fuel economy.
Therefore, we have developed techniques to design operating strategies for hybrid electric commercial vehicles that manage the trade-off between battery health and energy consumption costs, which consists of fuel and electrical energy costs. We pursue this goal by adopting an experimentally validated battery aging model for a light-duty commercial vehicle. The daily trip information is based on logged data from a logistics company. Moreover, the multi-objective optimization problem is solved by using a genetic algorithm. One of the optimization results is shown in figure 6.

![Figure 6: Cost distribution of different operation strategy](image)

As shown in figure 6, through an operation strategy which considers the battery wear, savings up to 12 % could be reached. The battery life prolonged from 4.1 to 15.7 years.

Acknowledgment

Special thanks to Ministerium für Innovation, Wissenschaft und Forschung des Landes Nordrhein-Westfalen for funding the “ANFAHRT”-project under grant 321-8.03.04.03-2012/01.

(Bio-)Methylethers as Alternative Fuels for Bivalent Diesel Engine Operation

In order to limit global warming to below 2 °C the CO₂ emissions have to be drastically reduced until the year 2050. This poses huge challenges especially on the energy and transport sector which rely to a great extent on fossil resources. Therefore, solar, water and wind power generation has to be extended to supply the vast energy demand of modern society. Due to the fluctuating nature of these power sources supply and demand do not always meet and therefore a buffer has to be found to compensate for the overcapacities and shortages. One possibility is to store the energy chemically in liquid carriers, since they are easy to store and have high energy density. In order to produce such a liquid carrier the overcapacities from regenerative electricity are used to produce hydrogen via electrolysis. The hydrogen is then used in combination with a carbon source, ideally CO₂ from the air, to produce a so called e-fuel, which can also be used as transportation fuels.

Within the from the Federal Ministry for Economic Affairs and Energy (BMWi) funded project “xME Diesel” two e-fuels for the compression ignition engine are investigated. These fuels are dimethyl ether (DME, C₂H₆O), which is gaseous, and dimethoxymethane (OME, C₃H₈O₂), which is liquid. Both fuels are linear ethers with no C-C bonds and relatively high oxygen contents. The goal of the project is to characterize both e-fuels and build an optimized combustion system for the bivalent operation of DME and Diesel. Over the course of the project the mixture formation of both fuels will be characterized using a high pressure chamber (HPC) and CFD simulations and the combustion behavior will be assessed in a single-cylinder engine. Furthermore, the combustion system will be optimized using computational tools to achieve the best possible results for DME but also enable bivalency with Diesel for better customer acceptance. After the optimized combustion system is defined a demonstrator vehicle will be built which will be able to run on both fuels, DME and Diesel.

Mixture Formation of E-Fuels

To investigate the mixture formation and the ignition behavior these fuels were tested at the high pressure chamber. The same injectors and fuel systems were used as in the single cylinder but a three-hole nozzle was used to avoid optical interaction of different spray plumes. In case of mixture formation the liquid penetration (LPL) and gaseous penetration (GPL) were calculated out of the measured high-speed videos. It was found out that the mixture formation of OME should perform very well because of the short LPL compared to Diesel. All fuels are compared in figure 1. Concerning ignition OH−-Radiation measurements were performed, to calculate ignition delay and lift of length (LOL). The LOL of OME is very long compared to Diesel which could lead to fail ignitions at low loads in an engine.
In order to obtain further insight into the mixture formation and to validate the injection model for the subsequent computational engine optimization CFD simulations were conducted. In figure 2 GPL and LPL of the high pressure chamber and simulations are presented. Furthermore, a cut plane through the spray showing the n-heptane mass fraction is depicted in comparison with the shadowgraphy images from the high pressure chamber. N-heptane was chosen as surrogate fuel for Diesel and real Diesel fuel is used in the high pressure chamber. One can see that the GPL and LPL as well as the overall spray structure of the simulation are matching the experimental results very well. Merely the overshoot at 0.4 ms is not identical to the experimental findings. This could on one hand be due to the shadowgraphy measuring technique, where it is difficult to distinguish the interface between the gaseous and liquid phase. On the other hand the discrete droplet description of the simulation could lead to a droplet clustering in the beginning of injection due to the strong deceleration of the first droplets which enter the stationary ambient gas phase. This cluster possesses high inertia and would cool down the ambient gas quickly leading to slow evaporation and therefore, the high penetration could be explained. Furthermore, droplet coalescence within the tightly packed cluster might outweigh the break-up, further hindering mixture formation.

Discussion of Engine Results

For the single-cylinder investigations a new cylinder head was derived from the PSA DV5 engine, which will be used for the demonstrator vehicles. The engine has a compression ratio of 16.1 and a displacement of 370 cm³. In order to compensate for the lower net calorific value of OME and DME three different nozzle sizes are investigated. So far Diesel and OME were screened using the series nozzle which is the smallest of all three nozzles.

In the following a comparison of Diesel and OME is discussed with the smallest Nozzle. Figure 3 shows a part load point with n = 1750 min⁻¹ and IMEP = 8.6 bar. In order to compare the fuels, the engine calibration as well as the center of combustion was kept constant for both fuels. The HC- and CO emissions, filter smoke number (FSN) as well as the combustion noise, the relative air fuel ratio and exhaust gas temperature are shown over the indicated specific NOₓ emissions.

As one can see from the filter smoke number Diesel is showing the well-known soot-NOₓ trade-off where a decrease in NOₓ emissions causes an increase of soot. OME is not showing this behavior even at lowest soot emissions and furthermore no soot emissions could be detected with the used measuring devices. This is on one hand due to the very high oxygen content of the fuel, which is providing enough oxygen for a complete oxidation even in zones of insufficient mixture formation. On the other hand the Cetane number of OME is ~25, which is far below the one from Diesel fuel. Therefore, the ignition delay of OME is longer which leads to higher mixture homogenization and hence, less fuel rich zones in which soot can be formed. This however is leading to increased noise emissions which are up to 4 dB higher than Diesel. Furthermore, the molecular structure of OME is suppressing soot formation as well since no C-C bonds are present. This means that in the molecular structure of OME every carbon atom is adjacent to an oxygen atom and therefore CO is predominantly formed instead of free c-atoms or dehydrated carbon chains.
With regard to HC emissions OME is generally showing higher ones compared to Diesel fuel and a strong increase in HC can be seen for relative air fuel ratios below $\lambda_{\text{stoich}} \leq 1.1$ due to the partially fuel rich zones and quenching. This increase can become problematic since in literature it has been reported that OME is predominantly forming formaldehydes close to stoichiometry, which is carcinogenic. This seems reasonable since formaldehyde is usually used in order to synthesize OME from methanol. Furthermore, the exhaust gas temperatures of OME are more than $50 \, ^\circ C$ lower than the ones of Diesel which makes it difficult for catalysts to convert the HC emissions especially at lower loads.

The CO emissions of OME are also slightly higher compared to Diesel, which can be attributed to the lower exhaust gas emissions and therefore less post oxidation.

In figure 4 the pressure trace, normalized burning rate, burned mass fraction as well as the injector current are depicted at indicated NOX emissions of 1 g/kWh. In the pressure trace plot in the top of the figure the very different combustion behavior of both fuels can be seen. First, the different pressures at the end of compression are noticeable. This is due to the higher EGR-rates of OME which are necessary to achieve the same specific NOX emissions which lead to a lower heat capacity ratio and therefore lower pressures. Furthermore, due to the higher enthalpy of vaporization of OME compared to Diesel and the higher mass of injected fuel due to the lower heating value the cooling effect is greater, additionally decreasing the pressure.

In addition, the pressure rise due to combustion starts later and higher peak burning rates are achieved with OME as can be seen from the normalized burning rate. This is caused by the much lower Cetane number of OME and therefore a higher amount of premixed combustion. Besides the rapid pressure rise it can be seen from the injector current, that the closing of the solenoid valve injector is not initiated before more than 25% of the total fuel amount are converted. Therefore due to the hydraulic lag times, fuel is still being injected long after ignition occurred which would generally lead to high soot emissions. This however is not the case with OME due the high oxygen content of the fuel and its beneficial molecular structure without any C-C bonds.

Summary and Outlook

It has been shown that for OME no soot emissions could be detected with the used measuring devices in the investigated load point. This behavior can be attributed to the high oxygen content, low Cetane number and the beneficial molecular structure of the fuel. The low Cetane number however leads to high noise emissions and increased HC and CO emissions, especially close to stoichiometry. Furthermore, the exhaust gas temperatures are drastically reduced by 50 °C which can become challenging for the design of after-treatment systems and the catalyst light off time.

In future investigations the fuel screening will be completed with DME and the piston bowl design as well as the injector nozzle will be optimized for the bivalent operation of DME and Diesel by means of CFD. Additionally, an engine calibration optimization will be done for bivalent operation in order to exploit the whole potential of the novel fuel.

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Figure 3: Emissions, relative air fuel ratio and exhaust gas temperature of OME and Diesel over the indicated specific NOx emissions at part load

Figure 4: Combustion analysis at part load of OME in comparison to Diesel
Knock with EGR at Full Load

Cooled exhaust gas recirculation (EGR) at high engine loads is a promising technology to inhibit knock and thus to increase the fuel economy of gasoline engines. Especially due to the rising load levels in the upcoming driving cycle WLTP and “Real Driving Emissions” (RDE) test procedure this technology may be one key to achieve the legislation limits. Furthermore, full load enrichment can be reduced or even completely avoided if cooled external EGR is applied. Within the research project “Knock with EGR at Full Load” not only the thermodynamic potential of cooled EGR is investigated, but also the effect of EGR composition and its single components on engine knock is evaluated.

Experiments were carried out with a state of the art single-cylinder research engine. The engine features central gasoline direct injection, a variable charge motion port, cam phasers and external cooled low pressure EGR. The compression ratio was set to 11 in order to reflect the trends in current gasoline engine development. As a fuel RON95E10 was selected. The test matrix consists of three different engine speeds and three different intake temperature levels at a constant indicated mean effective pressure of 16 bar. At each operating point the EGR rate was varied. Spark timing was advanced with increased EGR rate in order to evaluate the gain in engine efficiency while maintaining a constant load. A summary of the results is given in figure 1. With rising EGR rate the spark timing can be advanced. However, the combustion process is slowed with rising EGR rate, which is reflected in the increasing heat delay and duration. At all three engine speeds the advanced spark timing is not compensated by the slower combustion and an advanced center of combustion can be achieved. Besides these benefits in efficiency, EGR leads to a significant decrease of engine out NOx emissions due to the reduced temperature during combustion. The reduced flame temperature with EGR leads to earlier quenching of the flame which increases HC emissions.

Next to the benefits of cooled EGR during knock limited operation, EGR has a high potential to reduce full load enrichment. Since the exhaust gas temperatures of a single cylinder engine are difficult to compare to the ones of a multi-cylinder series production engine, a different test procedure was chosen. The engine was operated at 4000 1/min 16 bar IMEP with a relative air-to-fuel ratio of 0.85. The corresponding exhaust gas temperature was measured and set to be the limiting exhaust gas temperature for component protection. After this initial test the EGR rate was stepwise increased and the enrichment reduced in order to achieve the same exhaust gas temperature as the base point. The test bench results are shown in figure 2. The results show clearly that with rising EGR rate enrichment can be reduced. Eventually stoichiometric operation can be achieved with an EGR rate of 20%. However, the center of combustion only changes within the range of 2° CA for the performed investigation. During this specific investigation the reduction of enrichment and increase of EGR lead to a significant slower combustion process. Despite the earlier spark timing no advanced center of combustion can be achieved. Thus the huge gain in engine efficiency is solely achieved by the reduced enrichment. The effect of EGR on the cylinder temperature is however different to the one of enrichment. The evaporation cooling of the excess fuel is leading to a temperature with EGR leads to earlier quenching of the flame which increases HC emissions.

One key motivation of the project is the investigation of the exhaust gas reactive components. Despite many published papers on the comparison of pre and post catalyst extraction, no common opinion has been established yet. Thus the single cylinder engine was equipped with a three way catalyst from a gasoline passenger car. The catalyst was externally heated and the conversion monitored with thermocouple measurements inside the catalyst. Furthermore, the exhaust gas components where measured before and after the catalyst. A dedicated measurement approach was used to compare pre and post catalyst extraction. The engine was operated with identical boundary conditions (as long as possible) between both EGR extraction points. Due to the size of the catalyzed exhaust gas the complete conversion of NOx could be achieved for all conducted measurements. At high EGR rates a complete conversion of HC emissions could not be achieved and thus trace amounts of HC emissions still remain in the catalyzed exhaust gas. The results are shown in figure 3.

Figure 1: Influence of EGR on spark advance, combustion and emissions

Figure 2: Replacement of enrichment with EGR
measurements. At high EGR rates a complete conversion of NOx could be achieved for all conducted conditions (as long as possible) between both EGR after the catalyst. A dedicated measurement approach passenger car. The catalyst was externally heated and...

Center of combustion / °CA

Figure 3: Influence of catalyzed EGR on the center of combustion

For low EGR rates no differences between pre and post catalyst extraction were apparent from the measurement data. First small differences appeared at 15 % EGR rate which indicated a slightly less knock limitation for post catalyst extraction. With even higher EGR rates the spark timing could be further advanced with post catalyst extraction leading to a gain of about 2° CA in center of combustion. A comparison of internal NO concentration in the cylinder gives no clear indication if the reduced knock tendency with post catalyst extraction is connected to the level of NO concentration in the cylinder. Thus the influence of NO was investigated with a dedicated measurement program.

As for the influence of pre and post catalyst extraction, the effect of NO on engine knock is subject of a controversial discussion in literature. Thus measurements with NO addition to the intake charge were performed while running the engine with catalyzed exhaust gas. NO was added prior to the external boosting system in order to achieve a homogeneous mixing with the EGR and air. Measurements where performed with three different EGR rates and an intake NO concentration from 0 to 300 ppm. In order to take the cylinder NO concentration into account CFD simulations of the corresponding operating points were carried out to determine the internal residual gas mass fraction. With the exhaust gas measurement prior to the catalyst the internal NO concentration can be calculated. Finally the total NO concentration is derived with the addition of external NO. With rising EGR rate the internal NO rate is decreasing. The calculated NO concentration in the cylinder due to internal EGR is varying from 100 ppm at 0 % EGR to 20 ppm at 20 % EGR. If NO is added to the intake charge different effects are observed. The results are shown in figure 4.

The mean combustion is not affected by the addition of NO. At 0 % EGR the number of knocking cycles is reduced with the addition of NO. This gives an indication that the knock promoting effect of NO is already saturated at low NO concentrations in the cylinder. At 10 % EGR no big difference between 0 ppm and 100 ppm external NO is observed. With further increase of NO the number of knocking cycles decreases again. At 20 % EGR the number of knocking cycles is drastically increasing at 100 ppm external NO. Again a further increase of external NO reduces the number of knocking cycles. This behavior was confirmed at a second intake temperature.

From measurement results it can be concluded that a maximum knock tendency is observed within the area of 100 ppm cylinder NO concentration. Further increase of cylinder NO concentration leads to a reduction of knocking cycles. These results give a good indication about the different results obtained from literature. Often the internal residual gas mass fraction is unknown and thus the internal cylinder NO concentration cannot be derived from measurement results.

Within the project the colleagues from the Institute for Combustion Technology (ITV) of RWTH Aachen University developed a kinetic mechanism for a gasoline surrogate fuel. This mechanism was used to determine the influence of NO addition on ignition delay times. The results are shown in figure 5. It can be clearly identified that especially the low temperature chemistry is accelerated by the addition of NO. The effect is quickly saturated at 100 ppm NO, which is in line with the test bench results. The knock suppressing effect can be explained if the high temperature regime is investigated more closely. In this area the ignition delay time is increasing with addition of NO. This effect is not saturated up to the investigated range of 1000 ppm NO.

The gathered measurement results are currently used by the project partner IVK of Stuttgart University to develop and validate a knock model for gas exchange simulation. This novel knock model will take the influence of EGR on engine knock into account.

Thus the model will help to develop a high load EGR engine concept with accurate prediction of the EGR influence on the engine knock limit.

The next phase of research at VKA is focusing on 3D-CFD simulation. The measurement results will be investigated with advanced combustion model using the newly developed reaction mechanism for gasoline surrogate fuels. Furthermore, large eddy simulation will be used to take cycle to cycle variation of mixture formation, flame propagation and knock occurrence into account. With these simulation results a further insight into the underlying mechanism of knock occurrence with EGR is expected.
Potential of Valve Train Variabilities on Gas Exchange of Diesel Engines II

The cold start and heating phase of passenger car Diesel engines is essential to achieve today’s emission legislation target. The pollutant emissions HC and CO that are produced in this phase support more than 70 % of the total cycle results, due to the very low conversion efficiency of the exhaust aftertreatment components because of the low temperature level. The future requirements provide a further strengthening of the emission legislation, thus, these phases will become even more important. A fast heat up of the exhaust aftertreatment is aspired without fuel consumption penalties to reduce engine-out emissions efficiently. A variable valve train can be an additional technology to fulfill both requirements on a Diesel engine.

The FVV research project No. 1171 “Potential of Valve Train Variabilities on Gas Exchange of Diesel Engines II” has investigated the potential of valve train variabilities systematically in terms of pollutants and CO₂ emission reduction as well as to support the regeneration and heating behavior on a multi cylinder Diesel engine. The focus has not been only on steady state experiments at a full size laboratory engine but also on transient measurements at a demonstrator vehicle.

In the past, the former FVV research project No. 1027 “Variable effective compression ratio in a Diesel engine” had investigated lots of unconventional valve lift profiles on a single cylinder research engine. Furthermore, the fundamental impact of a variable valve train system had been analyzed on exhaust temperature management and engine-out emission reduction potential. The present research project was able to benefit from the expertise gained from the single cylinder investigations, because promising intake and exhaust cam lobe profiles have been transferred to the multi cylinder engine and different camshafts have been manufactured, a late intake valve open “LIVO”, a late intake valve open + Miller concept “LIVO+Miller” and 2nd cam lobe on exhaust side.

Within the investigations from the first work package, an extended engine speed and load range has been considered for the cycle relevant engine map. The impact of an exhaust cam phaser in combination with different intake cam lobe profiles (Base Max, LIVO, LIVO+Miller) was analyzed on the full size laboratory engine. By means of extended DoE campaigns and their evaluation, suitable VVT operation strategies were defined. In addition to this, the engine coolant temperature has become an important parameter for these measurements to simulate and identify their potentials under cold engine conditions as well. The “LIVO” delivered an improved gas exchange, if the exhaust cam phaser was activated by compensation of the re-compressed residual gas during the pumping loop. A further reduction of the cylinder filling by “LIVO+Miller” has shown a significant increase in the exhaust temperature by 56 K with a slight drawback in fuel consumption of 3 %. From the DoE campaign, it can be seen that a VVT system would not deliver additional advantages to lower engine-out emissions more efficiently at hot engine conditions (90 °C engine coolant temperature). However, the lower the engine coolant temperature is, the more efficient would be a usage of internal EGR. A cycle optimized VVT strategy of “LIVO” has delivered a CO₂ potential of 1 % and reduced HC and CO emissions by around 40 % in parallel. The analysis of a medium engine load at 1750 1/min approved an increased exhaust temperature by 50 K without fuel consumption drawbacks for the variant “LIVO” due to internal EGR only. These investigations provide a clear benefit to use selected VVT strategy during engine cold start and warm up. Figure 1 summarizes the model prediction results for the 1st phase of WLTC and highlights the explained potentials. There, the blue case of variant „Base Max” represents almost a base calibration under cold engine conditions.

![Figure 1: Summary results of the global model prediction of the 1st phase of WLTC](image)

The extracted experience of the full size laboratory engine investigations has been transferred afterwards to a demonstrator vehicle.

The second work package has addressed the VVT strategies in transient test cycles on a roller chassis dynamometer. The analysis has considered ambient temperatures of -7 and 22 °C to demonstrate the potentials of VVT with respect to both the exhaust temperature management and the cold start behavior. Furthermore, a sub-task of these investigations has considered engine modes specifically to Diesel engines, why investigations during DPF regenerations mode were also part of the project. The investigations at 22 °C ambient temperature have shown significant reductions of around 40 % on the pollutant emissions due to an increased exhaust temperature and an improved post oxidation and DOC conversion efficiency, see figure 2.
A “LIVO” in combination with an optimized exhaust cam phasing has provided additional soot reduction at a constant or even lower NOx engine-out emission level besides the reduction in HC and CO emissions. All this has been achieved without any penalty in fuel consumption. The engine heating capability was lowered with the variant “LIVO” due to the improved gas exchange, but reduced the time to raise 50 °C of coolant temperature (-13 °C). This supports the heating of the cylinder head significantly and achieved a maximum heating gradient of 8.8 K/min. The heat transfer is increased by the intake valve train variabilities for the WLTC. By the combination of the three different intake cam lobe profiles with an optimized exhaust cam phasing six promising heating strategies has been initiated. Besides an improved heating of the exhaust line all have reduced the pollutant tailpipe emissions HC (min. -17 %) and CO (min. -9 %), see figure 3.

In the third task, a mean value model has been setup and validated to generate heating strategies by means of valve train variabilities for the WLTC. By the combination of the three different intake cam lobe profiles with an exhaust cam phasing six promising heating strategies has been initiated. Besides an improved heating of the exhaust line all have reduced the pollutant tailpipe emissions HC (min. -17 %) and CO (min. -9 %), see figure 3.

The results have been achieved with some moderate CO2 deterioration of max. 2.3 %. Thus, five of them were able to drop the pollutant emissions below the EU6b legislation limit. The heating potentials have been analyze by the time to achieve particular temperature thresholds. Hence, a temperature of 180 °C upstream the DOC has been achieved after 14 s (faster by 5 s compared to the baseline) with strategy 2, 4 and 6. Besides a faster heat up of the exhaust system all strategies have also realized an increased exhaust temperature level upstream and downstream the DOC. This could support a more efficient operation of possible aftertreatment components for DeNOx, such as LNT or SDPF.

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Investigation of Pre-Ignition Characteristics of Different Fuel Components

The combination of direct fuel injection, downsizing and turbocharging is the established solution for fulfilling fuel consumption regulation in modern gasoline engines. However, novel fuels with biogenic components (ethanol, ETBE etc.) as well as increased degrees of downsizing introduce new challenges in terms of abnormal combustion, which are not covered by existing octane ratings such as the Research Octane Number (RON) and the Motor Octane Number (MON).

These combustion irregularities can originate from different sources. In the former FVV research project M1059 “Fuel characteristic numbers biofuels” an experimental procedure for the determination of a surface-ignition number and a gas phase auto-ignition number based on a single cylinder research engine (SCE) was proposed. This proposal was derived from experimental and numerical investigations and covers gasoline blend fuels containing bio-ethanol and further alcoholic components. However, the introduction of an innovative modern research engine procedure into the quality control system of oil refineries is unrealistic. The most promising alternative is a measurement procedure, which can be conducted on a Cooperative Fuel Research (CFR) engine, since these aggregates are the base for RON and MON determination and thus, are already part of the oil refinery process. In the context of the FVV research project M1709 “Downsizing fuel” such a CFR-engine was adapted from external mixture formation to a direct injection (DI) engine. Three different fuel ratings were developed on the basis of this DI CFR-engine, out of which two are addressing pre-ignition (PI). The compression pre-ignition number (CPI) covers the phenomena of premature gas phase auto-ignition and the hot spot pre-ignition number (HSPI) quantifies a fuel’s surface-ignition tendency.

One aim of the research project presented in this article is to evaluate the capability of the HSPI and CPI to predict a representative pre-ignition rating of a large variety of fuels for modern downsized direct injection spark ignition engines and to optimize these measurement procedures if necessary.

In this investigation experimental analyses were conducted for 29 different fuels. Ignition delay times were measured on a rapid compression machine (RCM), pre-ignition ratings were derived from recordings on a single cylinder research engine and CPI as well as HSPI were obtained from experiments on a modified CFR-engine. The SCE rating for surface-ignition was defined as the glow-plug temperature, which yields a pre-ignition frequency of 2 % PI events per recorded combustion cycles. For the gas phase auto-ignition the boost pressure level leading to 2 % PI-frequency was identified as a representative measure. Both numbers were developed in the predecessor project M1059 and were carried on to this ongoing study.

As depicted in figure 1 no correlation was found for those pre-ignition descriptors and the CFR numbers. The reason for this deviation can be resolved by a reaction kinetical analysis of the CFR procedures and the SCE measurements. For this purpose, ignition delay times were simulated in a zero-dimensional engine model with a global reaction model for conventional RON95 E0 gasoline, which was developed in the Chair for Physico-Chemical Fundamentals of Combustion of RWTH Aachen University and validated on the basis of the underlying RCM measurements. The resulting ignition delay times are shown in figure 2.
From figure 2 it is obvious that the differences in charge air pressure and temperature of the CFR-engine and the SCE lead to significant differences in terms of reaction kinetics. Since both, surface-ignition and gas phase auto-ignition are strongly determined by the ignition pathways of the air-fuel mixture, those reaction kinetical differences basically lead to different pre-ignition characteristics in both test engines. Thus, a correlation of the CFR-numbers and the SCE pre-ignition ratings must not be expected.

Finally, in order to predict the pre-ignition rating of a fuel appropriately, the CFR test procedures for the HSPI and CPI determination have to be adjusted. Currently the intake air temperature of the CFR-engine for the HSPI test is set to 149 °C and 200 °C for the CPI test. These high temperatures were derived from the MON test procedure and were necessary to find appropriate engine conditions for pure alcoholic fuels. However, the ongoing research indicates that an intake temperature level close to the RON definition of 52 °C will lead to a better accuracy of the pre-ignition numbers. This new test definition is currently under investigation at the Institute for Powertrains and Automotive Technology of the Vienna University of Technology, where the modified CFR-engine is located.

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Selected New Projects

Several new research projects with the involvement of the Institute for Combustion Engines started in 2016. This overview gives insight into selected highlights. Further research projects in cooperation with the Federal Ministry of Education and Research, ministries of the state of North Rhine-Westphalia, FVV - Research Association for Combustion Engines e.V. and other funding organizations will be launched soon.

P2X Kopernikus - “Research, Validation, and Implementation of Power-to-X concepts”

The large-scale project “Research, Validation, and Implementation of Power-to-X concepts” is concerned with the storage and use of electrical energy from renewable sources by converting it into material energy carriers and chemical products. Like this, energy from renewable sources can be used with high added value for example in tailor-made fuels for automobiles. Within the scope of the “Kopernikus” program of the Federal Ministry of Education and Research (BMBF), the project “Power-to-X (P2X)” will establish a national research platform for this complex issue. Besides the Institute for Combustion Engines, further 17 research institutions, 27 industrial companies and 3 civil society organizations contribute to the project.

EAGLE - “Efficient Additivated Gasoline Lean Engine”

The EAGLE project, funded by the European Commission, aims to improve energy efficiency of road transport vehicles by developing an ultra-lean spark ignition gasoline engine, adapted for future electrified powertrains. A peak brake thermal efficiency of 50 % shall be reached with the help of lean combustion, while particulate and NOx emissions shall be reduced by a new exhaust aftertreatment system developed for this combustion process. Besides the Institute for Combustion Engines, an interdisciplinary consortium made of 8 partners contributes to the project.

PaREGEn - “Particle Reduced, Efficient Gasoline Engines”

The PaREGEn project is funded by the European Commission and includes 16 partners which are concerned with research on the innovation of gasoline engines for light duty vehicles. Specifically, engines used in mid- to premium passenger cars will be addressed due to the need for clean, efficient, and economic inter-urban transport. Within this scope, the Institute for Combustion Engines and the project house “Center for Automotive Catalytic Systems Aachen” at RWTH Aachen University examine an efficiency increase of gasoline engines with the help of water injection. Further information is available on www.paregen.eu.

FOR2401 - DFG Research Group 2401: Optimization-Based Multiscale Control of Low-Temperature Combustion Engines

An important goal for mobile propulsion consists in the reduction of engine combustion-related emissions of the greenhouse gas CO2 as well as pollutants. For realization of high efficiency with simultaneously low pollutant emissions, the FOR2401 investigates the promising low temperature combustion. In the context of the FOR2401, a detailed physico-chemical understanding of the low temperature combustion and the related possibilities for control shall be gained, enabling a description of the process with mathematical models. Based on this knowledge, tailored control methods shall be developed which rely on real-time optimization and allow for control on time scales that are smaller than the ones achievable with state-of-the-art concepts.

IMPERIUM - “IMplementation of Powertrain Control for Eco-nomic and Clean Real driving emission and fuel ConsUMption”

Fuel economy is a key aspect to reduce operating costs and improve efficiency of freight traffic, thus increasing truck competitiveness. The main objective of the IMPERIUM project is to achieve fuel consumption reduction by 20 % (Diesel and urea) whilst keeping the vehicle within the legal limits for pollutant emissions. The Institute for Combustion Engines, the Junior Professorship “Mechatronic Systems for Combustion Engines”, and the Institute for Automotive Engineering of RWTH Aachen University together with 17 partners contribute to this project, which is funded by the European Commission, with research activities concerning hybridization and connected driving.

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Events in 2016
The automotive world is facing rapid changes. Real world driving emissions are in the focus of the public, well-established technologies are reassessed and new players enter the global market. To achieve a sustainable and green mobility the development of efficient and clean combustion engines is one of the key requirements. Most of the promising and novel approaches require innovative closed-loop control approaches, detailed physical models, powerful control logics and new sensor concepts. Therefore, the Symposium for Combustion Control took place in Aachen on June 15th and 16th, 2016, for the second time.

The annual Symposium for Combustion Control fosters the interaction between the scientific community and the automotive industry. Its focus are the latest theoretical and application driven developments for the control of next generation combustion engines, 19 lecturers presented latest results and developments in these fields. In addition, especially the keynote speeches gained high attention. Professor Anna Stefanopolou, Ph.D., from the Mechanical Engineering Department of the University of Michigan talked about combustion control beyond the rugged edge of high cyclic variability. Professor Dr.-Ing. Gunnar Stiesch, Vice President “Advanced Engineering & Exhaust Aftertreatment, 4-Stroke” of MAN Diesel & Turbo SE, dedicated his lecture to closed loop combustion control as a key enabler for large bore engine efficiency. Last but not least, Fabio Borean, Senior Manager of Powertrain Advanced Calibration & Controls at Jaguar Land Rover Ltd., presented hybridization, emissions and key enablers as future challenges for combustion control in the automotive world.

After two exciting and successful symposia in 2015 and 2016, the third Symposium for Combustion Control will take place on June 28th and 29th, 2017.

Tailor-Made Fuels: From Production to Propulsion
4th International Conference, June 21st to 23rd, 2016

Again in 2016, the Cluster of Excellence Tailor-Made Fuels from Biomass hosted an international conference in Aachen to present the latest results and to strengthen the interdisciplinary research work. For the fourth time, the international conference opened up the stage for experts from around the globe to present their work in the fields of synthesis, production and combustion of modern biofuels. Moreover, alternative fuels from CO₂ and renewable electricity were discussed.

In various sessions, fascinating topics like selective biomass conversion, biomass fractionation and processing, biofuel application and combustion, or fuel design were addressed.

In addition to high-level keynote lectures, the conference program included presentations held by national and international biofuel experts as well as updates regarding the research activities of the Cluster of Excellence Tailor-Made Fuels from Biomass. Furthermore, the conference offered a poster session to discuss further research findings and plenty of opportunity to exchange with other researchers.

In 2017, the “Tailor-Made Fuels: From Production to Propulsion - 5th TMFB International Conference” will take place from June 20th to 22nd in Aachen.
In 2016, the Aachen Colloquium Automobile and Engine Technology celebrated an anniversary: For the 25th time, the Institute for Automotive Engineering (ika) and the Institute for Combustion Engines (VKA) of RWTH Aachen University invited numerous automobile-enthusiastic experts to a professional exchange of ideas. Organized by Professor Stefan Pischinger (VKA) and Professor Lutz Eckstein (ika), the Aachen Colloquium was again fully booked with 1800 participants.

Europe’s largest congress in automobile and engine technology offered more than 100 technical presentations and a technical exhibition with 65 exhibitors, which once more illustrated the high significance of the conference.

After a welcome by Professor Ernst M. Schmachtenberg, Rector of RWTH Aachen University, Professor Pischinger and Professor Eckstein gave insights into the history of the Aachen Colloquium during their speech on the occasion of the 25th anniversary. Afterwards, especially the plenary speeches of high-ranking executives from the automotive industry gained attention.

Professor Thomas Weber, Member of the Board of Management of Daimler AG and responsible for Group Research & Mercedes-Benz Cars Development, talked about a further anniversary: in the year 1886, Gottlieb Daimler and Carl Benz brought to market their first vehicles with combustion engines. Professor Weber was convinced that even after 130 years of automobile history, the most exciting times are yet to come.

From Mercedes-Benz’ point of view the supreme discipline consists of optimally intertwining the topics “Connected”, “Autonomous”, “Shared” and “Electric”. In his opinion, especially the area of data infrastructure is gaining importance: “Mobile data are the new oil”, according to Weber.

Masanori Sugiyama, Executive General Manager of Toyota Motor Corporation, dedicated his plenary speech to the presentation of Toyotas new vehicle architecture and the course for meeting future challenges.

Klaus Fröhlich, Member of the Board of Management of BMW AG with responsibility for development, presented the drivetrain development at BMW and gave an outlook on future driving pleasure.

In the future the varied topics of automobile and engine technology will continue to be of high significance for research and industry. In 2017, participants from about 30 countries will again experience technical innovations and exciting discussions about latest developments in the automotive industry.
In the field of battery research, Abhishek Khetan showed his findings on using electrolytes for Li-Air batteries. Felix Schrader gave insight to the state of research for in-situ TEM for Lithium Ion batteries. In the session for power electronics, Annekret Klein-Höffling presented ways to optimally operate switched reluctance machines with full bridge converters. Silvano Taraborrelli introduced a tap changer for a dual active bridge converter to extend the voltage range. Jan Karthaus gave details about the deterioration in magnetic properties of the electrical steel sheet due to cyclic mechanical stress. Jan Schröter talked about high speed drives for electrical machines. Marco Davidovic gave a presentation on large-eddy simulation of Diesel spray combustion and pollutant formation.

The session about the interdisciplinary field simulation and control had three presentations by doctoral candidates. Dominik Raudszus talked about the assessment of communication based driver assistance systems by stochastic simulation. Un-Jae Seo showed his findings on using a linear generator for a range extender. Rene Savelberg presented means to co-simulate real-time-systems. For a better understanding of thermal management, Damian Backes introduced thermal comfort modeling for automotive climatization based on a modeled passenger perception. Wilko Rohffs presented Johannes Jörg’s findings for liquid jet imping cooling for power electronics.

More than 70 people from industry and various universities took part in the colloquium and the discussion after the presentations. External speakers from the University of Ulm, Bosch, FEV and Hanon Systems enriched the colloquium with industry expertise. Several doctoral candidates presented posters in the poster sessions, which took place during the breaks.

The 4th mobilEM Colloquium will take place in October 2017.

In further seminars Dr.-Ing. Kai Ruchmeyer from Caterpillar Motoren GmbH & Co. KG showed solutions for large engines with regards to the emission legislation IMO Tier 3, while Dr. Wolfgang Demmelbauer-Ebner from Volkswagen AG talked about the brand-new EA211 TSI evo engine from Volkswagen. Moreover, Richard Moore from Jaguar Land Rover Limited gave insights into the electrification view and prognosis of JLR.

Dipl.-Ing. Diethard Plohberger from Liebherr-Components Colmar SAS concluded the seminar series for 2016 by presenting the development of the Liebherr D98 high speed engine.

The program of the Engine Technology Seminar 2017 is available online: www.vka.rwth-aachen.de
Summer Party
of the Institute for Combustion Engines

August 10th, 2016
Christmas Celebration of the Institute for Combustion Engines

December 16th, 2016