The Year 2017
at the Institute for Combustion Engines and the Center for Mobile Propulsion
Dear Readers,

The year 2017 at the Institute for Combustion Engines and the Center for Mobile Propulsion came to a successful end and we cordially invite you to have a look at our work. Thanks to all our dedicated employees, a constant scientific progress in numerous projects was made possible. We are glad to share these developments in our review. Please do not hesitate to contact us for further information.

Yours,

Stefan Pischinger, Head of the Institute for Combustion Engines and Leading Principal Investigator of the Center for Mobile Propulsion
At the Institute for Combustion Engines (VKA) and the Center for Mobile Propulsion (CMP) 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 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 play an essential role in the future of our Institute and Research Center. 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 270 scientific, technical and administrative employees as well as student assistants.
The Institute for Combustion Engines (VKA)

274 Employees in total

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

4 Chief Engineers
Research
Operations
Cluster of Excellence TMFB
Infrastructure & Center for Mobile Propulsion

1 Junior Professor
Mechatronic Systems for Combustion Engines

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

83 Student Assistants
Research & Administration

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

10 Completed Dissertations

127 Completed Master and Bachelor Theses
Fuel Design Center (FDC)

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 ω-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

The Institute for Combustion Engines (VKA)
The “Center for Mobile Propulsion” is an ultramodern 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 and highly modern HiL-test bench environments. To satisfy the progressing electrification of powertrain components, the CMP capacities have been extended. Several component test benches for transmissions and combustion engines are now prepared for high voltage applications. All test benches provide the capability to test different components in-the-loop with a co-simulation. This means that the component exchanges bidirectional physical data in real-time with a state-of-the-art simulation of the vehicle. It enables the possibility to investigate the component in a transient and realistic environment. 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 Research Training Group “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.

The Center for Mobile Propulsion is funded by the German Council of Science and Humanities (Wissenschaftsrat) and by Deutsche Forschungsgemeinschaft (DFG).
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.

Implementation of the New WLTP Regulation

To measure the fuel consumption of a vehicle and the compliance with emission limits, standardized test procedures are required by legislation. For the type homologation of new passenger cars, the new test procedure “Worldwide Harmonized Light-Duty Vehicles Test Procedure” (WLTP or WLTC test cycle) became valid EU-wide on September 1st, 2017. WLTP follows the NEDC (New European Driving Cycle), which was valid since 1992. From September 1st, 2018, emission and fuel consumption figures measured in WLTP need to be available in Europe for all newly registered passenger car and light-duty vehicle models. This implies new challenges for manufacturers and of course also for test laboratories with.

Like NEDC, WLTP is conducted in certified test laboratories under exactly defined boundary conditions. Like this, test results are stable and reproducible on the one hand and enable a direct comparison of different vehicles independent from the test bench or test laboratory on the other hand.

The fulfillment of “WLTP Regulation” 2017/1151 at VKA’s Emission Chassis Dynamometer is not only expected by the Technical Inspection Association (TÜV) for certification, but also by customers for their development tests. Essential steps to comply with legal requirements were already implemented in 2017. Further requirements will be fulfilled in 2018 to receive a Euro 6d certificate for testing and measurement installations from the Technical Inspection Association (TÜV).

With the four-wheel-drive emission chassis dynamometer, a facility will be available that will provide an outstanding and future-oriented combination of features for research as well as certification tasks.

Commissioning of a Driving Robot

To optimize fuel consumption and emissions in chassis dynamometers, maximum reproducibility of the mode of operation is required. It can be realized with the help of a computer-controlled driving robot. The automatic driving robot enables the automated use of the accelerator, brake and clutch pedal as well as the use of shift mechanisms of manual and automatic transmissions. Optionally, ignition keys or start-stop buttons as well as the steering-column shift of the vehicle can be operated in an automated way.

For that purpose, the MAHA driving robot “JAMES” was implemented in the test bench automatization environment and taken into operation.
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 and an Autobahn segment in direct vicinity, automotiveGATE and a mobile communications test field enhance ATC. 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.

Connectivity

Digitalization plays an important role thanks to the coverage with a simulated signal of the European satellite navigation system Galileo. In addition with Europe’s most advanced mobile communications test field and further wireless networks, ATC is the ideal place for connected mobility (V2X) research, development and validation.

Mobile Communications Test Field

Thanks to a cooperation with Vodafone an open mobile communications test field, which provides – besides dedicated WiFi – current and future mobile communication generations for connecting vehicle and infrastructure is installed. The test field for mobile communication provides one of the most advanced development and testing environments for connected and autonomous traffic of the future. Besides LTE standard configurations, specific, individual configurations are possible. In connection with customer-specific ICT components and solutions, the required ecosystem for automotive and mobility applications and related services can be generated.

Galileo

The worldwide one-of-a-kind Galileo automotive-GATE allows development and testing of applications, systems and components already now, i.e. before a sufficient number of satellites is available from the orbit. 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. An open mobile communications test field, which provides – besides dedicated WiFi – current and future mobile communication generations for connecting vehicle and infrastructure is also installed. In addition, workshop, office and conference facilities are available while working on site.

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.

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.

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.

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New in 2017
Changes in the Board of Management

In October 2017 Thomas Laible was appointed as chief engineer. His main focus is the operations area.

Thomas Laible finished his studies in Mechanical Engineering with the focus on Automotive Engineering at the Karlsruhe Institute of Technology in 2010. Afterwards, he worked as a research assistant at the Institute for Combustion Engines (VKA) at RWTH Aachen University. In 2013, he became head of the test field at the Institute for Combustion Engines.

Following the appointment of Thomas Laible, a shift in tasks took place. Chief engineer Peter Dittmann will now mainly address the strategic development of the Center for Mobile Propulsion (CMP) test field concerning important future topics. In addition, he is Program Manager of the Project House "Center for Automotive Catalytic Systems Aachen" (ACA) at RWTH Aachen University since 2014 and Coordinator of the Profile Area "Energy, Chemical and Process Engineering" (ECPE) since December 2017.

Conferment of Doctorate

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

Arthur Back

Marius Böhmer
Simulation of Exhaust Emissions considering Real Driving Conditions

David Hemkemeyer
Thermal Management of Electric Passenger Cars Utilizing the Waste Heat of the Propulsion System

Konrad Herold
Highly Dynamic Generator Control for Range Extenders with Rolling Torque Compensation

Björn Höpke
Analysis and Modeling of the Thermal Behavior of Passenger Car Exhaust Gas Turbochargers

Axel Kuhlmann
Development of the Structure Components of a Fuel Cell Module with Integrated Balance of Plant Components

Peter Methfessel
Reduction of the Number of Cylinders of a Commercial Vehicle Engine while Retaining the Engine Displacement

Markus Podworny
Development of New System Components for Internal Combustion Engines with Continuous Variable Compression

Rene Savenberg
Real-Time Coupling of Test Benches

Andreas Selle
Noise Measurement Decomposition for Passenger Car Noise Target Auralization
mobilEM continuation granted

It is great news for all involved researchers: the research training group “Integrated Energy Supply Modules for Roadbound E-Mobility” (GRK 1856 mobilEM) will be continued in a second grant phase. A successful inspection in October 2017 laid the foundation for the German research association (DFG) to grant a new fund for the next 4.5 years of research. Congratulations to all for this great achievement.

The post graduate program explores the physical foundations of electro-chemical energy storage and its combination with novel fuel-operated range extender units. Scientists from the areas of electrical energy storage, power electronics, chemical energy conversion, electric motors, powertrain topology, thermal management and control cooperate. This interdisciplinary approach addresses the challenging topics of electromobility on many levels. The second grant phase will include exciting research on fuel cell range extenders. Professor Angelika Heinzel and the Chair of Energy Technologies at the University of Duisburg-Essen will be a part of the research training group to support this new research topic. The second grant phase will start in April 2018.

Clearly arranged and with modern appearing - this is the way the new homepage presents itself. In 2017, the newly designed website of the Institute for Combustion Engines went online. The affiliation with RWTH Aachen University is a key factor expressed in the new design which will be adapted by all RWTH Aachen University institutions. Website visitors can find detailed information on academics, research, job advertisements, and the Institute as well as contact persons for all kinds of questions. Have a look at our lecture offer, browse through our research facilities and projects or get to know the Management Board at www.vka.rwth-aachen.de.

“Meet RWTH Aachen” hosted at VKA and CMP

Once a year, partners and sponsors of the RWTH Education Fund are invited to visit Aachen during the event “Meet RWTH”. Besides the annual sponsoring banquet including the presentation of certificates for scholarship holders, sponsors can participate in an institute visit to learn more about promising scientific developments. This year, the Institute for Combustion Engines was selected to give insights into research and facilities at the Center for Mobile Propulsion (CMP). Professor Schmachtenberg, rector of RWTH Aachen University, welcomed the representatives of sponsoring companies and foundations as well as private supporters. Professor Stefan Pischinger, Leading Principal Investigator of the Center for Mobile Propulsion, gave a speech on the future of mobile powertrains, followed by a lively discussion with the visitors. In the following tours through the Center for Mobile Propulsion the chief engineers explained the interdisciplinary research on all sections of electrified and highly efficient propulsion systems.
Welcome to Our New Employees in the Year 2017

Selina Cakmakci
Accounting

Max Conrath
Workshop

Nicole Gallus
Secretariat

Christine Peiter
Accounting

René Scheer
Research Associate
Hybrid & E-Mobility

Ragupathi Soundara Rajan
Research Associate
Hybrid & E-Mobility

Daniel Hancigullari
Research Associate
Software and Testing Solutions

Arne Tobias Harz
Workshop

Ivo Hoekstra
Workshop

Sören Tinz
Research Associate
Hybrid & E-Mobility

Marius Wegener
Research Associate
Hybrid & E-Mobility

Carsten Wulf
Research Associate
Vehicle Integration / Thermal Systems

Sebastian Hupppertz
Workshop

Ralf Lürken
Facility Management

Mamin Miah
Electrics
Recent News of Aldenhoven Testing Center (ATC)

Opening of the 5G Mobility Lab and 2nd Aldenhoven Testing Center Business Day

In August 2017, the Vodafone 5G Mobility Lab at Aldenhoven Testing Center (ATC) was opened. Vodafone extends the urban environment of ATC with highly modern mobile communication technology resulting in an ultimate automotive research, development and test field which is unique in Europe. The 5G Mobility Lab offers a complete connected and configurable test environment with traffic infrastructure and communication. The test field enables for example to test the interoperability of automotive solutions of different OEMs, network suppliers and network providers.

The opening was connected with the 2nd Aldenhoven Testing Center Business Day. More than 300 guests attended the event, among them Minister President of North Rhine-Westphalia Armin Laschet, CEO Dr. Hannes Ametsreiter and CTO Dr. Eric Küsch of Vodafone Germany, Parliamentary State Secretary to the Federal Ministry of Education and Research (BMBF) Thomas Rachel, rector of RWTH Aachen University Prof. Ernst Schmachtenberg as well as the head of Düren county Wolfgang Spelthahn. After a festive celebration, the speakers officially opened the mobile communications test field. Afterwards, all guests were invited to have a look at future mobility. Several demonstrations gave an outlook on the possibilities which connected vehicles offer: to improve security, efficiency and comfort in traffic.

Open Day of the Future Mobility Lab

The Future Mobility Lab is an initiative of RWTH Aachen University which unites the competencies of several university institutions in the field of mobility research. At the Open Day of the Future Mobility Lab (FML) automotive experts had the opportunity to gain insights into the RWTH Aachen University’s many activities in state-of-the-art mobility research.

More than 100 experts from automotive research and development visited the Future Mobility Lab’s exhibition in October 2017. FML members presented showcases of some of their various research projects in the field of automated and connected driving. The participants could not only learn more about current activities in research projects, but also get to know the newly opened urban test environment by visiting live demonstrations on the test track. Thus, highlights of the Open Day included the newly established real-world intersection for research purposes, equipped with intelligent traffic lights, sensors, and an infrastructure for communication; Vodafone’s 5G Mobility Lab test environment; and the Galileo research environment, automotiveGATE. FML researchers showed how connected safety systems are able to avoid collisions with pedestrians and crossing vehicles and how automated valet parking can contribute to make parking the car more convenient. Also, the potential of infrastructure-based sensor fusion has been demonstrated and visitors could see how vehicles on the test track interact with traffic in simulation.
Research at the Institute for Combustion Engines
NET-ECU: Connected Engine Control

The emission values of passenger cars in real world driving are often very different from those measured during the homologation process. The main reason for this is the variability of real road traffic compared to the current compulsory emission test cycles for homologation. Only the a priori knowledge of the up-coming driving allows an improved control of the vehicle and its powertrain.

Target of the NET-ECU research project is to develop a new hard- and software demonstrating the potential of a predictive and connected engine control unit. On the hardware side, the Online Calibration Tool (OCT) with an integrated ITS-G5 (Dedicated Short Range Communication) module for Car to Car (C2C) and Car to X (C2X) communication, a GPS module, and an inertial sensor system is developed. The software algorithms allow to predict the future driving dynamics and to influence the behavior of the Engine Control Unit (ECU) by mean of dedicated real-time modification of calibration values. Within the research project, the latter are developed by the Institute for Combustion Engines (VKA) specifically for a Diesel powertrain due to its difficulties into meeting the future challenging emission targets. The influence of novel, but simplified predictive strategies is investigated for different prediction horizons and Diesel engine sub-systems. The investigations are performed on a C-Segment vehicle equipped by a 2.0 L 4 cylinder Diesel engine with single stage turbocharger, cooled high pressure and cooled low pressure Exhaust Gas Recirculation (EGR). The aftertreatment system considers the Lean NOx Trap (LNT) and the Diesel Particulate Filter (DPF).

For a short prediction horizon, the air path is considered. The approach was to compensate the turbo lag providing in advance the desired boost pressure, which is assumed to be known by means of predictive information. Soot emissions are reduced by up to approx. 5 % in the WLTC with a prediction of 1.3 s (see figure 1.a). Also engine-out NOx emissions are improved of around 2 % while the fuel consumption slightly increases up to 0.5 % due to the higher gas exchange losses.

For a medium prediction horizon, the regeneration events of a LNT are investigated. With the help of the predictive strategy the abortions of the DeNOx events could be prevented. This resulted in a reduction of the average fuel consumption over several RDE cycles up to approx. 1 % with the same average DeNOx efficiency (see figure 1.b). The investigations also show that in the urban areas the required prediction horizon goes up to 2.5 km, which is much longer than the maximum communication range for C2C and C2X communication (max. 500 m).

For long prediction horizons, the regeneration strategy of the DPF is optimized with regard to fuel consumption and it aims to prevent aborted DPF regenerations. The comparison between conventional and predictive strategies confirms the expectation showing lower fuel consumption with longer prediction horizons. At the longest horizon (here 30 min), the fuel saving potential over one dedicated RDE cycle is 5.5 %. Additionally the Ki factor, which considers the regeneration interval in the fuel consumption calculation, over the WLTC improves of 1.63 % compared to the conventional strategy (see figure 1.c).

![Figure 1: Summary of the simulation results during the system evaluation phase](image)

(a) Emission potential in the World wide harmonized Light duty Test Cycle (WLTC) as function of the prediction horizon with respect to the non-predictive control strategy

(b) Fuel penalty and Lean NOx Trap regeneration process (DeNOx) efficiency scatter-band considering several Real Driving Emissions (RDE) cycles

(c) Fuel saving potential in one dedicated RDE cycle (left) and Ki factor in WLTC (right) depending on the prediction horizon
Due to the shorter, and consequently more probable, prediction horizon and the emission improvements shown, the air path system is selected for the next stage of the research project, where a dedicated rule-based algorithm is developed. This last is able to control the boost pressure by means of predicted information (vehicle speed and gear). The control shows a very good behavior in the transient operations, providing in advance the boost pressure set point so that the actual boost value is closer to the desired of the conventional system. Therefore, a higher boost pressure (when requested) can be reached faster reducing the peaks in soot emissions (see figure 2). Furthermore, a better filling of the cylinder allows a higher EGR rate reducing the NOx emissions too. Additionally, the algorithm is able to change at the same time the EGR request (KNOx in figure 2) giving the possibility to choose the desired NOx-soot trade-off (see figure 3). Small drawbacks in terms of fuel consumptions are related to the increase of the gas exchange losses, due to the higher boost pressure.

The developed algorithm is then coupled with a prediction module, which provides the predicted vehicle speed and engaged gear in the prediction horizon. Both algorithms are compiled in OCT and running in the demonstrator vehicle. Key results expected by the on-road validation are the reliability of the prediction module and the response of the air path rule-based algorithm to wrong predictions.

Acknowledgements

This research is performed within the scope of the NET-ECU research project, which is founded by the Deutsche Bundesstiftung Umwelt (DBU). The VKA likes to thank the association members and all the companies who supported the project with the hardware resources, therefore contributing to the success of the project.
Progress in the Definition and Investigation of Novel Biofuels for Optimized Combustion Engines

Within TMFB, a novel tailored catalytic system has been developed opening a sustainable synthetic pathway to a liquid energy carrier via the combined utilization of ethanol as bio-based feedstock and CO₂ as carbon source together with “green hydrogen” from water electrolysis [1,2]. The activities at VKA shall be explained using the newly synthesized “bio-hybrid fuel” di-ethoxy methane (DEM), as an example. This fuel was derived within TMFB by applying 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 HCCI type combustion it is well known that a fast mixture formation and high oxygen content enable a significant soot reduction. For this reason TMFB is seeking for fuels that feature an increased oxygen content, a moderate self-ignition tendency as well as a low boiling point. Since DEM perfectly meets these requirements, its potential for highly efficient controlled autoignition was assessed by single cylinder investigations using Combustion Chamber Recirculation (CCR) as exhaust gas strategy.

The autoignition behavior of DEM is very prone. As a consequence a very low internal residual gas fraction is necessary to initiate autoignition. Compared to conventional RON95 E10 fuel, DEM shows a high enleanment potential leading to good efficiency and low NOₓ emissions (figure 1).

Figure 2 illustrates the combustion of pure DEM and DEM in combination with \( x_{\text{exp, ext}} = 30\% \) external exhaust gas recirculation in comparison to conventional RON95 E10 pump fuel using the indicated cylinder pressure traces around firing Top Dead Center (TDC). The calculated pressure trace for compression without combustion is plotted as reference.

**Figure 1:** Variation of negative valve overlap to determine the impact of the internal residual gas fraction at \( n = 1500 \text{ 1/min} \) and IMEP = 4 bar
Pure DEM possesses a multi-stage ignition behavior. Nevertheless, the cylinder pressure gradient of the main combustion is still high, and hence increases engine noise. The ignition behavior of DEM and RON95 E10 can be aligned by external EGR. It can be seen that DEM in combination with \( x_{\text{EGR}} = 30\% \) presents a similar combustion behavior as RON95 E10. However, external EGR reduces the enleanment capability and no efficiency advantage is achieved. The advantage of low NOx emissions remains.

For DEM with external EGR there is no multi-stage ignition visible in the cylinder pressure trace and the cylinder pressure gradient is reduced by \(-40\% \) to \( \Delta p/\Delta \alpha_{\text{max}} = 2.99\text{ bar }/\text{ }\alpha_{\text{CA}} \).

In future work, the full potential of DEM will be exploited by taking into account further measures to adjust combustion phasing and reduce the maximum pressure gradient.

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In future work, the full potential of DEM will be exploited by taking into account further measures to adjust combustion phasing and reduce the maximum pressure gradient.
**Thermodynamic Combustion Characteristics**

The investigations revealed that by blending OME1 into Diesel, the burning behavior of the fuel improved. To illustrate the latter, figure 2 shows monitored pressure traces and burned mass fractions for different OME1-Diesel blends at an exemplary load point (imep = 6.8 bar, n = 1500 min\(^{-1}\)). It can be seen that with increasing OME1 content in the blend, a higher fraction of the fuel burns close to top dead center (TDC), thereby reducing the fraction of fuel burned inefficiently in the so-called burn-out phase. In other words, a higher fraction of the fuel is burned at an early crank angle location, subsequently undergoing a larger expansion. As a result, lower exhaust gas temperatures and higher indicated efficiency are measured – as shown in figure 3.

![Figure 2: Cylinder pressure traces and burned mass fraction curves for OME1-Diesel blends at LP2: imep = 6.8 bar, n = 1500 min\(^{-1}\), NO\(_X\) = 0.2 g/kWh](image)

**Emission Characteristics**

A significant reduction in filter smoke number was observed with increasing content of OME1 in the blend as shown in figure 4. The 80:20 OME1-Diesel blend shows filter smoke number (FSN) values as low as the detection limit of the AVL415s smoke meter (0 ≤ FSN ≤ 0.01), even at very low NO\(_X\) levels. The strong soot reduction is attributed mainly by the high amount of oxygen in the blend. Furthermore, the low boiling temperature and high volatility of OME1 contribute to improved mixture formation and air utilization. Also, the relative reduction of aromatics with increasing OME1 content in the blend contributes to a further suppression of soot formation.

![Figure 3: Indicated thermodynamic efficiency and exhaust gas temperature for the investigated load points](image)

Similar to soot emissions, unburned hydrocarbon emissions (HC) are continuously reduced at all the investigated load points as OME1 content increases in the blend. This behavior is surprising; bearing in mind that the addition of OME1 reduces the cetane number. The reason for the lower HC emissions could be attributed to the complete burning of the fuel close to TDC, resulting in higher in cylinder temperatures and thus into improved oxidation conditions. The latter is also true for the reduced CO emissions observed at moderate towards higher load points.

Combustion sound levels (CSL) are presented in figure 5 for LP2 and LP3. At lower loads, CSL is mainly controlled by the cetane number of the fuel. Therefore, CSL continually increases with increasing OME1 content in the blend.

![Figure 4: Soot emissions at higher loads for OME1-Diesel blends](image)

![Figure 5: Combustion sound level (CSL) at moderate loads](image)
In contrast to low loads, at higher loads the heating value of the fuel becomes more dominant in determining the combustion sound level. Due to the lower volumetric heating value of OME, longer injection durations occur leading to a reduced energy supply rate to the cylinder and thus to a lower heat release rate during combustion. This behavior is captured at LP3, where the CSL values decrease as the OME content in the blend increases, with the exception of the 80:20 OME-Diesel blend. For the latter, the cetane number is at such a low level (CN = 37) that CSL remains higher than Diesel.

Optimal Blending Ratio for OME-Diesel Blends

For the identification of an optimal blending ratio, the soot reduction potential is considered with respect to the deterioration of important fuel properties, e.g., heating value and cetane number. The measured data were analyzed with a Gaussian process regression method to evaluate the soot reduction dependency on OME, blending ratio. As can be seen from figure 6, the major reduction in particulate mass (PM) occurs up to a blending ratio of 35% OME in Diesel. Beyond 35%, the heating value and CN are continuously deteriorated without a worth improvement in PM reduction. Based on the latter, 35% (vol) OME in Diesel was selected as an optimal blending ratio enabling a ~90% soot reduction with only 10% and 15% deterioration in CN and heating value, respectively.

Evaluation of Emission Reduction Potential in a WLTP Cycle

Considering the fact that a particulate filter will remain a substantial part of the exhaust gas aftertreatment system in the future, the benefit of low soot emissions provided by OME blending shall be utilized to further reduce the NOx emissions. To assess the engine-out NOx reduction potential by a dedicated engine calibration for a 35% OME-Diesel blend, a global design of experiment investigation was performed on the single cylinder engine. The data was used to parametrize a simulation tool for subsequent evaluation of engine-out NOx emissions in a WLTP cycle. Figure 7 shows that under quasi-drop-in conditions, (equivalent NOx to Diesel), the engine-out soot emissions with the 35% OME-Diesel blend are reduced by 95%. However, when an optimized engine calibration was applied (mainly an increase of exhaust gas recirculation rates), a 53% NOx emission reduction could be achieved while still maintaining a 90% soot reduction compared to Diesel.

Acknowledgement

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EAGLE - Efficient Additivated Gasoline Lean Engine

Latest studies on future mobility are indicating an increasing share of electric vehicles for passenger cars. However, same studies came to the conclusion that most of the cars in the coming decade will still have an internal combustion engine. These engines will mostly be combined with an electric propulsion system, as hybrid powertrains are one enabler to fulfill future emission targets while maintaining customer acceptance with regard to costs and traveling range.

As the internal combustion process of the engine still has a major role in defining the overall vehicle emissions in such cases, the European funded EAGLE project (Efficient Additivated Gasoline Lean Engine) aims at improving the energy efficiency of passenger cars by developing a highly efficient gasoline engine adapted for future electrified powertrains.

By combining new advanced technologies, the EAGLE project is designing an innovative engine concept to reach a peak efficiency of 50 % for hybrid powertrains. This new concept will thus support to reach the project CO₂ emission target of 50 g CO₂/km while complying with standards in terms of particulates and NOx emissions.

The engine efficiency will be significantly increased by the use of advanced insulating coating materials and ultra-lean mixtures. Furthermore, the ultra-lean combustion process helps to reduce particulate and NOx emissions. As the flame propagation is being unstable in lean mixtures, the combustion process will be supported by a high cylinder charge motion, an advanced pre-chamber ignition system and the use of hydrogen. Finally, to meet upcoming challenges for NOx emissions, a new exhaust aftertreatment will be developed.

The consortium of this EAGLE project consist of IFP Energies nouvelles (IFPEN), the Engine Simulation Team (EST) of the Università degli Studi di Napoli Federico II, the CMT-Motores Térmicos of the Universitat Politècnica de València, Renault, Saint-Gobain CREE, Continental, FEV Europe GmbH and Institute for Combustion Engines (VKA) of RWTH Aachen University.

Pre-Chamber Ignition System

In 2017, the Institute for Combustion Engines (VKA) together with FEV Europe GmbH has been developing the pre-chamber tailored for a small bore gasoline engine in a hybrid powertrain. Starting with a concept layout for an actively scavenged pre-chamber a new cylinder head has been developed to fit the pre-chamber and to achieve the project targets of the EAGLE project.

The arrangement of the valves, combined with the intake port and the combustion chamber shape, provides the base for a sufficient charge motion level of the ultra-lean combustion process. Furthermore, the intake system was designed to provide different levels of charge motion.

For a flawless central arrangement of the ignition system in the combustion chamber a lateral DI injector position was chosen. To allow a fair comparison between pre-chamber and conventional ignition system, the engine can either be operated with a conventional ignition system or with the pre-chamber ignition system. The pre-chamber assembled to the new cylinder head is displayed in figure 1.

The active pre-chamber is scavenged with fuel during gas exchange and compression phase. While in the main combustion a lean homogenous mixture is created, the mixture in the pre-chamber is slightly rich to stoichiometric at spark timing. This layout enables a stable combustion and low emissions in the pre-chamber. The combustion initiated in the pre-chamber leads to a rising pressure in the pre-chamber. In consequence, flame jets propagate out of the pre-chamber into main combustion chamber. Compared to the spark of a conventional ignition system these flame jets ignite a much higher mixture volume.

The pre-chamber itself was subject to thorough detail optimization by 0-D and 3-D CFD simulation. While the in-pre-chamber mixture formation and turbulent kinetic energy have been investigated using 3-D CFD simulation within FEV’s charge motion design (CMD) process, the optimization of the pre-chamber hole layout has been optimized using 0-D tools as well as by a 3-D CFD simulation modelling the combustion in the pre-chamber. An exemplary flame jet propagation is shown in figure 2.

Figure 1: Top end design of VKA’s single cylinder engine for EAGLE

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Currently the hardware is being manufactured and next the pre-chamber will be tested on the single cylinder test bench. After this first testing phase the findings will be taken into account for the design of the final EAGLE combustion system. In a further step the pre-chamber is provided for the integration in a multi-cylinder engine.

Innovative NO\textsubscript{x} Storage Catalyst

In cooperation with Center for Automotive Catalytic Systems Aachen (ACA), VKA started to develop an innovative NO\textsubscript{x} storage catalyst (NSC) from material to full size demonstrator. Mainly the influence of new NO\textsubscript{x} storage and support materials as well as material combinations with regard to synergistic effects is investigated. With this purpose a methodology of catalyst design and catalyst for lean burn SI engines is introduced.

For measurements at VKA’s laboratory gas test bench (LGB) materials of different groups are synthesized and prepared as granules. In this synthesis step a variation in material composition and doping was considered. Table 1 shows the list of NO\textsubscript{x} storage materials and their combinations. The main reason of choosing these materials is their NO\textsubscript{x} storage activities at different temperature windows, which are known from literature. Hydrotalcides are well known with their high NO\textsubscript{x} storage at low temperatures. In this case 2.5% Pt on Al\textsubscript{2}O\textsubscript{3} with an Mg-Al substrate without any chemical treatment is synthesized. Secondly, a mixture of 50% Pt on Al\textsubscript{2}O\textsubscript{3} and 50% none-dotted CeO\textsubscript{2} is chosen because of its NO\textsubscript{x} storage capacity at middle temperatures. Last material is 2.5% Pt on 20% BaO/Al\textsubscript{2}O\textsubscript{3}, which is a high temperature NO\textsubscript{x} storage material. Besides that, 2.5% Pt on Al\textsubscript{2}O\textsubscript{3} material is prepared, in order to understand the behavior of support material and use it afterwards at modelling. Additionally, combinations of 3 materials are synthesized for LGB measurements. While aiming a high NO\textsubscript{x} storage performance from catalyst, a lower oxygen storage capacity (OSC) is also required, in order to maximize NO\textsubscript{x} reduction performance in regeneration phases and hence to lower additional CO\textsubscript{2} production during NO\textsubscript{x} regeneration.

<table>
<thead>
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<th>No.</th>
<th>Content</th>
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<tbody>
<tr>
<td>1</td>
<td>2.5 % Pt on Al\textsubscript{2}O\textsubscript{3}</td>
</tr>
<tr>
<td>2</td>
<td>2.5 % Pt on Mg-Al (Hydrotalcides)</td>
</tr>
<tr>
<td>3</td>
<td>50 % Pt/Al\textsubscript{2}O\textsubscript{3} + 50 % CeO\textsubscript{2}</td>
</tr>
<tr>
<td>4</td>
<td>2.5 % Pt on 20% BaO/Al\textsubscript{2}O\textsubscript{3}</td>
</tr>
<tr>
<td>5</td>
<td>Mixture of 2 and 3</td>
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<tr>
<td>6</td>
<td>Mixture of 2 and 4</td>
</tr>
<tr>
<td>7</td>
<td>Mixture of 3 and 4</td>
</tr>
<tr>
<td>8</td>
<td>Mixture of all materials</td>
</tr>
</tbody>
</table>

The granule samples are tested in LGB. These tests are performed under idealized and under realistic conditions. Idealized conditions are used to gain a mechanistically understanding of the reactions occurring on the materials and realistic conditions are necessary to evaluate the performance in the relevant operation range.
In order to investigate mechanisms in detail, a measurement program was developed, which is used for each granules. NO\textsubscript{x} storage capacity and oxygen storage capacity are measured at different temperatures between 150 °C and 450 °C. Additionally, light-off measurements with a realistic gas mixture including HC, CO, NO, O\textsubscript{2} and inert gases as well as a gas mixture including H\textsubscript{2}, CO, NO and inert gases are carried out, in which an increasing temperature ramp is programmed with feed gases. Performance of different chemical reactions is evaluated with these measurements.

Meanwhile three pure materials (Material 2 to 4) were investigated at LGB of VKA. Results of NO\textsubscript{x} storage capacity are shown in figure 3. In order to have an idea of NO\textsubscript{x} storage capacity, experiments with a NO\textsubscript{x} storage catalyst from serial production and perowskites, which were run at VKA, are depicted as reference. A remarkable increase of NO\textsubscript{x} storage at low and high temperatures can be observed in comparison to perowskites. At high temperatures NO\textsubscript{x} storage level is even higher than optimized series NSC catalyst. After chemical treatment further increase at low temperatures is expected, as seen between LSFC and LSFC with optimized porosity (LFSC+BET).

On the other hand oxygen storage capacity (OSC) measurements were carried out for these materials. Results are shown in figure 4 in comparison with OSC of serial NSC. While material 2 and 4 have very low OSC, a high OSC is observed with material 3. These results make material 2 and 4 promising candidates for further investigations.

As outcome of LGB measurements a selection of the promising materials and material combinations will be coated on ceramic lab scale honeycomb supports. A variation of the process parameters (e.g. milling, slurry preparation, calcination) will evaluate their influence on coating structure and therewith on catalyst performance by testing them on LGB under similar conditions. Handing over the experimental results to the simulation both experimental and model data can be considered for the optimization steps.

Figure 3: NO\textsubscript{x} storage capacity of chosen materials in compare to perowskites (SV = 90000 1/h)

![Figure 3](image)

Figure 4: OSC of chosen materials in compare to reference serial NSC

![Figure 4](image)

The EAGLE project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 724084.

https://h2020-eagle.eu/

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Recent Progress in the Center for Automotive Catalytic Systems Aachen (ACA)

New Materials to Maximize Engine Efficiency and Minimize Emissions

In February 2014, the Center for Automotive Catalytic Systems Aachen (ACA) was founded at RWTH Aachen University. The Project House was initiated 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 interdisciplinary work 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 legislations for combustion engines put high requirements on engine and exhaust gas aftertreatment concepts through strict pollutant limits and demanding test cycles as well as through CO₂ fleet limits respectively combustion engine efficiency targets.

These core competences of ACA and its partners are essential to investigate a new NOₓ reduction approach within the recently started research project “DeNOx”. DeNOx is a three year research project funded by the Federal Ministry of Education and Research (BMBF). Besides the ACA, six industrial partners (Clariant, Sasol, Umicore, FEV, Ford, Deutz) joined the consortium. This research group combines for the first time all competences from material design to engine and vehicle testing, including control systems and upscaling to industrial production processes. The DeNOx system will combine the existing approaches for NOₓ reduction, NOₓ storage catalyst (NSC) and Selective Catalytic Reduction catalyst (SCR) in one system. The NOₓ storage catalyst can store emitted NOₓ in its catalytic layers. Once the storage is filled, what usually takes a few minutes, the engine operation is changed to a mode with fuel excess in the combustion chamber so that hydrocarbons, carbon monoxide and hydrogen are emitted. These components are used to reduce the stored NOₓ to nitrogen. In contrast to the NSC the SCR system operates continuously, using ammonia as reductant. This ammonia is generated within the system from an injected urea water solution (AdBlue®).

The new DeNOx system shall now combine these two approaches within one system to use synergistic effects and the advantages of both. In the first phase the system acts similar to the NSC and stores the emitted NOₓ in its catalytic layer. In the following regeneration an optimized catalyst for the watergas-shift reaction is used to convert most of the emitted hydrocarbons and carbon monoxide to hydrogen. This high concentration of hydrogen can be used to reduce the stored NOₓ beyond nitrogen, to ammonia. This ammonia will be stored in the SCR layer of the system and can be used in the standard SCR reaction. In the following phase of normal operation this ammonia will reduce the emitted NOₓ to nitrogen and therewith the time until the NOₓ storage is full and regeneration is needed is much longer than in NSC systems. Similar to the SCR system an additional AdBlue® dosing can be used to have an even longer continuous operation but with lower AdBlue® consumption as in comparable SCR systems.

Figure 1: DeNOx catalytic converter (cover picture)
To realize this functionality, new materials for the main tasks - NOx storage, SCR reaction, and WGS reaction - are essential. These materials will be investigated by the ACA Institutes IEK1, IAC, and ITMC. Based on the following characterization in VKA’s laboratory gas test bench, material models will be developed to realize a model-based material optimization. In further development, these models will be used to find the best composition of all materials for several applications in transient cycle simulations.

The later upscaling and coating of materials will already be considered in the optimization process. Once the optimized materials are defined, our industrial partners can investigate the right processes to produce these materials on an industrial scale and the best methods to realize the coating on honeycomb substrates.

Based on the simulation models, a control strategy and software will be investigated so that the demonstration units can be used on engine test benches. These final tests can be used to optimize the catalytic composition and the control strategy as well as to validate the functionality and to evaluate the efficiency of the full-scale system.

The project “Efficient DeNOx strategy for lean combustion engines” is sponsored by the Federal Ministry of Education and Research (BMBF).

Diesel-Hybrid Vehicles for Environmentally Conscious Mobility: A Networked System Development in a Physical and Virtual Environment (DUETT)

An important step towards reaching ambitious climate- and environment protection goals is the progressive hybridization of powertrains. Especially the potentials of Diesel hybrid powertrains, which are burdened by increased development costs, have not been fully exhausted yet. Specifically, the advantages of combining innovations in the field of powertrain electrification and digitalization, such as Car-2-X-technologies, need to further be exploited in this context.

To achieve progress regarding this objective, a new interdisciplinary research project has been launched with the goal of implementing a new development methodology (“virtual development”, figure 1) that allows investigating an extensive variety of vehicle hybrid powertrains with respect to their compliance with future legislations like Real Driving Emissions (RDE). For that purpose, the simulated vehicle is interconnected with other traffic participants in a virtual environment, which is connected with physical components in the real world. This kind of simulation, called Hardware-in-the-loop (HiL) simulation, is a technique that successfully is being used in the development and test of complex real-time embedded systems.

As shown in figure 1, such real-time embedded systems have a very high degree of complexity, which substantially increased during recent years. In order to work within certain standards, structures that are even more complex are needed for some projects, because there is no methodology or other established way of implementation at this stage. Coming from the age of testing, the technical development has passed through the age of simulation to the current age of HiL testing in combination with simulation. Because of this, a

![Figure 1: Transition to the new future development process](image)
new development methodology is needed to bring the next paradigm shift to the age of virtual development. This is important to lower the already high degree of complexity to a new manageable level.

As shown in figure 2, optimization of hybrid powertrains and their operating strategies as well as the combination of virtual and physical systems are selected applications for introducing the new development methodology within the scope of a Diesel hybrid powertrain research project.

The new development methodology is being implemented for two different applications. In use case 1 (individual mobility), the methodology is applied to a vehicle with a Diesel hybrid powertrain, where the powertrain configuration and the operating strategy are optimized in particular to achieve lowest possible emissions under RDE conditions. This scenario is of overriding relevance due to the latest emission legislation in Europe. Especially the possibility of emission-free driving in the inner-city area in combination with low fuel consumption on longer driving distances is a sustainable and efficient contribution of a full hybrid powertrain to future mobility. In this context, the relationship between the distribution of electrical and internal combustion engine power plays an essential role.

Figure 3 shows the selected topology for this use case, a P2 Plug-in Hybrid Electric Vehicle (PHEV).

In use case 2 (logistics), the focus is on the distribution traffic of vehicles with up to 3.5 t weight. With the aid of virtual scaling, concepts for hybrid powertrains of such light commercial vehicles are simulated and evaluated analogously to use case 1. The focus in the area of operations management is on economic route optimization (economic efficiency strategy). In order to avoid downtimes with high local pollution of the environment, bottlenecks in urban areas can be specifically bypassed. The online optimization of driving routes helps to reduce energy consumption and improve traffic flow.

Essential parts of both use cases are real-time capability and scalability of the powertrain component simulation models, which are the outcomes of this interdisciplinary working environment. In summary, a new development method, which enables a cost-efficient introduction of optimized powertrain technologies in the context of digital and networked mobility, is created in this way.

The Center for Mobile Propulsion (CMP) of the RWTH Aachen University with its real-time capable system for test bench interconnection as well as the environment for close cooperation of research specialists provides optimal conditions for realizing this new development methodology. The research project unites several departments of engineering from the RWTH Aachen University and external enterprises: Institute for Combustion Engines (VKA), Institute for Automotive Engineering (IKA), Institute for Machine Elements and Machine Design (IME), Institute of Electrical Machines (IEM), Institute of Automatic Control (IRT), Institute for Power Electronics and Electrical Drives (ISEA) – Chair of Switched Mode Power Supplies and Electrical Drives (ISEA-LEA) as well as Chair of Electrochemical Energy Conversation and Storage Systems (ISEA-ESS) and BatterieIngenieure GmbH, DENSO Automotive GmbH, Ford-Werke GmbH as well as dSPACE GmbH.

The next steps will be the creation of real-time simulation models based on real components and their integration into a real-time Hardware-in-the-Loop environment. The topics Engine-in-the-Loop, Electric Machine-in-the-Loop and Battery-in-the-Loop will be implemented as hardware integrations. The topics gearboxes and various electrical and electronic components will be implemented in this HiL-Application on a pure simulation level.

Acknowledgements

The research project DUETT (Diesel-Hybrid Vehicles for Environmentally Conscious Mobility: A Networked System Development in a Physical and Virtual Environment) is funded by the European Regional Development Fund (ERDF) under the project number ERDF-0800841.
Reducing the displacement in combination with a boosting system (Downsizing) is an effective method to lower the CO₂ emissions of combustion engines. In addition to this, the efficiency of gasoline engines can be increased via de-throttling the engine in part-load operation, for example with a fully variable valve train. Increasing the compression ratio leads to better efficiency at part-load while for full-load a lower compression ratio is advantageous in order to reduce knocking. This conflict can be traded off through using a variable compression ratio (VCR).

The VARIMOT research project has the goal of achieving a 15 % fuel consumption benefit (NEDC) for a compact class passenger car by combining key technologies: fully variable valve train, two-step variable compression ratio and two-stage boosting. Project partners are Ford, FEV, Pierburg, Schaeffler and Hochschule Heilbronn. The base engine is a modified Ford EcoBoost 1.0 I TC-GDI engine with split exhaust ports, an integrated Pierburg “Up Valve” valve train on both the intake and exhaust side as well as FEV’s two-stage VCR. A new boosting concept based on the given variabilities has been developed by the VKA in cooperation with FEV. Honeywell provides the turbochargers for the prototypes and has adapted the turbochargers according to the requirements of the charging concept.

Key tasks of the project are performed by the project partners (see figure 1). In a first step, VKA studied existing boosting concepts, which led to a completely novel mixed-sequential boosting concept. While its manifold variabilities provide a good basis for reducing the fuel consumption and improving the engines transient characteristics, it poses a significant challenge for the engine control unit (ECU) and particularly for the calibration. To address this, a physical based ECU software is being developed with the goal of maximizing the potential of the hardware as well as providing good drivability of the demonstrator vehicle. The project concludes with a detailed validation of the developed technologies both on the engine test bench and in the vehicle.

Mixed-Sequential Boosting Concept

Initially, VKA evaluated existing boosting concepts. Target for this project was an increase of the rated power by 10 % with at the same time reduced Low-End-Torque speed by 7 %. For that reason a more complex boosting concept compared to the base single stage turbocharger needed to be developed.

The engine is equipped with two separated and integrated 3 to 1 exhaust manifolds. The left exhaust valves are connected to the first, the right exhaust valves to the second exhaust manifold. Furthermore, the exhaust valve lifts can be changed independently of each other within some limits. These technologies enable a new boosting concept which combines the benefits of a parallel-sequential boosting concept and a serial-sequential boosting concept. The mixed-sequential boosting concept consists of two parallel turbines, each connected with one of the two exhaust manifolds, and serial compressors (see figure 2). Both turbochargers have a different size. The compressor inlet of the smaller ‘High Pressure (HP)’ turbocharger is connected to the outlet of the compressor of the bigger ‘Low Pressure (LP)’ turbocharger. The operation strategy (see figure 3) is as follows:

At low engine speeds exhaust valve 2 (EV2) is closed. All exhaust mass flow enters the HP-turbine. The small turbine and small compressor provide high boost pressure already at very low engine speeds. This enables a reduced Low-End-Torque speed of 1400 1/min and 200 Nm.

In the second operation area the valve lift of EV2 is increasing continuously with rising engine speed instead of opening the HP-wastegate. Both compressors provide boost pressure and the bigger LP-TC can be sped up. A continuous switch over from one operating mode to the other provides a smooth engine torque curve without drop.

At high engine speeds, the turbine of the HP-TC can be bypassed with the HP-wastegate and the passive compressor bypass valve. The compressor of the LP-TC is providing the boost pressure. The load can be controlled through the lift of EV1. Reducing the lift provides more exhaust mass flow to the LP-turbine, which increases the boost pressure. Due to this control strategy, no LP-wastegate is required, which leads to an increased turbine efficiency and reduced costs.
A further advantage of the mixed-sequential boosting concept is apparent by the full load engine operating points in the compressor maps, shown in figure 4. The envelope curves show the operation area of the HP- and LP-compressor, highlighting the different size. With higher engine speed, the increased lift of EV2 leads to a rising boost pressure provided by the LP-TC. The petrol curve shows the overall pressure ratio of both compressors referred to the inlet conditions of the LP-compressor. The boost pressure provided by the HP-TC is reduced with increasing engine speed.

Starting at 3500 1/min the HP-wastegate is completely open and the boost pressure is provided only by the LP-TC. The engine full load operation points are centered in the compressor maps enabling high compressor efficiencies. This is another advantage of the mixed-sequential boosting concept. At rated power, the big LP-turbine and the parallel arrangement of the turbines reduce the back pressure, thus increasing the engine efficiency.

Summarizing, the novel mixed-sequential boosting concept shows many benefits compared to other boosting concepts. It enables a high specific power, a high torque at low engine speeds and a fast transient response. The turbocharger operation control via the exhaust valves allows a continuous switch over between the operation modes without additional flaps in the exhaust system. This system can also be realized with other valve train concepts which are not fully variable. The boosting concept provides high boost pressure which can be used to increase the engine efficiency by using the Miller cycle. Finally, strategies for cold start have been investigated: exhaust valve 2 should be closed and the exhaust gases pass through only one exhaust manifold. Subsequently, the thermal loss of the exhaust gas upstream the catalyst is minimized due to relatively small surface areas in the exhaust system.

**Engine Control**

The development of the engine controls represents one key element in the VARIMOT project. The engine’s complex hardware poses a significant challenge for the engine control, in particular the valve train and separated exhaust manifolds. VKA is involved in two main topics of the ECU software. Firstly, the air charge estimation is the element of the ECU that calculates the amount of fresh air entering the cylinders in real time. It is essential for achieving a precise fuel metering and thus emissions control based on the engine test bench results.

The second topic for the ECU software is the load control, i.e. the determination of setpoints for all air path actuators in order to achieve the load requested by the driver. One major part of the load control for a turbocharged engine is the boost pressure control. Its goal is to achieve the requested boost pressure as precise and fast as possible, while maintaining high efficiency. Conventional boost pressure control strategies often rely on some form of PID-controller that adjusts the wastegate based on the difference of nominal (or requested) and actual boost pressure. The system behaviour of the mixed-sequential boosting system is neither linear nor monotonic for changes of the valve lifts and the HP-wastegate. This means that, for example, increasing the valve lift sometimes increases and sometimes decreases the resulting boost pressure. A conventional PID-controller is not feasible for this type of control problem. Thus, advanced control strategies are required.

For this research project, a physical model of the entire air path has been set up as the basis of the boost pressure control. The required exhaust gas mass flows for both exhaust ports and turbines are calculated directly from the requested boost pressure. Further functionalities translate these values into target valve lifts and a wastegate angle.
Figure 5 shows the concept of the boost pressure control with the boost pressure and intake air mass flow setpoints as model inputs and exhaust port mass flows and wastegate angle as outputs.

\[ \dot{m}_{\text{air}} , P_{\text{boost}} \rightarrow \Pi_{\text{compr},\text{HP}} , \Pi_{\text{compr},\text{LP}} \rightarrow \text{turbocharger} \]

\[ P_T,dyn = 2 \cdot \pi^2 \cdot J \cdot \left( \frac{\dot{m}_{\text{EV1}}}{P_{\text{Boost}}} \right) \]

Since the described models are built for real-time application on an ECU, they are highly efficient and a complete optimization for the entire engine map can be performed in less than 30 minutes. The result of this part of the boost pressure control is a pressure ratio setpoint for each of the two compressors.

The project underlying this report has been funded by the Federal Ministry of Economy and Energy (BMWi) under the funding indicator 19U15011. The authors are responsible for the content of this publication.

**Acknowledgement**

The described physical calculations represent a feed-forward type control, the pre-control. This means that there is no feedback of the actual boost pressure. Since the physical model has to be a simplified version of reality, there will always be deviations between modelled and actual system behaviour. Also, the model identification with measurement data has inherent inaccuracies. However, the boost pressure must be controlled precisely. Thus, a feedback type control is required.

Based on the pre-control, a PI-controller is implemented into the model structure. If there is a difference between actual and nominal boost pressure, the required additional pressure ratio is calculated for each compressor. This is then converted into the required additional turbine power using the same calculations as the pre-control. At the end, the turbine with the smallest additional power requirement is chosen. By utilizing the existing model, the result is a fast and precise but also efficient boost pressure control. Another considerable benefit is the small effort for calibrating the boost pressure control. The physical model is formulated analogous to an also implemented observer model and uses the same data sets. Thus, only values specific to the control task, like the characteristic time, need to be adjusted. Compared to conventional control strategies for advanced boosting concepts, the calibration effort is reduced significantly.

The described physical calculations represent a feed-forward type control, the pre-control. This means that there is no feedback of the actual boost pressure. Since the physical model has to be a simplified version of reality, there will always be deviations between modelled and actual system behaviour. Also, the model identification with measurement data has inherent inaccuracies. However, the boost pressure must be controlled precisely. Thus, a feedback type control is required.

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Compared to early versions of physical turbocharger models for engine controls, a more detailed description was implemented to increase model accuracy. Included are a detailed TC heat transfer, absolute pressure and temperature on the exhaust side as well as cyclic fluctuations of the conditions upstream the turbine due to the exhaust pulses. The increased accuracy is particularly important for 2-stage boosting concepts with sequential compressors. Errors in the calculation of the first compressor are amplified in the second compressor, resulting in an incorrect setpoint calculation on the exhaust side.

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To achieve current and future emission legislation limits more and more effort is necessary especially regarding exhaust aftertreatment. In addition to commonly used approaches to reduce nitrogen oxides (NO\textsubscript{X}), new techniques are being developed and tested. One of those newer methodologies is the injection of fuel upstream of an NSC (NO\textsubscript{X} Storage Catalyst) to extend the effective temperature range of NO\textsubscript{X} reduction. Those technologies as well as urea injection for SCR (Selective Catalytic Reduction) catalysts or fuel injection for an active regeneration of a DPF (Diesel Particulate Filter) bring more attention to the design and thereby simulation of the exhaust system. Whenever a fluid is injected into the exhaust system a high uniformity is one of the major challenges regarding the design of the system. For exhaust fuel injection upstream NSC also the peak shape in axial flow direction at catalyst inlet has to be taken into account.

Transient 3D CFD (Computational Fluid Dynamics) simulation is used to model a purpose-built exhaust system with exhaust fuel injection. The simulation results of the distribution of hydrocarbons (HC) at catalyst inlet in radial and axial direction are compared with measurements performed at an engine test bench. The measurements include optical measurements using Mie-scattering to determine if droplets occur at the NSC inlet and LIF (Laser Induced Fluorescence) measurements, where a tracer indicates the HC concentration in the gas phase. Additionally, the HC-concentration is measured using an emission measurement device (Fast FID (Flame Ionization Detector)). The project target is the alignment of simulation methods and measurement techniques to predict the HC distribution in radial and axial direction at catalyst inlet. This includes finding suitable measurement techniques to determine hydrocarbon concentration at catalyst inlet respectively catalyst outlet.

To achieve best results, steady state simulations were performed to support the design of the exhaust system. The target was to realize a uniform flow at the injection position and an equally distributed exhaust mass flow at catalyst inlet. Different pipe lengths and different bends at the injector position were simulated.

The designed exhaust system is shown in figure 1.

In simulation and experiment different parameters are varied to investigate their influences and to check the capability of the simulation to model them. In the following the parameters, which are varied, are listed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variation</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust temperature</td>
<td>Engine operating point</td>
<td>340 °C – 545 °C</td>
</tr>
<tr>
<td>Exhaust mass flow rate</td>
<td>Injection control</td>
<td>70 kg/h – 360 kg/h</td>
</tr>
<tr>
<td>Injection quantity</td>
<td>Injection control</td>
<td>4 mm\textsuperscript{3} - 62 mm\textsuperscript{3}</td>
</tr>
<tr>
<td>Injection frequency</td>
<td>Pressure control</td>
<td>2 Hz (constant)</td>
</tr>
<tr>
<td>Injection pressure</td>
<td>Pressure control</td>
<td>5 bar – 200 bar</td>
</tr>
<tr>
<td>Mixer type</td>
<td>Different pipes to insert in exhaust system</td>
<td>Tumble, swirl</td>
</tr>
<tr>
<td>Mixer position</td>
<td></td>
<td>Top, middle, bottom</td>
</tr>
</tbody>
</table>

Table 1: Variation parameters used for simulation and experiment

Through the operating point of the engine, certain exhaust gas mass flow rates and temperatures were varied. Those showed high significance in the pre-simulations. Regarding the injection, only injection quantity and pressure were varied, because they showed a high impact on the HC-distribution, while injection frequency and injector position were held constant throughout the experiments, because their influence on the HC-distribution were comparably small. Additionally simulations and experiments were performed with different mixers in different positions in the pipe downstream injector.

For the test bench investigations the designed exhaust system was build and mounted on a 1.4 l Diesel engine provided by Toyota.

To measure the HC concentration at different positions, a flange was designed with 13 tubes in different positions downstream the inert catalyst brick. From the tubes the exhaust gas is transported through heated lines first to a valve switch and then to a dilution tunnel where the measurement head of the fast FID was positioned.

The HC-concentration averaged over the 13 measurement positions is plotted over time to compare the HC peaks that would reach the catalyst surface (as the criteria to compare the axial uniformity). Secondly, the HC-concentration averaged over time at the different measurement positions is compared as well as the uniformity index (as a criteria to compare the radial uniformity).

Figure 2 and figure 3 show the comparisons for the four different operating points with the highest possible injection quantity in each point.
Due to the fact that the simulation does not match the peak heights at low and at high concentrations, the figures showing the time averaged concentration at catalyst inlet is scaled from minimum to maximum for each point.

With those comparisons it can already be said that the simulation can predict several trends and differences between different scenarios, but it cannot be used to predict exact concentration peaks at exact positions.

In figure 4 the average HC-concentration over time is shown for the different operating points with 1 ms injection duration.

Figure 3 depicts the HC-concentration distribution over the catalyst surface averaged over time for the different operating points. It shows that the general trends are modeled well in the simulation. In OP1 the fuel is distributed all over the catalyst inlet with no strong trend towards one corner while in OP2 the fuel is more dragged to the left and in OP3 and OP4 it is rather drawn to the right.

The comparison of the average HC-concentration over time in figure 2 shows that general trends are predicted well, but that the simulation is overestimating the high concentration in OP4. The peak duration and the gradient match well for OP3 and OP4.

Here the same can be observed, the trends are quite comparable but at lower concentrations in contrast to higher concentrations, the simulation underestimates the peaks.
In figure 5 the time averaged HC-concentration is shown for the four operating points with 1 ms injection duration.

The fuel distribution over catalyst inlet is comparable to the distribution with higher injection amounts (figure 3), which can be seen in simulation and measurement and was also expected. The results from the first simulation phase showed already that the distribution is not influenced significantly by the injection quantity (at 5 bar injection pressure). This is also confirmed by the simulation and measurement in OP4 with different injection quantities at 5 bar injection pressure.

Comparing the uniformity indices (UI), calculated from the measurement and the simulation, results show again that the trends are modeled well but do not predict the uniformity exactly. Remarkable is that the range of the modeled UI is very close to the range of the measured UI for almost all simulated and measured points. The comparison shows that also for the smaller injection amount in the higher operating points the range of UI can be predicted well.

To summarize all comparisons the different tests were evaluated regarding their compatibility of simulation and measurement for the three different categories, peak shape, distribution and UI. The evaluation for peak shape and distribution was combined to one. Because there is no quantitative significant evaluation for the conformity of the peak shape and the distribution, this evaluation is subjective just as the above descriptions (If both matched it is green and the cell contains “X”, if one of the parameters matched well it is orange and contains “O” and if both did not match well it is red and contains “-”). The deviation is the absolute deviation between both UIs. Table 2 shows an evaluation of the simulation quality for all compared tests.

For 17 from the 21 modeled variations the deviation between the calculated UI for simulation and measurement is below 3 %. For 10 Hz and for 200 bar the measurement data was not reliable, which was probably caused by droplets at catalyst inlet. It is also noticeable that for OP2 both tests do not match very well regarding the UI. For all other variations it can be summarized that the simulations without any mixers match better than the simulations with mixer. Over all it can be said that the simulation does predict the peak shape as well as the UI quite well, so it is possible to model the range of the UI and the trend of the peak shape. For 13 variations it was possible to predict the UI with a higher accuracy than +/- 2 %, and also slight deviations in peak shape can be predicted.
Engine Noise Components II

Within the framework of the FVV research project “Engine Noise Components II” a methodology was developed to separate the engine noise into noise fragments and allocate these to the emitting engine components. Furthermore, the annoyance level of the engine components is calculated and a new target sound can be synthesized weighting the noise fragments manually.

Introduction

The engine noise is always a symposium of many different engine components and processes, i.e. fuel injection pump (FIP), combustion, turbocharger, alternator noise and many more. Due to the cross-influence of the sounds sources, it is often difficult to assess the influence of single components.

In two predecessor projects noise separation methodologies have been developed to extract impulsive and tonal noises from monaural sound measurements. Taking up these techniques, the objective of this research project was to separate the monaural engine sound measurement, separate it into single sound fragments, cluster them according to their correlation and determine the emitting engine component.

Approach

In order to assess the acoustic component characteristics an extensive database is created. This database consists of several component measurements as well as engine measurements with predefined component noise shares. From the beginning, the noise is separated into two classes, impulsive and tonal noises.

Regarding impulsive noises the characteristics consist among others of the frequency fingerprint, the cyclic fluctuation strength and the structure of the modulation spectrum.

Figure 1: Frequency Fingerprint

It can be shown that although the injector and FIP have similar frequency characteristics due to the same noise generation mechanism, the cyclic fluctuation differs highly. Since there is generally only one fuel injection pump, the noise pattern is to some extent constant over time, whereas considering a multi-cylinder engine it varies for each injector and its location. Another important step forward is to divide the frequency spectrum in subsec-
tions, which are then defined by local frequency centers and corresponding widths. Since it is a well-known fact that injectors have a sharp frequency amplitude raise around 1 kHz and valve landing excites a broadband noise around 2 kHz, this technique enables to distinct between these two component noises.

From the comparison of simulation and measurement the following conclusions are drawn:

- The comparison of simulation and corrected HC distribution measurement showed good correlation regarding UI for 17 of the 21 compared variations (< 3 % deviation), while 13 showed very good conformity (< 2 % deviation).
- The variations without mixer showed better comparability than the variations with mixer, which indicates the importance of the wall film related models.
- The simulations were overestimating high concentrations and underestimating low concentrations. However, the peak shape was predicted well regarding gradient and duration for 13 of the 21 compared variations.
However, looking at tonal noises, very different characteristics have to be considered. First a distinction must be made between noises which have a midfrequency proportional to the engine speed and those which are independent.

The k-Means algorithm is applied with different NoC and the silhouette coefficient is calculated. The combination with the highest silhouette coefficient is taken.

Therefore one can reach an improved separation quality using the NNMFD.

Tonal Noises

As described before, firstly, the detected tonal noises have to be separated into order dependent and order independent noises. Considering a run up or coast down, this can be achieved using either the measured or the calculated engine speed over time.

The more challenging problem is to cluster single line segments. Regarding the rotation speed dependent noises it is of major importance to consider that the order resolution decreases with decreasing engine speed. Due to this increasing uncertainty, a cascaded clustering algorithm has to be implemented using the standard deviation as a measure to quantify the clustering process. Furthermore, a tonal noise can be a composition of neighboring orders, they have to be split beforehand.

Order independent noise (here: turbocharger noise) can be divided into unbalancing whistle, rotation noise and constant tone. Each effect has a characteristic frequency area, which is well analyzed and documented in literature. These limits are implemented, and furthermore, line segments are clustered according to their width, sound pressure level over frequency and local gradient.

Classification

Since the database is not sufficient for training a neuronal-network, a naïve Bayes model is trained based on chosen discrete attributes. The tonal noises are classified using a decision tree, which also considers effects such as slip effect, integer quality of the order and sound pressure level over engine speed.
Evaluation of a Homogenous CNG-DI Combustion System

The reduction of climate effective CO₂ emissions in the transport sector is one of the main targets in modern engine development. Gas fuels have a high CO₂ reduction potential and knock resistance due to their chemical and thermal properties, which make them an interesting fuel alternative for the use in modern spark-ignited engines. Especially Compressed Natural Gas (CNG), which mainly consists of methane, offers a high potential of CO₂ reduction not only because of its low carbon to hydrogen ratio. Moreover, the generation of natural gas from biomass and the synthetic production of methane from renewable electricity, hydrogen and CO₂ offers further possibilities for a CO₂ reduction due to the consumption of CO₂ during the production process.

The operation of a gasoline engine with natural gas nevertheless faces some challenges based on the characteristics of natural gas, which need to be considered during the evaluation of the potential of CNG in combustion engines. The goal of this research project in cooperation with the University of Magdeburg is the definition of an ideal combustion process exploiting the advantages through the direct injection of compressed natural gas. The stoichiometric and homogeneous combustion system with direct compressed natural gas injection is investigated in combination with high-load exhaust gas recirculation (EGR), Miller cycle and alternative ignition systems.

Optical investigations in a low pressure chamber were used to characterize the direct injection of CNG with the target to derive a validated 3D-CFD injector model for the subsequent numerical investigations. Figure 1 shows the comparison between the optical measurement of the CNG injection via Schlieren technique (left half of the images) and the results of the 3D-injector model (right half of the images) for three timings during injection. The injection pressure is set to 16 bar with a back pressure of 1 bar. For numerical results the iso-surface of 5 % CH₄ concentration is illustrated. The arrows emphasize the correspondence between the simulation and optical results: the primary structure (dark blue), the transition structure (light blue) as well as the roll-up structure (red) are reproduced sufficiently accurately by the simulation.

Further, the injector model is validated by Particle Image Velocimetry (PIV) measurements on a motored, optically accessible single-cylinder engine. The evaluation of the PIV raw images shown in figure 2 confirms a high accordance between the numeric 3D-simulation model results and the optical results for both lateral and central injector position.

Figure 1: Validation of 3D-CFD injector model with optical measurement (Schlieren technique)

Figure 2: Validation of 3D-CFD injector model with optical engine measurement (PIV raw images)
The analysis of the charge motion for measured and calculated injection timings as well as injector positions reveals that lateral injection generally improves the second tumble peak compared to central injector position (see figure 3), what should result in an advantageous, higher turbulent kinetic energy near ignition spot. In terms of the charge motion an early start of injection (SOI = 320° CA bTDC) appears to be advantageous for both injector positions. While a late lateral injection (SOI = 160° CA bTDC) seems to support the tumble motion, the central late injection destroys the second tumble peak entirely. The negative influence on volumetric efficiency has to be considered in case of an early injection strategy.

Experimental studies on the fired single-cylinder research engine show that an injection timing after closing of the intake valves is especially advantageous regarding the volumetric efficiency and combustion stability in low end torque engine operation at 20 bar indicated mean effective pressure and an engine speed of 1500 1/min. The maximum injection pressure of 16 bar provides enough time for a homogeneous mixture formation. Despite the high compression ratio of 14.7:1 an optimal center of combustion of 8° CA bTDC can be reached in this load point, leading to an indicated efficiency of 39.5 %.

Figure 3: Calculated tumble ratio at low end torque for central and lateral injection as well as early and late injection timing

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Figure 4: Load sweep at 1500 1/min

Acknowledgment

The scientific works presented on pages 62 to 75 were performed within the scope of different research projects of the Forschungsvereinigung Verbrennungskraftmaschinen e.V. (FVV) which were partly co-funded by the Arbeitsgemeinschaft industrieller Forschungsvereinigungen "Otto von Guericke" e.V. (AiF). The Institute for Combustion Engines likes to thank the working group members and their chairmen for the great support in all of those research projects. Besides, the Institute for Combustion Engines likes to thank all companies who supported the projects with hardware contributions and therefore considerably contributed to the success of each project.
Several new research projects with the involvement of the Institute for Combustion Engines started in 2017. This overview gives insight into selected highlights. Further research projects in cooperation with the Federal Ministry of Education and Research, the Federal Ministry for Economic Affairs and Energy, ministries of the state of North Rhine-Westphalia, German Research Foundation (DFG), FVV - Research Association for Combustion Engines e.V. and other funding organizations will be launched soon.

ALIGN-CCUS – “Accelerating Low-Carbon Industrial Growth through CCUS”

The ALIGN-CCUS project aims at transforming six European industrial regions into economically robust, low-carbon centers by 2025. 34 research institutes and industrial companies have secured European and national funding for six specific but interlinking areas of research into carbon capture, utilization and storage (CCUS). One pathway which is investigated in ALIGN-CCUS, is the reuse of captured CO2 as synthetic Diesel fuel (OME & DME). At the VKA, research focuses on the investigation of flow analysis, fuel preparation and combustion with the purpose of energy saving and engine-related avoidance of emission generation of those synthetic fuels. VKA will build up two technology demonstrators for CCU-fuels: A passenger car fueled with OME and a generator engine fueled with OME.

HIFI-ELEMENTS – “High Fidelity Electric Modelling and Testing”

HIFI-ELEMENTS is a three-year research and innovation action involving 16 European partners. HIFI-ELEMENTS will develop, validate and publish a recommendation for standardization of model interfaces for common e-drive components, and will implement compliant versions of existing models. Secondly, the project will implement a seamless workflow linking extended versions of existing tools – a model/data management tool and a co-simulation tool for MiL and HiL environments – augmented with effort-saving automated methods for model parameterization and test case generation.

FC-SIM – “Fuel Cell System Simulation – Membrane Humidification Management”

The last years of development led to a significant progress in fuel cells for mobile applications up to fuel cell electric passenger cars in series production. The research project “FC-SIM” aims to develop a fuel cell system model to describe the membrane humidification under dynamic conditions as well as to develop a methodology to transfer the model to a HiL application to be able to optimize the operation strategy. The Institute for Combustion Engines and ZBT GmbH contribute to this project.

Oil Input into Combustion

The combination of gasoline direct injection and turbocharging offers a high potential especially for gasoline engines to reduce the fuel consumption without limiting driving dynamics. Therefore it is essential to reduce the tendency to preignition. Based on novel basic research, the application of numeric flow simulations as well as engine experiments, the project studies the oil input from external sources in the intake system as reason for preignition of a turbocharged gasoline engine.

X-EMU

The X-EMU project will face the challenge of efficient and environmentally friendly railroad traffic on non-electrified sections. On various railroad sections the installation of catenaries is neither economical nor ecological resulting in Diesel systems as current state of the art for transportation and especially commuter trains. An electrical multiple unit (EMU) could electrify these sections and replace several Diesel systems. The X-EMU will form a special unit operated with a hybrid system of a battery electric powertrain and a fuel cell system. The system setup and operation strategy will be researched and optimized at RWTH Aachen University’s Center for Mobile Propulsion by VKA, IEM and ISEA researchers.


The simultaneous reduction of fuel consumption and pollutant emissions, namely NOx and soot, is the predominant goal in modern engine development. Reactivity Controlled Compression Ignition (RCCI) is a promising high efficient combustion concept that combines Euro-VI engine-out NOx and PM emissions with 25 % CO2 reduction compared to mono-fuel Diesel reference. The project consortium consisting of the Institute for Combustion Engines and three more project partners studies two novel RCCI combustion systems in combination with an innovative dual-fuel injector to reduce in-cylinder CH4 emission and maximize thermal efficiency. With Diesel as a reactive base fuel, natural gas as well as ethanol are used as homogeniously injected RCCI fuel component.

2030+ – “Requirements on Emission Control - MD/HD”

Until now, there are no CO2 emission limits for commercial vehicles given yet in Europe, but the preparations for their introduction will be finished soon. The aim of the research project “2030+” is to define the thermodynamic and chemical boundaries for exhaust aftertreatment systems of medium and heavy-duty vehicles as well as non-road machinery.

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Events in 2017
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. To discuss these topics, the third Symposium for Combustion Control took place in Aachen on June 28th and 29th, 2017.

The symposium focused on the latest theoretical and application-driven developments for the control of next generation combustion engines. 18 lecturers as well as 7 poster presenters showed latest results and developments in these fields. Moreover, the participants enjoyed excellent keynote speeches. In his presentation, Dr.-Ing. Michael Krüger, Senior Vice President of Robert Bosch GmbH, reflected on the question of future combustion control as rather open loop or closed loop. Professor Dr. Christopher Onder from the Department of Mechanical and Process Engineering at ETH Zurich talked about combustion control as an enabler for efficient and reproducible engine systems research. Finally, Professor Bengt Johansson from Clean Combustion Research Center at the King Abdullah University of Science and Technology presented his topic “Partially Premixed Combustion – Temperature Sensitive as HCCI and Injection Timing Sensitive as Diesel”.

The annual Symposium for Combustion Control fosters the interaction between the scientific community and the automotive industry. The fourth edition will take place on June 28th and 29th, 2018.

Tailor-Made Fuels: From Production to Propulsion
5th International Conference, June 20th to 22nd, 2017

The international conference “Tailor-Made Fuels: From Production to Propulsion” hosted by the Cluster of Excellence “Tailor-Made Fuels from Biomass” took again place in Aachen in 2017. Experts from around the globe as well as Cluster researchers presented their latest results in the fields of synthesis, production and combustion of modern alternative fuels from biomass, CO2 or renewable electricity strengthening the interdisciplinary research work.

In various sessions, fascinating topics like fuel design, selective biomass conversion or fuel application 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 2018, the “Tailor-Made Fuels: From Production to Propulsion - 6th TMFB International Conference” will take place from June 19th to 21st in Aachen.
The Aachen Colloquium Automobile and Engine Technology, organized by Professor Lutz Eckstein, Institute for Automotive Engineering, and Professor Stefan Pischinger, Institute for Combustion Engines of RWTH Aachen University, took place for the 26th time already. Europe’s most renowned congress in automobile and engine technology again offered more than 100 technical presentations, a technical exhibition with more than 60 exhibitors and an excellent social program. Hence, the Aachen Colloquium was again fully booked with 1800 participants.

After a welcome by Professor Ernst Schmachtenberg, Rector of RWTH Aachen University, the plenary speeches of high-ranking executives from the automotive industry gained undivided attention.

Toshihiro Hirai, Alliance Global Director and Corporate Vice President of Nissan Motor Co., Ltd., presented Nissan’s powertrain technology strategy accompanied by the “Nissan Powertrain Vision – Zero Emission”, which is meant to save 90 % of emissions until the year 2050.

Thomas Anliker, Senior Vice President Global Sales, Marketing & Aftersales of Borgward Group AG, talked about the topic “Agile, Flexible, Fit – The New Ease in the Automobile Industry”. The OEM plans to launch one new model every year.

Professor Ralf G. Herrtwich, Senior Vice President Automotive of the company HERE, completed the opening plenary session. He reported about learning maps for automated vehicles. Besides conventional information about the road course, HERE’s HD maps also include precious meta data for automated driving functions.

In the closing plenary session, Christian Müller, Vice President Global Propulsion Systems of Opel Automobile GmbH, explained how the Opel Ampera-e does not only convince with range and offers electromobility without compromising.

Finally, Professor Peter Gutzmer, Chief Technology Officer and Deputy CEO of Schaeffler AG, looked into the future with a presentation of his topic “Mobility for Tomorrow – Between the Poles of Electrification.”

In the future the varied topics of automobile and engine technology will continue to be of high significance for research and industry. In 2018, participants from about 30 countries will again experience a lively exchange on technical innovations and latest developments in the automotive industry.
The Institute for Combustion Engines hosted the fourth mobilEM Colloquium in Aachen in October 2017, which took place at the Center for Mobile Propulsion (CMP). The different research areas covered by the research training group were presented. For each research area a professor gave an overview over the current state of the art and the fields of research. Moreover, speakers from industry shared their perspective on current challenges in each field. Posters and presentations by doctoral candidates delivered a further insight into current research topics and the progress of their work.

In 2017, ten lecturers gave insights into latest works. Dipl.-Ing. Peter Lückert from Daimler AG opened the seminar series by presenting the Diesel Engine OM654 and solutions for RDE fulfillment. Two more engine presentations followed: Dipl.-Ing. Dirk Häcker from BMW M AG showed the high performance engine of the M4 GTS with water injection and Dipl.-Ing. Jürgen Königstedt from Audi AG explained the new 3.0l-V6-TFSI Audi engine. In another lecture, Dr.-Ing. Frank Casimir from GETRAG FORD Transmissions GmbH talked about the effect of powertrain hybridization on transmission development. Afterwards, Andrew Brumley, M.Sc., from Ford Motor Company presented the new Ford EcoBlue family of Diesel Engines, while Dr.-Ing. Hans-Otto Hermann from Daimler AG gave a lecture on Daimler Trucks engine development and solutions for emerging markets up to future CO2 and ultra-low emission limits. Dr.-Ing. Nikolai Ardey from AUDI AG talked about the mild hybrid transmission in the new Audi A8.

The following presentation given by Dipl.-Ing. (FH) Thomas Werner from Winterthur Gas & Diesel Ltd. informed about “Generation XEngines. 2-Stroke Engine Concepts, Design, Performance and Emission Compliance”. Dr. techn. Wolfgang Demmelbauer-Ebner from Volkswagen AG explained why e-gas is an important component on the way to CO2-neutral mobility. Finally, Dr. Peter Ramminger from Opel Automobile GmbH concluded the seminar series for 2017 with his presentation of the Opel Ampera-E propulsion system.

Especially the presentation of Dr. Peter Ramminger from Opel Automobile GmbH about the propulsion system of the Opel Ampera-e gained attention. In addition, power electronics for electric axle drives where presented by Dr.-Ing Matthias Bösing from Robert Bosch GmbH. In the field of battery research, Professor Rüdiger Eichel from Forschungszentrum Jülich thought about future concepts of “post lithium-ion” electrochemical energy storage. Marco Roggero from The Mathworks concluded the colloquium with his speech on the development of perception systems for autonomous driving.

Numerous further presentations of doctoral candidates from the research training group mobilEM reflected on the varied research areas of electrical energy storage, power electronics, thermal management, range extender modules as well as control and system simulation. Several doctoral candidates presented posters on research results in the poster sessions, which took place during the breaks. Around 70 people from industry and various universities took part in the colloquium and the discussions after the presentations resulting in an inspiring scientific exchange.

The 5th mobilEM Colloquium will take place in October 2018.

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The Institute for Combustion Engines was represented by Konrad Herold sharing his findings on generator control for range extenders with rolling torque compensation. Moreover, Stefania Esposito gave insights into her research on emission simulation for range extender and hybrid vehicles.

 already since the winter semester 1973/1974, the Institute for Combustion Engines offers the series of events “Engine Technology Seminar”. Experts from the automobile and engine industry hold lectures on recent issues from engine development as well as on interdisciplinary topics. Like this the Engine Technology Seminar especially serves as connection between university research and professional practice. Following the presentation, the audience has the opportunity to discuss with the speaker about his findings. The Engine Technology Seminar is open for all interested visitors.

In 2017, ten lecturers gave insights into latest works. Dipl.-Ing. Peter Lückert from Daimler AG opened the seminar series by presenting the Diesel Engine OM654 and solutions for RDE fulfillment. Two more engine presentations followed: Dipl.-Ing. Dirk Häcker from BMW M AG showed the high performance engine of the M4 GTS with water injection and Dipl.-Ing. Jürgen Königstedt from Audi AG explained the new 3.0l-V6-TFSI Audi engine. In another lecture, Dr.-Ing. Frank Casimir from GETRAG FORD Transmissions GmbH talked about the effect of powertrain hybridization on transmission development. Afterwards, Andrew Brumley, M.Sc., from Ford Motor Company presented the new Ford EcoBlue family of Diesel Engines, while Dr.-Ing. Hans-Otto Hermann from Daimler AG gave a lecture on Daimler Trucks engine development and solutions for emerging markets up to future CO2 and ultra-low emission limits. Dr.-Ing. Nikolai Ardey from AUDI AG talked about the mild hybrid transmission in the new Audi A8.

The following presentation given by Dipl.-Ing. (FH) Thomas Werner from Winterthur Gas & Diesel Ltd. informed about “Generation XEngines. 2-Stroke Engine Concepts, Design, Performance and Emission Compliance”. Dr. techn. Wolfgang Demmelbauer-Ebner from Volkswagen AG explained why e-gas is an important component on the way to CO2-neutral mobility. Finally, Dr. Peter Ramminger from Opel Automobile GmbH concluded the seminar series for 2017 with his presentation of the Opel Ampera-E propulsion system.

Especially the presentation of Dr. Peter Ramminger from Opel Automobile GmbH about the propulsion system of the Opel Ampera-e gained attention. In addition, power electronics for electric axle drives where presented by Dr.-Ing Matthias Bösing from Robert Bosch GmbH. In the field of battery research, Professor Rüdiger Eichel from Forschungszentrum Jülich thought about future concepts of “post lithium-ion” electrochemical energy storage. Marco Roggero from The Mathworks concluded the colloquium with his speech on the development of perception systems for autonomous driving.

Numerous further presentations of doctoral candidates from the research training group mobilEM reflected on the varied research areas of electrical energy storage, power electronics, thermal management, range extender modules as well as control and system simulation. Several doctoral candidates presented posters on research results in the poster sessions, which took place during the breaks. Around 70 people from industry and various universities took part in the colloquium and the discussions after the presentations resulting in an inspiring scientific exchange.

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Open Day at the Aldenhoven Testing Center (ATC) for the Employees and their Families

June 24th, 2017
Christmas Celebration of the Institute for Combustion Engines

December 22nd, 2017