The Year 2014 at the Institute for Combustion Engines
Dear Readers,

The Year 2014 at the Institute for Combustion Engines (VKA) was a year full of work, but also a year full of great research results and events, only made possible by the great cooperation of all employees.

With this review of our year 2014, we are happy to give you insights in our facilities and research projects. Enjoy reading!

Yours,

Stefan Pischinger, Head of the Institute for Combustion Engines

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The Institute for Combustion Engines (VKA)
The Institute for Combustion Engines (VKA) covers classical engine topics like innovative engine design and research and development of new more efficient and clean combustion systems. In addition, topics with more and more rising importance like the virtual engine development, research at the complete powertrain of hybrid powertrains and engine electronics are considered. All this is associated with the ongoing development of intelligent methods for test procedures and engine calibration, e.g. by “Design of Experiment” (DoE).
281 Employees in total

71 Scientific Employees
- Combustion Development
- Optical Diagnostics
- Exhaust Gas Aftertreatment
- Mechanic / Design / Acoustics
- Hybrid Systems & Electromobility
- Fuel Cells

100 Student Assistants
- Research
- Administration

11 Completed Dissertations

1 Head of the Institute
Professor Dr.-Ing. Stefan Pischinger
The Institute for Combustion Engines (VKA)

3 Chief Engineers
- Research
- Operations
- Cluster of Excellence TMFB

1 Junior Professor
- Mechatronic Systems for Combustion Engines

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

136 Completed Diploma, Master and Bachelor Theses
The inauguration of the „Center for Mobile Propulsion“ at RWTH Aachen University marked a further milestone in Aachen’s history of high-quality research centers. Led by the Institute for Combustion Engines (VKA), 16 institutes joined forces to investigate and optimize electrified mobile powertrains in an interdisciplinary approach. The upcoming worldwide changes in energy production and distribution will have an impact on the mobile sector. Fossil energy resources are limited and thus will become more expensive within the next years. Simultaneously, the share of energy produced by renewable resources rises. Both effects inevitably lead to an increase of the share of electrical energy in the society’s energy mix. New technical developments in mobile propulsion, especially hybrid and battery technology, widen the development of propulsion systems to an integrated research field of numerous different disciplines. Tasks concerning the research of new powertrains hence become constantly more complex and therefore require interdisciplinary cooperation.
The interdisciplinary approach chosen for the establishment of the Center for Mobile Propulsion is also reflected in the experimental instrumentation of the research center: Within the CMP, component test benches for batteries, electric motors, transmissions, combustion engines and powertrains are installed. By focusing all these test benches at one facility, real-time communication between the different component test benches is enabled via network. The integration of a simulator facilitates to simulate a systematic behavior of early stage components. Thereby, virtual powertrains can be outlined independently from individual setups. By this, researchers can examine interactions of single components in dynamic use, consider the effects of different topologies and explore necessary control strategies of the overall system in an early project phase. Moreover, the test laboratory has an integrated workshop to conduct setups and alterations on-site. The test benches are designed highly flexible for time saving and an effective use.
Since 2007, the Cluster of Excellence “Tailor-Made Fuels from Biomass” (TMFB) has been working on a solution for one of the major challenges that our society is facing today: a rising energy demand and the limited availability of fossil energy resources. For this purpose, researchers from the fields of chemistry, biology, process engineering and mechanical engineering have joined forces in this Cluster of Excellence to develop new alternative fuels from biomass which will not be competing with the food chain.

The vision of the cluster of excellence is to establish innovative and sustainable processes for the conversion of whole plants into fuels which are tailor-made for novel low-temperature combustion engine processes with high efficiency and low pollutant emissions, paving the way to the 3rd generation of biofuels. A tailor-made fuel as aimed for by the researchers in TMFB is defined as a well-defined blend of distinct molecular components with optimized physicochemical properties for future combustion systems, which can be produced by sustainable and economical production processes. In an interdisciplinary approach, more than 70 scientist are engaged in analyzing, understanding and optimizing the synthesis and combustion of such fuels.
The research activities of TMFB are organized in two major „Integrated Research Fields“ (IRF): IRF-A „From Biomass to Biofuels“ and IRF-B „From Biofuels to Propulsion“. These research fields are linked by the „Core Interaction Field“ (CIF) „Fuel Design“ under management of Professor Stefan Pischinger of Institute for Combustion Engines (VKA). The major goal is to describe a „Fuel Design Process“ with which a tailor-made fuel with any desired properties can be developed from biomass. Therefore, the direct link and interaction between the fuel production (addressed in IRF-A) and the fuel combustion (addressed in IRF-B) through the CIF „Fuel Design“ is crucial as well as unique worldwide.

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.
The area of the former coal mine Emil Mayrisch now comprises testing facilities for automotive research and development. Besides the vehicle dynamics area, which is operational since 2009, the testing center has been completed with an oval circuit, a braking test track, a rough road, a handling track and a hill section. In addition to these rather classical elements of a conventional automotive proving ground ATC is completed with automotiveGATE, a worldwide unique infrastructure to simulate Galileo satellite signals. This enables the development and trial of new Galileo-based systems or components even before a sufficient amount of satellites is up and running allowing positioning with the signals from space.

The Aldenhoven Testing Center of RWTH Aachen University GmbH is a subsidiary of Düren County and RWTH Aachen University. Besides these two the Institute for Combustion Engines (VKA), the Institute for Automotive Engineering (ika) and the Institute of Control Engineering (IRT) of RWTH Aachen University have contributed to the costs directly. The state of North Rhine-Westphalia and the European Union supported this project financially. The ATC GmbH built the testing center and operates it.
The Test Track Elements

Oval Circuit
The oval circuit is the central element of the testing center. It provides a total length of approximately 2 kilometers and comprises 3 lanes. Lateral force free driving is possible up to 117 km/h. Event trucks can use the oval circuit.

Braking Test Track
The braking test track with different friction linings, which are floodable, allow tests to analyze the braking performance of a vehicle.

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.

Hill Section
The hill sections offer different slopes of 5%, 12% and 30%. The 12% track can be flooded.

Rough Road:
Different road surfaces are available on a straight part of the oval circuit to conduct evaluations of ride comfort.

Handling Track
The handling track with various curve radii allows the testing of driveability and chassis in extreme situations.
New in 2014
Professor Dr.-Ing. Jakob Andert directs the Junior Professorship for mechatronic systems for combustion engines and coordinates research in this interdisciplinary field. Structurally, the professorship is affiliated with the Institute for Combustion Engines under the direction of Professor Dr.-Ing. Stefan Pischinger.
Both the proximity to the VKA and access to the infrastructure of the Center for Mobile Propulsion allow the efficient use of synergies and the direct interaction with researchers who are working on various topics related to combustion engines and mobile drive technology.

The research focus of the new professorship is in regard to complementary fields such as mechatronic engine components, hybrid drive technology, real-time combustion control by high-speed indication analysis, as well as topics relating to connected mobility and interactive test benches. In order to further strengthen the testing capabilities of electronic components at the VKA, a “hardware-in-the-loop” test rig will be installed and used for real-time simulation and testing.

“Powertrain electrification and the use of smart components is a very promising approach for further improving efficiency and reducing emissions of combustion engines. However, the new degrees of freedom have to be calibrated and optimized carefully to tap the full potential of mechatronic systems. Holistic approaches to combine real-time simulation and component development at early stages are required to handle the rising complexity.”

Contact
Prof. Dr.-Ing. Jakob Andert
Junior Professor for Mechatronic Systems for Combustion Engines
Phone: +49 241 80 48071
andert@vka.rwth-aachen.de

2015
The new Symposium for Combustion Control (SCC) will take place from June 17th to 18th, 2015.
Grand Opening of the Aldenhoven Testing Center
After an intense period of planning and building the Aldenhoven Testing Center (ATC) was inaugurated in April 2014. The former coal mine Emil Mayrisch now comprises testing facilities for automotive research and development.

Garrelt Duin, Minister for Economic Affairs, Energy and Industry of North Rhine-Westphalia, Wolfgang Spelthahn, District Administrator of Düren, and Prof. Dr.-Ing. Ernst Schmachtenberg, Rector of RWTH Aachen University, officially opened the testing center on April 11th, 2014 with a presentation of the project and a visit of the test track. An open day enabled interested guests to explore the testing facilities on foot or bicycle and in test drives.

ATC grounds allow research on full vehicles and their subsystems alone or in total and thus add to safety, energy efficiency and driving pleasure. Multiple driving situations like platooning, the impact of driver assistance systems such as advanced cruise control (ACC) or curve detection and warning, but also collision- or intersection-situations can be analysed here safely, reproducible and without constricting real road traffic. Furthermore, topics regarding the combustion engine, such as the reduction of fuel consumption or pollutant and noise emissions, can be inquired in Aldenhoven. Some of the current research projects also focus on hybrid drive concepts and fuel cell systems.
Rebuilding and Modification of the Chassis Dynamometer

Motivation

In order to strengthen strategically the profile areas „Mobility and Transport Engineering“ as well as „Energy, Chemical and Process Engineering“ of the RWTH Aachen University, the chassis dynamometer of the Institute for Combustion Engines is rebuild since march 2014. This is intended to accommodate the scientific and legal requirements for research infrastructure in the development process of modern passenger car powertrain concepts.

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

Consequently there are powertrain concepts, which cannot be investigated with a conventional single axle test bench. In order to meet the future technical requirements, the old single axle dynamometer is replaced by a brand new 4-wheel drive chassis dynamometer. This 4-wheel drive dynamometer consists of two driven and independently operable axles. The front axle is installed fix, while the rear axle is arranged slidable/variable and a wheelbase between 1.800 mm and 4.400 mm can be realized.

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

Figure 1: New 4-wheel chassis dynamometer of VKA
Technical data of the new 4-wheel drive chassis dynamometer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. testing velocity:</td>
<td>250 km/h</td>
</tr>
<tr>
<td>Max. power (front axle):</td>
<td>220 kW (short-time overload up to 330 kW)</td>
</tr>
<tr>
<td>Max. power (rear axle):</td>
<td>220 kW (short-time overload up to 330 kW)</td>
</tr>
<tr>
<td>Max. power (4WD):</td>
<td>440 kW (short-time overload up to 660 kW)</td>
</tr>
<tr>
<td>Max. traction force (front axle):</td>
<td>6.400 N</td>
</tr>
<tr>
<td>Max. traction force (rear axle):</td>
<td>6.400 N</td>
</tr>
<tr>
<td>Max. traction force (4WD):</td>
<td>12.800 N</td>
</tr>
<tr>
<td>Mass simulation:</td>
<td>150 kg up to 4.536 kg</td>
</tr>
<tr>
<td>Diameter:</td>
<td>48&quot; (1.219,2 mm)</td>
</tr>
<tr>
<td>Wheelbase:</td>
<td>1.800 mm bis 4,400 mm</td>
</tr>
<tr>
<td>Max. axle load:</td>
<td>2.500 kg</td>
</tr>
<tr>
<td>Dynamometer width:</td>
<td>700 mm</td>
</tr>
<tr>
<td>Inner distance:</td>
<td>900 mm</td>
</tr>
<tr>
<td>Outer distance:</td>
<td>2.300 mm</td>
</tr>
</tbody>
</table>
Modernization

In order to operate the modernized climate 4-wheel chassis dynamometer of the Institute for Combustion Engines at its best in the near future additionally the extension of the sampling system as well as the modernization/upgrading of the automation system happened. Thus it is possible to feed the exhaust gases of gasoline engines via an additional dilution tunnel to the exhaust gas measurement system (e.g. particle mass and particle number). A slidable Mixing T (variable fresh air supply) is mounted to compensate the different restraints of vehicles and motorcycles.
Implementation (Hardware)

- Common path for dilution air for both tunnels -> shifting process realized by variable flaps
- Additional isolated dilution tunnel for gasoline vehicles
- Additional particle sampler for gasoline vehicles, gravimetric measurement principle
- New and compact mobile mixing point for vehicles and motorcycles
- Sampling system switch for the particle number measurement for gasoline and diesel vehicles
- Particle sampling system for four phases; 2x particle filter set 47 mm EPA compliant for primary and secondary filter application
- US/EU probes with pneumatic shift

Implementation (Software)

New Automation System (MPAS) features:

- Path-dependent editor, MPAS offline
- Integration of new analysis tool for subsequent test review
- Integration of old exhaust gas measurement systems and all subsystems to MPAS via standardized AK interface protocols
- FEVER exhaust analysis with 3rd raw sample line
- Fourier Transformation Infrared Spectrometer (FTIR spectrometer)
- MSS AVL 483 Smokemeter
- TSI/Matter 3790 and AVL APC 489 (PNC measurement)
- Carflow 150 Sick Maihaik (Exhaust volume flow measurement)
- Power analyzer HIOKI 3390 with clamp meters HIOKI 9278

Data analysis

- Data analysis with MPAS offline
- Additional evaluation tool with dynamometer individual scripts to extend the calculations in MPAS offline
- Dead time correction (phase corrected or individually for each vehicle)
- Fuel consumption calculation for various fuels (e.g. E5, E10, E85, Diesel, B5, B100, LPG, CNG)
- All relevant emission legislations (ECE; US, Japan, Brazil, India, China) are captured for vehicles as well as for motorcycles, including the path dependent speed curves and evaluation in accordance to the emission legislation
Figure 4: Schematic overview of the new chassis dynamometer

Pre-design of flow conditions within the new climate chamber

During the modernization detailed numerical flow simulations were conducted. By means of those simulations significant enhancements regarding the flow conditions within the dynamometer test bench could be achieved. An additional intermediate ceiling and baffle leads to an improved flow motion within the chamber and especially at the topside of the vehicle between vehicle roof and ceiling (Figure 5 below). Besides, a better homogenization at the cooling fan inlet is also achieved and results in a good uniformity of the cooling air for all types of vehicles and reduced flow resistances at the cooling fan outlet (Figure 5 below).
In the line of the modernization and the flow motion analysis the rebuild of the air speed fan was also implemented. This now enables a simulation of the airstream up to 135 km/h, while at the same time with the air speed fan the global requirements for the WLTP cycle and of the EPA regarding homogenization and flow velocity are met. The modernized air speed fan is versatile due to the flexible arrangement (hover cushion and height-adjustable jack screws) and therefore is highly suitable for the application of different types of vehicles.

Extended test program – Motorcycle operation now also possible!

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

The complexity and the number of components used in modern powertrains rise continuously. The typical development process can be described using the V-Process, with requirement definition on the left and testing on the right side of the process (Figure 1). In the subsystem layer of conventional powertrain testing, all components are analyzed separately on different test benches. The internal combustion engine usually is tested on a conventional engine test bench which fulfills all needs of thermal, thermodynamic and mechanical analysis. The test object is connected to a dynamometer which defines the operation point and simulates the engine load. On the same level of the V-Process, the transmission is tested by a separate testing layout which consists of at least two dynamometer machines which are coupled with transmissions engine and output shaft. On both test benches steady state tests at constant speed as well as dynamic transient tests with varying boundary conditions are carried out.

Each element of the powertrain system is analyzed separately with high effort on the component specific requirements. Combustion engine test benches offer great possibilities of emission or NVH analysis. Transmission chambers usually are focused on durability tests, NVH analysis and offer the possibility to supply hybrid transmissions with electrical power. These testing facilities are highly optimized on the requirements of each subsystem type.

However, no interaction of the components is possible at that stage of development. In order to test the powertrains system behavior, the tests have to be carried out on the next level of the V-process. Engine and transmission have to be disassembled and mounted on a specialized powertrain test bench. This task requires additional effort for mechanical adaptation, software calibration and is typically done at a late phase of development process.

Figure 1: Extension of V-Model for vehicle development by Powertrain in the Loop
To reduce time and cost for setting up these separate powertrain tests a so called virtual shaft connection of two test objects was build up. For this virtual shaft connection, the loads of the dynamometer at the engine test bench and the input dynamometer at the transmission test bench are controlled in a way that speed and torque at both devices match at any time. The behavior of the system should be similar to a rigid shaft with low inertia and torsion.

The Center for Mobile Propulsion in Aachen, Germany offers great testing facilities for powertrain development. This includes all kinds of test benches which are necessary for modern hybrid or conventional powertrain development e.g. combustion engine testing chambers with modern emission analysis equipment and powerful transmission testing facilities.

Figure 2: Testing facilities at Center for Mobile Propulsion
The new approach of testing tries to reduce the gaps between the levels of powertrain design and testing by coupling of subsystem or component test facilities to virtual powertrain test benches. This combines the advantages of highly optimized subsystem test facilities and the possibility to analyze the interaction and interdependencies of all systems involved in the powertrain at an earlier point in time of powertrain design process. As proof of concept, VKA emulates the mechanical connection of the system by a software solution called “Virtual Shaft Control Logic”.

Each of the testing facilities consists of a controlled dynamometer connected to the test object. The crankshaft of the combustion engine is directly connected to a load dynamometer as well as the input and the shaft drives of the transmission. The aim of the “Virtual shaft Control Logic” is to control the engine output dynamometer and the transmission input dynamometer to operate as the two subsystems were directly connected. Mechanically spoken torque and speed of both dynamometers representing the connection has to be the same.

To verify the technical concept and to define requirements for the real time communication protocol, extensive simulations have been carried out. As a first step, the dynamometer’s signal transfer function was determined and transferred in a MATLAB/Simulink simulation environment representing the Center for Mobile Propulsion test infrastructure. Additionally, a model for the road load and an autonomous driver was established to control accelerator- and brake pedal regarding the defined driving cycle.

The initial simulations show, that a virtual shaft connection by the use of conventional dynamometers could be realized. The governor controller has to be fine-tuned and optimized to achieve a sufficient transient system behavior. It could also be shown that the overall system behavior heavily depends on communication latency. Increasing latency could lead to unstable situations of the Virtual Shaft connection and potentially damage the test object.
Results from the simulation were used to setup an experimental layout which connects two test-benches with a combustion engine and a transmission. The inverters of the dynamometers are connected to an electronic control unit with a high speed EtherCAT connection to ensure deterministic data transfer. The Virtual Shaft Controller was established and calibrated to achieve minimal differences between torque and speed at both sides of the virtual shaft connection. Starting from a base calibration of the dynamometers and after some iteration loops of governor tuning the System has been operated stable.

On the next picture you can see the measurement data directly recorded on the control units of the dynamometers.

![Measurement data of the virtual shaft experiment](image)

This control concept works even with no a-priori-knowledge or external information of the transient speed and torque profiles. The speed signal shows a high accuracy and a minimum latency. Prevention of malfunction and damage of the components had major priority for this very first proof of concept. This leads to partial deviations in torque of the two test objects. Next steps within this project are further investigations in system performance and improvement of calibration methodology of the different governor parameters.

This work is funded by Deutsche Forschungsgemeinschaft (DFG).

Contact
Dipl.-Ing. Rene Savelsberg
Phone: +49 241 5689-6868
savelsberg@vka.rwth-aachen.de
Cluster of Excellence
“Tailor-Made Fuels from Biomass”

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

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

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

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

The experiments applied in the TMFB activities at VKA shall be explained using the tailor-made fuel 2-butanone as an example. This fuel was derived in the Fuel Design Process, an interdisciplinary methodology that has been developed with complementary groups in the cluster of excellence: here, based on pre-defined boundary conditions, new fuel candidates are derived using a model-based, data driven approach. By setting specific boundary conditions such as the ignition tendency or the boiling behavior, only fuel candidates fulfilling these desired properties are considered. In this example, a new gasoline-type fuel was aimed for so that an extremely low self-ignition tendency as well as a low boiling point was set as boundary conditions. Among others, the group of the ketones was returned out of an initial set of more than 10 Million possible components. As a promising representative of this group, 2-butatone was chosen, the molecular structure is depicted in figure 1.

![Figure 1: Molecular structure of 2-butanone](image_url)
In Figure 2 the full load results obtained in the VKA single cylinder research engines. It can be seen that the performance is at the same high level that the highly knock resistant benchmark fuel ethanol achieves. Even at full load conditions and increased intake air temperatures of 40 °C neither of the fuels is knock-limited, so that indicated efficiencies above 40 % can be achieved.

![Graph](image)

**Figure 2: Full load engine test results**

In addition to that, also the catalyst heating behavior of 2-butanon was analyzed. Here, it even outperformed ethanol with regards to the critical HC emissions as the heat of vaporization is much lower than of its alcoholic counterpart.

With 2-butanone, a large step in the development of possible future tailor-made fuels from biomass could be taken. The interdisciplinary approach “Fuel Design” successfully lead to the identification of this promising fuel candidate. By the advanced VKA research facilities, the potential of 2-butanone to increase engine efficiency and decrease engine-out emissions could be demonstrated.

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

Contact
Dr.-Ing. Florian Kremer
Chief Engineer
Phone: +49 241 80 95352
kremer@vka.rwth-aachen.de
Interdisciplinary Research in the Center for Automotive Catalytic Systems Aachen (ACA)

Exhaust Gas Aftertreatment Systems of the Future

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

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

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

Defined goals in this context are the reduction or the abolishment of the proportion of noble metal as well as the expansion of efficient temperature range to cover exhaust gas temperature degrease as result of CO₂ emissions reduction. For this purpose materials, fabrication methods and adjusted operating strategies are developed whereas ACA functions as the central contact for national and international cooperation partners of science and industry.

Figure 1: Research at ACA
A special feature of the Project House is the interdisciplinary and multirange approach. Figure 1 depicts the research focuses—material synthesis, analytics, material transport and simulation—as well as possible research topics.

In the area of material synthesis different methods, build on one another, are analyzed, which contain an optimization of carrier structures with the catalytically active metal species supported by simulation and their pore design. Another aim consists in the substitution respectively reduction of the proportion of noble metal in the catalytic active component accompanied at constant or improved activity.

Standard analytics at ACA comprises the analysis of elemental composition, distribution, crystal structure, specific surface, porosity and pore size distribution. Besides, tests concerning coating structures and to determine active centers are conducted. Moreover, the material produced at ACA is analyzed under realistic conditions to characterize material developments and to provide data for a later application at the engine test bench. The area of simulation shall provide a detailed understanding of the adsorbate-surface-interactions with calculations of the electronic structure combined with experiments. Additionally, simulations of the engine operation including the entire exhaust gas aftertreatment system are conducted to enhance boundary conditions of catalyst development for the expected exhaust gas temperatures, volume flow and compositions.

A new measurement technique for in situ characterization of mass flow in the boundary layer between the free gas flow and the catalytic surface will be developed. The collected empirical data is finally used to develop a concept for a test bed.

Based on experimental and simulative findings the catalysts are specifically synchronized and new approaches for the system configuration are developed. Modern testing facilities for engine, powertrain and vehicle enable the validation of the system structure as well as the adjustment of the engine operating parameters. The pointedly usage and influence of these processes already take place at ACA at laboratory level and can further be followed up into the vehicle.

For successful research a wide range of analysis methods are available. These cover primarily material characterization, component analysis, simulation and high resolution optical measurement instrumentation.

In ACA’s different projects single aspects of the core competencies are taken up and elaborated in an interdisciplinary research team. Due to close collaboration and therefore regular communication between scientists of different research fields ACA is able to yield optimal results.

A current project is the case study about the application of lanthanum-perovskites, which are analyzed concerning their activity as NO\textsubscript{x}-storage/reduction catalysts (NSR) respectively regarding their NO-oxidation capability to NO\textsubscript{2} for DOC (Diesel Oxidation Catalyst). The catalytically active lanthanum-perovskites should replace the noble metal component in the catalyst. Advantages are lower production costs as well as increased heat stability. Since former studies have shown that pure lanthanum-perovskites are less efficient than conventional catalyst, parts of the crystal structure were substituted by the elements strontium, cobalt, manganese and iron, so that following variants appear:

- LSM: La\textsubscript{0.7}Sr\textsubscript{0.3}MnO\textsubscript{3}
- LSC: La\textsubscript{0.6}Sr\textsubscript{0.4}CoO\textsubscript{3}
- LSFC: La\textsubscript{0.6}Sr\textsubscript{0.4}Co\textsubscript{0.3}Fe\textsubscript{0.7}O\textsubscript{3}

These are analyzed in powder and granule form. The partly parallel running well-matched work stages cover analysis methods, test on laboratory level up to vehicle level and development of simulation approaches.

Contact
Dipl.-Ing. Peter Dittmann
Phone: +49 241 80 48082
dittmann@vka.rwth-aachen.de

Figure 2: Microscopic picture of LSFC Perovskite
For the transport sector, the electrification of the drivetrain combined with increasing electrical power generation from renewable sources is a promising approach to decrease the dependency on shortening crude oil and gas resources. However, the energy density of mobile electrical energy storage systems is still less than appropriate at present.

This demanding topic is addressed by the new research training group „Integrated Energy Supply Modules for Roadbound E-Mobility“ (mobilEM) at RWTH Aachen University. VKA is the coordinating institute of this post graduate program, which has started on October 1st, 2013. The program is funded by Deutsche Forschungsgemeinschaft (DFG) and explores the physical foundations of electro-chemical energy storage and its combination with novel fuel-operated range extender units. Fuel-operated range extenders allow a reasonable dimensioning of the electrical energy storage system size and its thermal conditioning. Additionally, an efficient air conditioning of the passenger compartment can be achieved.

Within a period of at least 4.5 years, the interdisciplinary program gathers scientists from the areas of electrical energy storage, power electronics, combustion engines, electric motors, thermal management and control engineering.

Range extender module

The capability of electrical storage referring to capacity and charging operation will in the medium term not be sufficient to offer the accustomed and appreciated flexibility and range of traditional combustion engines. Furthermore, common materials which are needed in a corresponding battery are globally proportionally rare (in particular lithium). Therefore, it is necessary for the foreseeable future to replace pure electric mobile drive by a combustion...
Combustion engines

Significantly changed load spectrums, in particular a reduced dynamic, allow new approaches, e.g. an improved combustion management and control (such as HCCI), variability in the engine and the valve train as well as waste heat recovery.

New demands on the acoustic behavior arise from decoupling the power requirement of the vehicle from the power requirement of the range extender module. The focus of research lies not only on noise excitation through the combustion itself, but notably also on new approaches on an air and exhaust system. The unfavorable geometric boundary conditions compared to conventional powertrains exacerbate the problem of charge exchange noise of small range extender engines. Three dimensional and one dimensional simulation of the combustion process and gas exchange enables the determination of the excitation spectrum already in the context of the basic research. A noise level calculation of the generator dependent on speed and load attached to the cooperation of the researchers in matter of the acoustic behavior provide a basis for researching an optimal range extender module.

1st mobilEM Colloquium

In October 2014 the first mobilEM colloquium took place in the center of Aachen. Posters and presentations by doctoral candidates delivered insight into current research topics and progress of their work. Presentations by professors Pischinger, Sauer and DeDoncker and Eckstein as well as external speakers from Daimler, Infineon, dSpace and Halla Visteon enriched the colloquium with expert knowledge.

The session on range extender modules addressed NVH related topics, such as vibration reduction of electric motors and acoustic behavior of range extender drivetrains. Not only well-established, but also new and promising approaches were presented, i.e. a theoretical study on a free piston engine linked with a linear generator. Another presentation covered the infrastructure of the Center for Mobile Propulsion (CMP), also funded by DFG, which provided ideal surroundings and was employed for research on a real-time network, linking multiple test benches. Interesting input from other fields of research included that batteries with even lower voltage than 48V can be employed to electrify vehicles with the help of modern power electronics. Promising is the fact that prices of li-ion batteries drop even faster than predicted by optimistic prognoses and forecasts.

This work is funded by Deutsche Forschungsgemeinschaft (DFG).

Contact
Marius Böhmer, M.Sc.
Phone: +49 241 80 48161
boehmer@vka.rwth-aachen.de
Driven by the increasing number of electric cars, electric traction machines are produced in an increasingly higher quantity for the automotive industry. Current motor system dimensioning methods do not follow this development and neglect the operation conditions inside of automotive powertrains, which are much more dynamic as in industrial applications. This leads to a strong oversizing of the traction motors especially with regards to the peak load potential. To make electric vehicles more competitive the traction motors have to be optimized concerning the costs, resources and efficiency by a better knowledge and usage of the peak load.

Within the framework of the project “E-Lastsys” both, the RWTHs Institute of Electrical machines (IEM) and the Institute for Combustion Engines (VKA) are developing a method for system dimensioning with focus on ensuring a desired lifetime for traction machines windings and bearings, which are the most fault-prone components.

**Thermal system dimensioning**

The peak load potential of a traction machine crucially depends on the Joule heating of the windings and their effect on the permanent magnets. In order to calculate these effects on the motor’s efficiency and lifetime, a tool chain is developed leading to a conclusive thermal model.

First, different working points of the motor are defined, which represent typical and critical load scenarios such as for example full torque and maximum speed of the rotor and others. For these working points, the electromagnetic losses within the stator and rotor iron are evaluated. An exemplary result is shown in Figure 1a depicting a load case, here idle point. Generally, the loss densities are the largest at the tips of the stator teeth and at proximity points of permanent magnets and rotor surface.

Along with the losses at the winding, the computed results serve as spatially resolved heat input data for the thermal simulations (Figure 1d). The impact of the motor’s cooling yacked is calculated via 3D computational fluid dynamics (CFD) (Figure 1b).

From the CFD simulation, the heat transfer coefficient (HTC) between the stator and the jacket is evaluated.

In addition, different cooling strategies are investigated independent of the load scenario. In order to validate the simulation results, experimental analyses of individual motor components and the full machine are carried out in order to provide exact valuable information about the thermal characteristics (Figure 1c) presented mainly in the heat conductivity, specific heat, the heat transfer coefficient and heat conductance between the components. This includes also the capacities and anisotropic conductivities of the stator’s sheet metal. Altogether, the previous steps lead to detailed thermal 2D and 3D FEM models of the electric motor (Figure 1d,e).
Mechanical system dimensioning

The second project part focuses on the bearing dimensioning for a desired lifetime of 7000 hours. Therefore a specific load spectrum for electric vehicles is created. Based on this motor load point a realistic usage of the motor is derived, which is essentially needed for a systematic approach.

While combining the load spectrum with the bearing forces the Multi Body Simulation “Adams” is used. This model is shown in Figure 2 and basically consists of the housing including the stator and the shaft including the rotor, both parts are designed flexible. Although bearings connect those parts, they cannot be designed as flexible parts as well, because the system’s complexity and the entailed calculation time would increase dramatically. That is why maps with stiffness characteristics of bearings are used to modulate the interaction between shaft and housing in order to calculate the bearings’ deformations and reaction forces. Beside the load of the predefined load spectrum, two additional influences are considered to achieve realistic bearing forces. At first a skew gear is implemented inside of the simulation environment. Skew gears as used in electrical powertrains to ensure that gearbox noises do not degrade the acoustic customer detection. Caused by the skew gear an additional reaction force comes out of the powertrain and has to be absorbed by the motor’s bearings. As a second additional influence the radial displacement of the rotor shaft caused by unbalanced masses has to be considered. Through these displacement additional electromagnetic forces affects the bearing loads.

The combination of the motor loads and the interdisciplinary boundary conditions allows calculating the bearings’ forces and its occurrence. With the given calculation method in DIN ISO 281 the lifetime of bearings is determined. In a last step this methodology is used in an iterative way to find a matching bearing which fulfilled the desired lifetime of 7000 hours.

In addition the simulation environment is adapted to friction bearings. Thus, a usage of friction bearings in traction motors under worst case conditions is investigated and validated. The required oil mass flow for a safe application is determined up to 0.3 liter/minute. This liquid flow can be used for an additional cooling of the traction motor and is investigated as well. This offers an additional solution to achieve the projects goals at the same time.

Special thanks to Deutsches Zentrum für Luft- und Raumfahrt (DLR) and Bundesministerium für Wirtschaft und Technologie (BMWi) for supporting the E-Lastsys project.
BREEZE! Fuel Cell Range Extender for Battery Electric Vehicles: Zero Emission

The scope of the public funded project “BREEZE!” is to extend zero emission range of battery electric vehicles. Conventional range extender approaches use combustion engines to provide additional range and short refueling time on longer distances. Their disadvantages are pollutant emissions and noises during range extender operation. In the “BREEZE!”-project a fuel cell system is developed for that purpose working with hydrogen. At the end of the project this fuel cell range extender is integrated into a battery electric Fiat 500 developed by FEV GmbH in the public funded project “Smart-Wheels”.

Base vehicle FEV Liiona (Fiat 500)

Figure 1: FEV Liiona with “BREEZE!”-Pasting (Source: FEV)

<table>
<thead>
<tr>
<th>Maximum speed</th>
<th>120 km/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-Machine</td>
<td>PMSM, 60 kW (Peak), 180 Nm</td>
</tr>
<tr>
<td>Battery Range</td>
<td>80 km</td>
</tr>
<tr>
<td>Battery</td>
<td>12 kWh, Lithium Ion, 250 to 350 V</td>
</tr>
</tbody>
</table>

Concept and requirements

Determination of power demand for a range extender is discussed controversially in research and industry. It is consensus that the battery electric powertrain has to cover the entire transient performance of the vehicle in a range extender layout. In the “BREEZE!” approach the range extender provides stationary power for speeds higher than 100 km/h to enable charge sustaining mode of the battery during long distance driving. Because of that, the electrical gross power target of the system is minimum 30 kW for the battery electric Fiat 500. This vehicle is also known as the FEV Liiona. If the expected parasitic power of stack’s balance-of-plant components and power electronics are subtracted, the net output remaining in this full-load operating point is about 23 kW. This allows a permanent cruising speed of 110 km/h for the current vehicle configuration even with an empty battery.
The integration of an additional energy conversion and storage system in a very compact vehicle like FEV Liiona represents a great challenge. Also, in terms of customer acceptance, the advantage of the increased range must not be achieved at the expense of the usable interior volume. The vehicle’s electric powertrain is located at the front end, where the conventional powertrain was previously installed and the vehicle battery is mounted under the body between the axles. Hence, available installation space for a range extender is limited to the area below the backseats and the spare tire recess. Below the backseats the hydrogen high pressure vessel is mounted. Its volume of 34 l provides at 700 bars an additional range of 180 km. For realization of a fuel cell range extender in the remaining space, innovative concepts are required. Compared to fuel cell stacks on the market, stack’s cell pitch is reduced by metallic bipolar plates made by hydroforming from very thin sheet metal. In addition, balance-of-plant volume is decreased by the integration of components into one of the stack’s end plates and by system simplification enabled by range extender operation mode.
Stack development

At the beginning of stack development a benchmark of membrane electrolyte assemblies (MEA) was executed to determine stack operation targets like pressure level, stoichiometries and operation temperature. Parallel, a market monitoring provided boundary conditions of available or close to market automotive balance-of-plant components. The results of both processes combined with the constraints of the hydroforming process influenced the bipolar plate design. Finally, a flow field benchmark indicated the best variant which was built up as a short stack with an active area of about 100 cm². After successful testing of this stack both active area and number of cells were increased to about 300 cm² respective 150 cells.

Next to cell development the stack mechanics were considered. The clamping concept enables cell sealing against environment and affects the cell performance by gas diffusion layer (GDL) pressing. The GDL is part of the MEA. MEAs, bipolar plates, seals as well as clamping elements and springs to compensate stack movement caused by temperature, pressure or shrinking effects are part of the spring system fuel cell stack. In addition to the calculated clamping design, the different stack design stages were equipped with force and displacement measurement to optimize the clamping system for the final fuel cell range extender module (REM).

This year a manufacturing process for multi cell stacks was developed to realize a reliable stack assembly for the laboratory stack and the REM. In this process preassembled units of bipolar plates and MEAs are stacked on one of stack’s end plates. After that the unpressed stack is moved into a pressing apparatus to complete the manufacturing process by pressing the second end plate on the unpressed stack. For this purpose a preassembling facility and a spindle press was build up. Also, opportunities for automation were considered for the future. In October 2014 the first laboratory 150 cell stack was assembled in that way.
Development of the end plates for the REM was finalized as well in October 2014. This process was closely linked with system development because the end plate has to pick up all relevant components for stack operation like sensors and actuators. Because of structural optimization and weight reduction the end plates were simulated with finite elements method (FEM). The FEM simulation was executed for assembling process loads and for operation loads. The end plates are made from casted aluminum and are already in production.
System development

At the beginning of system development a safety concept was worked out. The fuel cell stack has to be supplied with air, hydrogen and coolant during operation. Sufficient supply of all these fluids is important for a reliable and safe operation. Because of that, this safety concept underlies the overall system and the fuel cell subsystems on hardware and software level.

The cathode system which is responsible for air supply consists of an air filter to reduce dust and air pollutants, an electric compressor, a charge air cooler and a pressure regulator. The cathode humidification was omitted because of package reasons. The electric air compressor and its power electronics were developed in this project to realize stack operation at pressure levels higher than 2 bar(a) and stoichiometry higher than 2. This allows a wide range of stack operation. The pressure level can be determined independent from the mass flow considering compressors surge and choke limits during operation.

The anode system is supplied with hydrogen from a 34 l type III pressure vessel with a maximum operation pressure of 700 bar(a). A pressure reducer followed by a dosing valve feed the fuel cell stack with hydrogen and keeps anode pressure level on a defined relative pressure level related to the cathode side. A recirculation blower combined with a jet pump increases anode stoichiometry. This year a compact water separator for the anode system was developed with integrated purge and drain valves. These valves discharge gas and liquid water into the cathode exhaust for dilution.

In the coolant system of fuel cells material compatibility and the lower temperature level compared to combustion engines are key issues. Components and materials have to be selected carefully to prevent rise of electric conductivity of the coolant. The fuel cell cooler is a special design with a maximum cooler surface which is applicable in the small front end of FEV Liiona. The elimination of an ion exchanger in the cooling system is tested.
Software development and testing

To control the subsystems and the overall system functions were developed and tested in a model in the loop environment with Matlab/Simulink. After that the software was compiled with dSpace tool chain for use on a MicroAutoBox with a RapidPro. The MicroAutoBox with “BREEZE!”-Software is called Fuel Cell Control Unit (FCU).
The FCU and the sensors and actuators were tested in a hardware in the loop environment before fuel cell testing with system components began.

In November 2014 the 150 cell laboratory fuel cell stack with an active area of about 300 cm² ran the first time with the FCU and the system components of the later REM. The fuel cell stack has got a power density of 2,5 kW/l at cell voltage higher than 0.6 V.

Next steps

In the first quarter of 2015 FCU application is finalized with the laboratory stack and the REM is build up and tested. In the second quarter the vehicle integration and vehicle application is finished to begin vehicle testing.

Acknowledgment

This report presents interim results from the “BREEZE!”-project funded by the state of North Rhine-Westphalia and the European Union in the context of the “Ziel 2” program. The project involved FEV GmbH, the Institute for Combustion Engines of Aachen University (RWTH), the Graebener Group and the Center for Fuel Cell Technology (ZBT). The project consortium wishes to thank the groups mentioned that funded the project.
The Profile Area
“Energy, Chemical and Process Engineering”

The provision of sustainable energy and materials is clearly one of the major global challenges which were identified in the future strategy of RWTH Aachen University. The profile area Energy, Chemical & Process Engineering (ECPE) addresses the two most important pathways to achieve this goal:

**Improvements in energy and material efficiency and the transition to renewable sources.**

Although on first thought one could believe that the profile area ECPE mainly addresses technology achievements in power generation the topics are much more multi-faceted and multi-scaled. To achieve a holistic view towards the mentioned goals it is necessary to interdisciplinary connect the research activities over all of these facets and scales:

- From energy resources, power generation and energy conversion across energy storage and infrastructure capabilities up to end-use in industry, buildings and transportation sector
- From the molecular scale across single components up to system integration and system analysis

Without doubt, there is still a significant potential for improvements in established technologies for energy and materials conversion and usage which has to be opened up. Breakthrough innovations, however, increasingly require expanding the classical scope of energy and chemical engineering to integrate novel insights from the molecular sciences. Based upon this common root, the existing division between the energy and chemical disciplines has to be overcome, since an energy and material efficient society will be built upon integrated processing, conversion, consumption and recycling strategies.

A Steering Committee consisting of its spokesman professor Stefan Pischinger and professors Regina Palkovits, Rik De Doncker, Peter Kukla, Reinhard Madlener, Albert Moser and Matthias Wessling from five different RWTH Aachen University faculties as well as professor Detlef Stolten from Forschungszentrum Jülich leads the profile area ECPE.

In 2014 all eight RWTH profile areas were challenged by a roadmap process initiated by the RWTH Aachen University to evaluate the status quo of the research in the respective sector as well as the strengths and weaknesses of the RWTH, identify promising research topics and initiate projects with high strategic relevance for the RWTH Aachen and Forschungszentrum Jülich. With his work as spokesman for the profile area professor Pischinger and the VKA strongly participate in this strategy process of the RWTH Aachen and help to identify upcoming “hot topics” in the field of energy research.

First, core topics and a research roadmap were developed interdisciplinary. For the steering committee with its spokesman professor Pischinger the support of research co-operations between institutes and faculties is the main focus for its work.
The illustration gives an overview about the structure of the profile area ECPE with the steering committee, its active members and the identified key topics. With its experience in interdisciplinary research approaches the institute for combustion engines could successfully support the creation of the ECPE roadmap. With the conclusions of this roadmap process four new project houses addressing innovative and promising research topics could be initialized in 2014 with support of the profile area ECPE:

- Project house ACA - Automotive Catalytic Systems Aachen
- Project house Power-2-Fuel
- Project house Technology-based system analysis
- Project house KESS - Municipal Energy Supply System of the Future

All these project houses utilize the interdisciplinary approach which is the foundation for the successful excellence cluster TMFB towards other research fields. The project house ACA is coordinated by VKA, in addition the institute for combustion engines participates in another two project houses and by this shows the multiple layers of its research expertise while still maintaining focus onto its core topics.

Also the CMP approach of a real-time network capable of connecting different kinds of test benches is a successful role model which is increasingly transferred towards other topics. The possibilities and benefits of evaluating components in different development stages up towards fully simulated components is now transferred to other applications - even across different test fields. Also in this matter the high innovation capabilities of VKA are manifested.

Contact
Dipl.-Ing. Daniel Henaux
Phone: +49 241 5689-6894
henaux@vka.rwth-aachen.de
Due to its high efficiency and wide performance spectrum the diesel engine will still be important in the future in many application areas like goods traffic and decentralized energy supply. Despite the comparably low emission level of modern diesel engine combustion processes, particularly with regard to emissions of particles and nitrogen oxides as well as fuel consumption, further development work is necessary. A possibility for a targeted reduction of diesel engine emissions is feeding water into the combustion. However known macroemulsion fuels were not able to establish in motoric operations due to mostly negative properties. In particular, the fast decomposition of diesel and water and as a consequence thereof variations in the combustion of emulsions impeded the use of emulsions. In this context microemulsions could offer distinct advantages. So an FVV and AIF founded research project was started in 2011 to investigate the influence of Diesel-Water-Microemulsions on diesel engine combustion and the usability of same in marine and rail applications. This project was a cooperative work of three research institutes, the Department of Chemistry in Cologne, the VKA in Aachen and the Trier University of Applied Science.

In Cologne microemulsions were produced with the aid of surfactants. Surfactants or emulsifiers are technical, surface active solubilizer. They exhibit an amphiphile (gr. „loving both“) character. The molecules have a hydrophilic (water-loving) „head“ and a lipophilic (fat-loving) “tail”. An amphiphile film develops if water is admixed to oil. By means of a suitable selection and combination of ionic and non-ionic surfactants it is possible to generate temperature invariant micro emulsions. For the engine tests, different microemulsions with varying water and surfactant contents were used. A micro emulsion with a water content of 24 % requires at least 20 % surfactants. The content of surfactants for micro emulsions with 16 % and 8 % water could be reduced to 15 % resp. 13 %. Therefore, to determine the sole influence of water besides producing the mixture for the solubilization of 24 % water and consequently 20 % surfactants, also mixtures with 0 %, 8 % and 16 % water were produced. Furthermore, formulations were created, which contained the smallest possible amount of surfactants. The determination of the most important physical properties of the micro emulsions resulted in the finding that these are mostly located in the tolerance range of diesel fuels. The density as well as the heat value varying in relation to water content.

Injection and combustion testing was performed at VKA in Aachen. Already the test for injection and ignition in an optically accessible high-pressure chamber showed that the water content of the micro emulsion has a significant influence on spray breakup and fuel vaporization. Adapting the nozzle cross-section to the reduced heat value and thereby the corresponding injected mass of fuel results, especially at low engine loads and high water contents, in a very high liquid penetration length. Caused by the associated deterioration of evaporation and ignition it could already be detected that a load-point-related mixture of micro emulsions is necessary for an unrestricted operation. In order to determine the influence on the combustion a single-cylinder engine was used. The testing of the micro emulsion was conducted at constant engine conditions in a variation of the position of 50% fractional mass burn by adapting the injection start. Herein a slightly declining NO\textsubscript{X} level appeared at constant position of 50% fractional mass burn and constant exhaust gas recirculation rate. Moreover, the influence on the fuel consumption is very low. The NO\textsubscript{X}-particulate-trade-off proofs that with the aid of micro emulsions a significant improvement can be realized. Already with a water content of 8 % one can reach a considerable reduction of particle emissions, which can be even more improved with increasing water content. For a micro emulsion with a water content of 24 % a measurement of particle emissions by measuring filter smoke number value is hardly feasible. By adapting the nozzles to the fuel heating value of the micro emulsions a constant injection duration could be yielded, but with this the combustion duration changed. The ignition delay, increasing with the water content, causes, a slightly
delay of the first combustion phase. A significant delay of 90% of the fractional mass burn at constant center of combustion indicates a faster combustion with increasing water content. Therefore, a minimal influence of the combustion duration even at an operating point-dependent mixture can be expected if no nozzle adaptation is possible.

Besides measuring the filter smoke number value, also filters were loaded to enable a detailed analysis of particle mass and composition in all operating points. Also with gravimetric particle measurement a significant reduction of the particles with increasing water content could be shown. One can also recognize that in the part-load points an increase of water content of more than 8% cannot generate a significant improvement and only in correspondingly high load points a further increase of water content is expedient. The particle samples were analyzed regarding their composition. Therefore, the parts of organically soluble (SOF), water soluble (WSF) and insoluble (NSF) components were determined, whereas the latter mainly consists of carbon. The analyses showed that microemulsions mainly reduce the carbon-rich components of the insoluble fraction. Whereas the mass of SOF and WSF is only slightly influenced; therefore, these fractions are the largest components by mass.

The necessity of load point depended mixture found in these tests was further addressed in Trier. Here different systems to mix microemulsions direct at the engine have been investigated. Thereby the volume between mixture formation and injection was the most important parameter to be optimized. With regard to a transient engine operation only a System with mixture formation in high pressure cycle upstream the injection was suitable.

The investigations showed that micro emulsions offer a very good possibility to insert water into the combustion chamber. In contrast to macro emulsions they only need a minimal energy input to form and are thermodynamic stable so that they are storable and phase separation will not emerge. Additionally, the spontaneous formation enables a mixture of the micro emulsions in a high-pressure circuit to realize transient engine conditions during the micro emulsion operation, too. However, an enhanced occurrence of cavitation could not be prevented with the usage of solenoid valve injectors. Adapting the injection system to a mixture in the injector in combination with modern leakage-free systems might lead to notable improvements. The positive influence of micro emulsions on the emission of NO\textsubscript{x} and particles could be proven in all tested operating points. At comparable NO\textsubscript{x}-levels and around 200 bar reduced injection pressure a reduction of the particle mass of 90% is possible.

![Figure 1: Injection spray visualisation of Microemulsion fuels including OH-chemiluminescence signal](image-url)
Research Cluster “Fuel in Oil”

The aim of the research cluster “Fuel in Oil” is to investigate and quantify the interaction between the fuel and the lubrication oil in diesel engines caused by late post injections, which are used for the regeneration of the particulate filter or the NOx storage catalyst. Due to the low gas density and the missing shielding effect of the piston bowl at late post injections timing, the fuel spray can reach the lubrication film. A share of this fuel enters the film and causes oil dilution. In the research cluster seven institutes from several universities shall investigate 10 sub projects over three years regarding this topic. The VKA is working on five of the sub projects. To achieve the objectives, different phenomena like the fuel entry into the lubrication film, the fuel-oil transport by means of the piston rings, the evaporation of fuel out of the oil pan and the impact of the oil separator of the oil dilution are to be investigated. A variety of fundamental experiments and engine tests, were set up and partly performed, during these investigations. Advanced measurement techniques were developed to quantify the phenomena. The droplet diameter and velocity of the post injection spray was measured with the help of high pressure chambers. The droplet film interaction was investigated with fundamental experiments. Furthermore, the film thickness of the wall film deposited by the post injection was measured in a diesel engine. To investigate the impact of the oil separator on the oil dilution process, the fuel concentration upstream and downstream of the separator and the droplet diameter of the aerosol was measured.

Another topic of the research cluster is the development of CFD simulation methods to simulate the effects of the oil dilution. For this purpose, simulation methods to calculate the fuel entry into the lubrication film and to simulate the lubrication film and blow by gas transport by means of the piston rings were developed. Moreover, it was possible to understand the fuel entry and fuel evaporation process with the help of CFD simulations of the crank train. These simulation methods will be validated with the measurements. Furthermore, a model based simulation method to determine the complete oil dilution considering engine and operating parameters as input will be developed.

VKA is responsible for all measurements performed on an engine, the 3D-CFD simulation of the fuel entry process in the combustion chamber and the development of a model based tool to calculate the oil dilution.

Engine measurements

The measurements are performed together with the institute of measurement technology University Hamburg on VKA test benches. For all measurements a four cylinder diesel engine with 1.6L displacement is used. The fuel concentration and the thickness of the lubrication film are analyzed for different post injection strategies. To measure the fuel concentration in the film a small glass capillary with a diameter of 380 µm is applied to the cylinder liner. Via the capillary a small probe of the film is rooted to a vaporizer and after that directly to a mass spectrometer to analyse the fuel concentration. To measure the film thickness a small window with a thickness of 0.5mm is applied to the cylinder liner. Through the window the film thickness is measured with an interferometric sensor. The sensor has a resolution of 4 kHz and a measurement range of 2 – 140 µm. Figure 1 shows the film that is generated by 5 post injections. The piston rings are not moving over the measurement position.
Engine Simulation

To calculate the fuel entry into the lubrication film 3D-CFD simulations of the post injection were performed. The simulation code KIVA was used and updated with new developed routines to calculate the droplet film interaction. Figure 2 shows that the spray reaches the lubrication film at the cylinder wall. After the injection 70% of the injected fuel mass of the post injection are entered into the lubrication film.

Figure 1: Film measurement in the spray target of diesel engine at 5 post injections. IMEP: 4.3 bar, Engine speed: 1500 rpm.

Figure 2: Post injection simulation results of a late post injection at 120°CA. a. TDC. IMEP: 4.3 bar, Engine speed: 1500 rpm.
LPG (Liquid Petroleum Gas) - a mixture of propane / propene and butane / butene - is the most widely used alternative fuel to gasoline and diesel fuel, with a significant potential to reduce the CO₂-emissions and with high anti knock properties.

For a more efficient use of LPG as automotive fuel the European LPG fuel standard (EN 589) needs to be updated with regard to modern engine technology, with the aim to ensure LPG quality to be future capable and to achieve maximum engine efficiency. The effects on modern direct injection gasoline combustion systems were analyzed. A 1.6 l Ford Ecoboost engine was used as a workhorse on a steady state engine dynamometer. It was equipped with 3 different LPG injection systems.

1. Gaseous Port Fuel Injection (Gaseous LPG PFI) [System supplied by Prins Autogs (NL) with Keihin injectors]
2. Liquid Port Fuel Injection (Liquid LPG PFI) [System supplied by TwinTec (D) with Continental injectors]
3. Liquid Direct Injection (LPG DI) [re-use of original Bosch gasoline injectors and fuel pump]

On the steady state engine dynamometer thermodynamic investigations were conducted with different LPG qualities in order to evaluate the full load potential and emission behavior under part load conditions. Additional investigations of the efficiency of the exhaust gas catalysis were conducted with different LPG mixtures and the c/o gasoline catalyst on a special synthesis gas test bench.

Octane numbers of each LPG test fuel were calculated in accordance to different calculation methods and compared with the real knock resistance on the Ecoboost test engine. Based on the results a recommendation for the current LPG standardization process has been developed.

The comparison of all calculated octane numbers (MON and RON correlated with the knock limitation on the used Ecoboost engine, for none of the investigated compression ratios (CR 10 …13) and for neither LPG DI nor for both tested LPG PFI systems. A correlation between the motor octane number (MON) and auto-ignition tendency could not be determined. The best correlation was found to be the Methane Number (MN) determined in accordance to the so called “AVL method”. The higher the MN is the higher are the observed knock resistance and pre-ignition (PI) resistance of the LPG fuel. Since the MN is strongly rising with increased propane content, propane is a significant contributor to high knock resistance of LPG fuel. Even if any of the tested LPG fuels showed a better knock resistance than RON 95 gasoline fuel, it is recommended for the EN 589 standard to implement a minimum propane content of 30 % (v/v) and a minimum Methane Number (MN) of 19 in order to be able to in-crease engine efficiency for future LPG applications. An increase to a minimum propane content of 70 % (v/v) and a minimum Methane Number (MN) of 29 would allow even higher efficiencies, but can probably not be agreed with the LPG industry for EN 589.

The comparison of different LPG fuels by means of LPG DI revealed improved auto-ignition characteristics compared to gasoline operation with c/o gasoline engine compression ratio (CR = 10). Therefore a compression ratio (CR) increase of 1.5 units to 3 units is possible for a decent LPG quality (min. 30 % propane; min. MN = 19 for CR = 11.5; min. 70 % propane; min. MN = 29 for CR = 13). As a result efficiency benefits of 3.6 % under part load conditions for BMEP = 10 bar can be gained. Concurrently under full load conditions maximum efficiency benefits in a range of 20 % (30 % propane; MN = 19, CR = 11.5) to 26 % (70 % propane; MN = 29, CR = 13) were achieved.

Furthermore the experimental investigations revealed the highest thermodynamic potential for the LPG direct injection system, which showed significant advantages over external mixture formation (PFI) systems. For the feasibility of an LPG DI concept it is crucial to ensure liquid fuel supply under all operating conditions. The emission level of all three systems was
significantly lower compared to conventional gasoline operation. Especially no considerable soot emissions could be detected.

During deposit tests carried out on the engine dynamometer, no deposit build up could be observed neither on the injector tips for LPG direct injection nor on the evaporator surface or on the injector tip of the gaseous port fuel injection system, for all investigated LPG fuels. Those include LPG qualities with assumed strong deposit tendency, as LPG with high olefin content (20 % isobutene) and LPG with high evaporation residue consisting mainly of tube plasticizers (80 ppm dioctyl adipate).

The kinetic exhaust gas catalysis investigations confirmed a significantly delayed light off for both LPG fuels tested vs. gasoline. As a consequence, the catalyst needs to be optimized eventually for vehicle application to meet the characteristics of LPG fuel.

Since LPG DI systems revealed a superior thermodynamic behavior, but no production ready, robust LPG DI systems are known to be offered by any supplier, further research should focus in detail on the injection behavior of LPG DI systems. Besides, LPG fuel formulations can become supercritical at high rail temperatures. Thus the behavior of supercritical LPG needs to be understood in order to support the application readiness for LPG DI systems. Both topics are addressed in the follow-up research project LPG II.

Figure 1: Full load results for an engine speed variation and different LPG fuel formulations with direct injection and CR = 10

Figure 2: Full load results for an engine speed variation with different injection systems and CR = 10

Contact
Dipl.-Ing. Marco Günther
Chief Engineer
Phone: +49 241 48080
Marco.Guenther@vka.rwth-aachen.de
Fuel Characteristic Numbers of Biofuels

Current fuel characteristic numbers regarding knock sensitivity (RON / MON) with standardized test methods are not entirely sufficient to describe anomalous combustion phenomena, therefore an advanced standardization of fuel characteristic numbers is essential for alternative gasoline fuels, especially for modern turbocharged gasoline engines.

Within the reported study, the auto-ignition characteristics of different fuel blends were investigated. The special focus was on two different root causes for pre-ignition. Firstly, low temperature auto-ignition in the gas phase due to a thermodynamically critical state of the mixture and secondly, the glow-ignition on a hot surface. The major research objective was to derive proposals for new characteristic numbers in order to describe anomalous combustion phenomena in modern highly turbocharged gasoline engines. For this purpose the different physical effects were isolated and investigated separately.

The study covered fundamental investigations in a shock tube to evaluate the ignition behavior, in particular the ignition delay time and optical investigations of glow-ignition tendency in a high-pressure chamber. In addition, single cylinder engine experiments for a research carrier with modern combustion chamber geometry were conducted for both low temperature auto-ignition and glow-ignition. The reference fuel in this study was a gasoline E0 RON95 fuel without any oxygenated components. Furthermore, five splash blend fuels with different biofuel components (ethanol, methanol, iso-butanol and ETBE) and blend rates were investigated. An E20 match blend formulation was investigated additionally, in order to study the impact of the base fuel quality. Neat ethanol (E100), wet ethanol (7 % volumetric water content) and an E85 market fuel supplemented the fuel matrix.

The kinetic investigations in the shock tube show a similar behavior of all fuels in the high temperature region with comparable ignition delay times. High ethanol content fuels reveal slightly shorter ignition delay times in comparison to standard gasoline. A less pronounced NTC-behavior (negative temperature coefficient) compared to the reference fuel E0 RON95 leads to significantly longer ignition delay times in the mid and low temperature regime for all tested biofuels and gasoline biofuel mixtures.

The pre-ignition propensity out of the gas phase is much lower for direct injection and optimized spray targeting compared to port fuel injection due to the charge cooling effect. The center electrode and the gas in the vicinity are preferred locations for pre-ignition. For port fuel injection the temperature difference between this area and the remaining combustion chamber is reduced, so that pre-ignition occurs stochastically in the entire combustion chamber. Additionally, the spray targeting of the direct injector reveals to affect the

![Figure 1: Location of initiation spots for pre-ignition for the investigated fuels with direct injection DI and port fuel injection PFI](image-url)
pre-ignition propensity significantly. For the investigated engine a wide targeting of the multi-hole injection increases the pre-ignition frequency, due to an increasing amount of spray-liner interaction. This causes a reduced usage of the enthalpy of vaporization and can lead to an increased auto-ignitability due to several interactions. The pre-ignition propensity decreases substantially with increased ethanol content for the investigated fuels. This effect is more dominant for direct injection than for port fuel injection. With DI the pre-ignition critical boost pressure for E20 is about 40 % higher compared to conventional fuel E0 RON95. For E85 and E100 it is about 60 % higher. For PFI this difference decreases to less than 20 % for E20 and less than 40 % for E85 (Figure 1).

It could be proven by engine tests with a hot surface that the glow-ignition tendency is influenced by the chemical heat release of the fuel and the charge cooling effect, due to the stoichiometric air requirement related enthalpy of vaporization. For the applied test configuration in this study all splash blend fuels (with 20 % (v/v)) improve the glow-ignition resistance. The high ethanol content fuels (E85 and E100) show an improved glow-ignition resistance as well. However, those fuels are less resistant than E20 (Figure 2).

In order to predict the pre-ignition behavior for gasoline biofuel mixtures, empirical correlations were made. The correlations are based upon common fuel properties determined in a conventional fuel analysis. The most pronounced correlations for the engine glow-ignition testing are found with the MON and the specific heat of vaporization (Δhv/Lst; R² = 0.6) as well as with MON and the vapor pressure of the fuel (DVPE; R² = 0.71). Correlations for RON, RON-MON and density are considerably less pronounced. Also the most pronounced correlations show only reasonable quality. Correlations for the gas phase triggered pre-ignitions show a good coherence between the boost pressure difference between DI and PFI operation and the fuel's sensitivity (RON-MON; R² = 0.95). However, a major weakness of all the empirical correlations is the limited database.

In conclusion, new proposals for different pre-ignition numbers could be derived from the various experiments within this project. The achieved test results represent valuable data regarding auto-ignition characteristics of gasoline biofuel mixtures and can be used by any company involved in the engine development process as well as by mineral oil companies to use the findings for further development and implementation of future gasoline fuel standards. Therefore future research work should focus more on the standardization process. The wide-spread utilization of a completely new developed test method in combination with a new re-search carrier seems to be unrealistic and is not possible with adequate effort. For an industrial implementation the only reasonable option remains a test method realized on the already established CFR engines. It also requires the transfer and evaluation of test results from a test engine with modern combustion chamber geometry to the standard CFR engine.

Figure 2: Influence of various biofuel components and the ethanol content on the glow-ignition tendency of a SI engine with direct injection

<table>
<thead>
<tr>
<th>Direct injection</th>
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<td>E0 RON95</td>
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<td>70 PI events</td>
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<th>Port fuel injection</th>
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<tr>
<td>E0 RON95</td>
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<tr>
<td>46 PI events</td>
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Contact
Dipl.-Ing. Marco Günther
Chief Engineer
Phone: +49 241 48080
Marco.Guenther@vka.rwth-aachen.de
Downsizings of engines as well as the blending of bio-ethanol into gasoline fuel are applied methods to reduce automotive well-to-wheel CO$_2$ emissions.

Modern gasoline downsizing concepts are usually equipped with a technology package consisting of gasoline direct injection, turbo charging and variable cam timing. Thereby the baseline engine displacement can be reduced significantly, while power and torque are maintained. The lower displacement of the downsized engine reduces the throttle losses as well as the friction losses and therefore significantly increases the engine efficiency, which results into reduced tank-to-wheel CO$_2$ emissions.

Another opportunity to reduce well-to-wheel CO$_2$ emissions is the addition of bio-ethanol to gasoline as blend component. An increase of the blend rate automatically reduces the well-to-wheel CO$_2$ emissions as long as the ethanol is produced sustainable. Furthermore ethanol is an excellent octane booster. When 95 RON gasoline fuel is splash blended with 20 % ethanol for example a knock resistance of 102 RON can be achieved. Due to the higher knock resistance a higher compression ratio can be realized and full load enrichment is reduced.

Particularly high boosted engines, as the described downsizing concepts, have a high octane demand than conventional naturally aspirated engines. Therefore the combination of high octave ethanol blends with extreme downsizing has been selected a very promising concept to gain further CO$_2$ reduction potential.

At the beginning of this FVV project downsizing concepts as described had been introduced down to an engine displacement of 1.2 liter and a cylinder volume of 0.3 liter with a minimum cylinder bore diameter of 71 mm. With the very small bore diameter of such a concept particularly the introduction of direct injection becomes critical because the package requirements of the injectors remain, while the package room gets narrower. Furthermore the spray has less room to expand and to evaporate which increases the hazard of wall wetting and oil dilution.

Based on those considerations a 0.8 liter 3-cylinder gasoline direct injection engine with a cylinder displacement of 266 cm$^3$, 65.5 mm bore diameter size, a specific power of 120 kW/liter was designed in particular for 102 RON E20 usage and then built and tested (see figure 1). The research focused on oil dilution, soot formation, boost pressure response and mass flow range, which are significant challenges considering the low engine capacity and high specific power.

The aim was to achieve optimized part load fuel consumption as well as good full-load fuel consumption by exploitation of the high

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**Figure 1: Approach**
knock resistance of the used ethanol blended fuels “E20SB” (ethanol splash blend with 20 % v/v ethanol and RON 102) and “E85SB” (ethanol splash blend with 85 % v/v ethanol and RON 106). The high knock resistance of the fuels allowed the introduction of a higher compression ratio than usual for gasoline downsizing concepts as well as reduced full load enrichment. Two compression ratios, CR = 11 and CR = 13, were considered and analyzed regarding their impact on engine efficiency and full load enrichment.

1D gas exchange simulation reveals that an absolute boost pressure of almost 3 bar is necessary to meet the performance target. The conventional exhaust gas turbochargers which reach the demanded peak power would lack low-end torque, because they are not capable of achieving the large mass flow spreading at such high pressure ratios. For that reason it is necessary to use two-stage charging. The combination of a mechanical supercharger and an exhaust gas turbocharger is selected in consideration of the previous FVV research project No. 1015 “Pilot Study for Small Gasoline DI Engines”. Using exhaust turbo charging restricts exhaust gas temperatures due to the temperature compatibility of the material. To avoid excessive enrichment for cooling down the exhaust gas at full load, the exhaust manifold is integrated into the cylinder head.

While the bottom-end is adopted from the OM 660 Diesel engine, due to its rigid engine structure with an average maximum combustion pressure capability of 142 bar (peak pressure capability 160 bar), the cylinder head is replaced by an all-new development with regards to high specific power and high peak pressure and temperature strength (see figure 2). The numerical investigations reveal that a 3-valve combustion concept is favorable. Especially in combination with a cooled, integrated exhaust manifold, the 3-valve concept offers advantages regarding the cooling capability of the exhaust port by reducing material accumulation.

Hence, the injector is located slightly decentrally, demanding an unsymmetrical spray pattern to avoid valve and wall wettening and to ensure good mixture preparation. Three different injector layouts were proposed for the experimental investigations.
By means of E20SB (RON102) with a compression ratio of CR = 11 the extremely downsized engine achieved the targeted specific power of 120 kW/liter at 5500 min⁻¹ (see figure 3). With low octane fuel (E10MB, RON 96) the maximum achievable power output was reduced to 116 kW/liter. E85SB enabled stoichiometric operation for the whole operation range, whereas the required fuel enrichment at rated power in case of E20SB exceeded the expectations. With an increased ethanol content NOx emissions at rated power rose respectively as the air/fuel ratio was approaching $\lambda = 1$. The soot emissions were reduced.

Supplementary 3D-CFD investigations at rated power conditions identified high flow velocities of over 150 m/s as the reason for the injector spray to be deviated considerably, which led to high wall wetting and poor mixture formation (see figure 4). The route cause for the high flow velocities was identified to be an unfavorable – not fully central – position of the injector.

Figure 3: Full load performance

Figure 4: 3D-CFD simulations at rated power for different injector positions
Further investigations addressed the transient behavior of the charging system. Therefore load steps from zero load to 90 % IMEP (Indicated Mean Effective Pressure) were carried out with the available engine setup, which did not include any optimization of the boost system ducting, compressor strategy or calibration. 90 % IMEP was reached after 1.5 seconds. 1D gas exchange simulations revealed that some combined optimizations of the charging system, ducting and in particular of the compressor gear ratio would improve the response time down to below 0.75 seconds.

Finally, simulations to estimate the potential CO₂ emission reductions in the New European Driving Cycle (NEDC) were carried out (see figure 5). The developed 0.8 liter engine achieved more than 11 % CO₂ emission reduction in NEDC when compared to a 1.4 l GTDI engine with a similar power output, when both powertrains were simulated with conventional 95 RON gasoline fuel and equal boundary conditions (vehicle, in-gear acceleration figures). With further friction optimization of the engine (the Diesel test engine was not optimized with regard to friction) between 13 % and 14 % CO₂ reduction seemed to be realistic.

By means of the additional use of E85SB fuel almost 15 % CO₂ reduction (no friction optimization) appeared to be possible because of the lower ratio between carbon (C) and hydrogen (H) of ethanol blended fuels and better knock resistance.

By optimization towards high-octane ethanol fuels, it was possible to reach a specific power output of 120 kW per liter with a displacement of only 0.8 liters. The chosen compression ratio – which is relatively high for this degree of supercharging - led to substantial efficiency advantages during part load, which also had a particularly positive effect in the NEDC (in addition to the load point shift as result of the displacement reduction).

The challenges of extreme displacement reduction have become apparent during full load operation. High compression pressures promoted unwanted combustion phenomena such as pre-ignition and knocking. Due to their high evaporation enthalpy and chemical knock resistance ethanol splash blended gasoline fuels offered a high improvement potential with regard to knock and pre-ignition resistance.

A compromise between a central spark plug position in favor of short flame propagation and a central injector position to prevent wetting the walls has been proven to be essential for a sufficient combustion system design. In particular in combination with long injection durations as consequence of the increased fuel flow with high ethanol concentrations a precise setup of the spray pattern, the injector position and the injection pressure is required.
The perceived noise quality of combustion engines is predominantly influenced by the occurrence and the characteristics of individual disturbing noise components. The Institute for Combustion Engines of the RWTH Aachen University has developed a methodology within the framework of a FVV project, which allows the extraction of audible noise components so that they can be listened to separately, and the annoyance level of these components can be quantified automatically. Furthermore, the methodology allows the synthesis of a newly weighted total engine noise from the separated noise components for target value definition. A Matlab-based calculation tool is provided to the partner companies of the research association which allows the application of the newly developed methodology.

**Methodology of noise separation**

The most important part of the developed methodology is the extraction of tonal, flow noise and also impulsive noise components from an engine’s total noise. These noise components have very different characteristics in the time domain as well as in the frequency domain. Impulsive noises of a combustion engine have a short temporal extension with a high repetition rate. On the contrary, tonal noise segments are usually singular events with a large temporal extension. Impulsive and tonal noise components are typically defined by a deterministic phase structure, whereas flow noise components have a stochastic phase. Due to these differences in signal characteristics, an individual algorithm, which is adapted to the respective signal characteristics, was developed for each group, instead of using a generic algorithm for the extraction of the three noise groups. The sequence of the individual separation steps is illustrated in Figure 1.

![Figure 1: Methodology of noise separation](image)
As a first step, tonal noise components are separated from the total noise. Therefore, the total engine noise is transferred from the time domain into the frequency domain and afterwards split into the amplitude and phase spectrum. Application of several acoustically motivated image processing algorithms to the amplitude spectrum allows for the separation of tonal and non-tonal signal segments into two amplitude spectra. The combination of these amplitude spectra with the overall phase spectrum yields two complex spectra of the separated noise shares which can be transformed back into the time domain, see Figure 2.

The remaining noise is then divided into deterministic and stochastic signal portions using statistical signal processing algorithms. Therefore, the engine speed is calculated from the given noise sample. This information is used to divide the time signal into segments which correspond to the length of one working cycle. Using these signal segments, the time signal of the deterministic components is derived by calculating the moving average over several working cycles. The subtraction of the deterministic components from the original signal yields the stochastic signal components, see Figure 3.

Due to the special properties of combustion engine noise, the deterministic signal components correspond largely to the dominant, impulsive noise components, e.g. injection and combustion. The stochastic signal components already are a good representation of the sought-for flow noise components. Possible impulsive residual shares can be eliminated via phase manipulation of the stochastic components.

Following the newly developed methodology, the algorithms from a preceding FVV research project are used to perform a further division of the already separated noise components into the sub-categories knocking, ticking and rattling.
Methodology of annoyance evaluation

Apart from the noise separation, the presented methodology also contains the quantification of the annoyance of an engine noise. Metrics have been determined which allow the assignment of annoyance ratings to the partial noises of the tonal, flow and impulsive noises. They also facilitate the deduction of the annoyance of the total noise.

In a first step, a noise data base was generated for the determination of these metrics for the automated evaluation of the individual annoyances. This noise data base then was evaluated by an inter-company expert jury with regards to the characteristics of the annoyance of tonal and flow noise components on a scale from 1 (unacceptable) to 10 (not perceivable) to map the perceived annoyances. In parallel the noises of the data base were subjected to the new noise separation methodology. Acoustic and psychoacoustic parameters of the partial noises and the total noises were identified by correlation tests. These allowed the automated mapping of the perceived annoyances of tonal and flow noise components. As a result the annoyance of tonal components is mapped in the calculation tool via the linking of three parameters:

- Level difference of the tonal components to the total noise
- Sharpness of the tonal components
- Tonality parameters calculated from the total noise

Figure 4 illustrates the correlation of the calculated disturbance parameter of tonal noise components over the respective jury evaluation.

The following aspects are considered for the determination of the annoyance of the flow noise components:

- Level difference of the flow noise components compared to the non-tonal noise components
- Sharpness of the flow noise components

For the evaluation of the annoyance of impulsive noises, extensive auditory experiments have already been performed during the predecessor research project. A calculation matrix for the automated identification of the parameters has been developed. The results of these tests are integrated into the methodology developed here to evaluate impulsive components. For the evaluation of the total annoyance of the engine noise, the evaluation of the individual components with the highest annoyance rating was used.
The methodology developed for noise separation and evaluation was realised in a Matlab-based calculation tool and provided to the partner companies of the research association. The tool allows the user to apply all steps of the developed methodology to a chosen engine noise without the need of in-depth knowledge of signal analysis. The user can upload a total engine noise via a graphical user interface and divide it automatically into the above mentioned noise segments. The evaluation of the annoyance of the separated components can also be performed automatically. The separated noises can be listened to individually and analysed with regards to their spectral composition. With the help of an export function it is possible to transfer the separated partial noises to other analysis programs for a more detailed analysis. Furthermore, the calculation tool offers the opportunity to synthesize a newly weighted total engine noise from the separated noise components, see Figure 5.

Figure 5: Calculation tool, synthesis of newly weighted total engine noise

This function allows the user to make noise quality target values audible and therefore more tangible than it would be possible with the evaluation of annoyance parameters. Also, individual noise segments can be reduced in their intensity or removed completely from the signal to evaluate the effect of possible acoustically motivated component modifications on the total noise. This allows for example to experience the complex effects of the reduced spectral masking through the reduction of flow noise and their possible negative effect on the perceived noise quality.
Thermal Management of Electrified Vehicles

Introduction

In cooperation the two institutes “Lehrstuhl für Verbrennungskraftmaschinen (VKA)” and „Institut für Kraftfahrzeuge (ika)“ of the RWTH Aachen University, realize a research project about the thermal management of electrified vehicles. Target of the project is the investigation of new cabin climatisation concepts. Active and passive measures will be examined to heat up the passenger cabin. Therefore a simulation model will be built up to evaluate potentials of different thermal measures. The simulation model will be validated by the results of a real demonstrator.

The demonstrator vehicle for the measurements is an electrified Fiat 500. For the driving performance an electric engine from UQM with a peak power of 75 kW and a maximum torque of 240 Nm is used. The maximum driving speed is limited to 125 km/h to prevent a too fast discharging of the battery. The battery system consists of 84 Li-Ion cells with an energy content of 12 kWh. This technical configuration approves a travelling range of around 80 km.

Motivation

The motivation of this project is to increase the overall efficiency of an electrified vehicle with optimized thermal management strategies.

In this research project the focus is placed on low temperature fluidic heating surfaces in the cabin which should support the climatisation of the passenger cabin. A scheme of such a heating concept is illustrated in figure 1. The fluid heating surface is directly connect to the cooling circuit of the electrical components (electrical engine, Inverter; DC/DC). The dissipated waste heat of the electrical components can be used by the fluidic heating surface to transfer radiation heat to the passengers.

In addition the electric power for heating up the cabin should be decreased by installing an improved isolation system. For this reason thermal insulations are mounted at the vehicle doors, rooflines, luggage boot and the ground of the passenger cabin with the target to decrease heat losses from the cabin to the environment.

Furthermore a thermal managed strategy of integrating a range extender is investigated. The motivation is the support of the cabin heating process by using the waste heat of the combustion engine. In this case the main function of the range extender is the production of heat for the cabin instead of charging the battery for extending the travelling range. Nevertheless the battery will be charged as a positive side effect.

On the one hand all these mentioned measures will be investigated in a simulation model. On the other hand these measures will be implemented in the Fiat 500 to validate the simulation model.
Development of a simulation model

A simulation model with the GT-Suite software is build up to check the potential of the thermal management system at different ambient conditions and driving cycles.

The car model is subdivided in 8 subsystems (Vehicle, cabin, e-motor, battery, powertrain, inverter, cooling system and range extender) as shown in figure 2.

A detailed overview of the cooling circuit is given on the right hand side of figure 2. The circuit consists of two parallel cooling lines. One for the electric engine and one for the DC/DC and the Inverter. With a 3/2-way valve the radiator can be bypassed.

The development of the simulation model and the validation measurements with the FEV Liona demonstrator are running parallel.

Validation of the simulation model

For the validation of the simulation model several tests are run in a climatic chamber. All driven tests are shown in table 1. As ambient temperatures -20°C, -10°C, 0°C and 20°C are chosen. For the wheel load points 5 kW, 10 kW, 15 kW and maximum Power (~22 kW) are adjusted. Additionally the two driving cycles Artemis Urban and NEDC are driven at an ambient temperature of 0°C.
At the beginning of the tests the battery has to provide around 28 kW. The electric engine has to generate 24 kW power to keep the 10 kW wheel power. Losses from the battery to electric engine occur due to internal energy conversion. Among others the power train losses are generated by the high viscosity of the oil in the gear box at low temperatures. The needed battery power decreases to 22 kW at the end of the test. The overall efficiency of the car at this load point at the end of the test constitutes 45%.

Table 1: Tests driven in the climatic chamber

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<td></td>
<td>-20°C</td>
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<tr>
<td>Wheel Power</td>
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<tr>
<td>5 kW</td>
<td>X</td>
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<tr>
<td>10 kW</td>
<td>X</td>
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<tr>
<td>15 kW</td>
<td>X</td>
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<td>P\textsubscript{max}</td>
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<tr>
<td>Driving Cycle</td>
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<td>NEDC</td>
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<td>Artemis Urban</td>
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For measuring purposes the demonstrator vehicle is equipped with temperature and pressure sensors. This is essential to determine the thermal and hydraulic behavior of the cooling circuit. The sensors are installed before and after the electric components (electric-engine, Inverter; DC/DC). During the measurements the power of the battery, electrical engine and wheel power are recorded. In figure 3 the simulated and measured results are illustrated. It shows the power of the battery and electric engine by the test conditions of 10 kW wheel power and an ambient temperature of 0°C.

Figure 3: Validation of simulation model at 0°C and 10kW wheel power

At the beginning of the tests the battery has to provide around 28 kW. The electric engine has to generate 24 kW power to keep the 10 kW wheel power. Losses from the battery to electric engine occur due to internal energy conversion. Among others the power train losses are generated by the high viscosity of the oil in the gear box at low temperatures. The needed battery power decreases to 22 kW at the end of the test. The overall efficiency of the car at this load point at the end of the test constitutes 45%.
Results

Main target is the investigation of the heat which is transferred from the electric components into the cooling fluid and to analyze if this heat can be used by the fluidic heating surfaces.

Figure 4 shows the emulated heat, the temperature of the seat surface and the cooling fluid outlet temperature. After 20 minutes the heat power level is at around 800 W and seat surface temperature increases up to 16°C.

Based on this results a potential for using the waste heat of the electric components by fluidic heating surfaces can be seen and will be further investigated.

![Figure 4: Emulated heat transfer of the cooling system](image)

Acknowledgment

The scientific works presentend on pages 48 to 67 were performed within the scope of different research projects of the Forschungsvereinigung Verbrennungskraftmaschinen e.V. (FVV) and the Forschungsvereinigung Antriebstechnik e.V. (FVA), which were partly co-funded by the Fachagentur für Nachwachsende Rohstoffe e.V. (FNR), the Arbeitsgemeinschaft industrieller Forschungsvereinigungen „Otto von Guericke“ e.V. (AiF) and the Deutsche Forschungsgemeinschaft (DFG). 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.

Contact

Dipl.-Ing. David Hemkemeyer
Phone: +49 241 5689-6827
hemkemeyer@vka.rwth-aachen.de
Events 2014
Every year an "International Workshop" is hosted in Aachen to present the latest results and to strengthen the interdisciplinary research work of the Cluster of Excellence Tailor-Made Fuels from Biomass. In 2013, the workshop was transformed into an international conference, opening up the stage for experts from around the globe to present their work in the fields of synthesis, production and combustion of modern biofuels.

The 2nd International Conference of the Cluster of Excellence TMFB took place from June 16th to 28th, 2014, in collaboration with SuBiCat. It was supported by the renowned journal Green Chemistry.

In separate sessions, several fascinating topics like biomass fractionation and pre-treatment, injection, ignition and combustion of biofuels and combustion process and exhaust gas aftertreatment optimization of biofuels were addressed.

In addition to 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 TMFB. Furthermore there was a poster session and plenty of opportunity to network.

2nd International Conference of the Cluster of Excellence TMFB
June 16th to 18th, 2014

CONTACT
Dr. Florian Kremer
Phone: +49 241 80 95352
kremer@vka.rwth-aachen.de

2015
The 3rd International Conference will take place from June 23rd to 25th, 2015.
After a welcome by Professor Dr.-Ing. Ernst M. Schmachtenberg, Rector of RWTH Aachen University, especially the plenary speeches of high-ranking executives from the automotive industry gained attention. Professor Dr.-Ing. Ulrich Hackenberg, Member of the Board of Management of AUDI AG, talked about changes in vehicle technologies, while Dr. Wolfgang Ziebart, Group Engineering Director of Jaguar Land Rover, examined which challenges a premium car manufacturer faces due to the customer’s expectations of the latest technology. Dr. Karsten Kroos, Chairman of the Management Board of Business Area Components Technology of ThyssenKrupp AG, presented the InCar®plus project by ThyssenKrupp. Michael F. Ableson, Member of the Management Board and GM Europe Vice President Engineering, showed how innovative technology is improving Opel’s Image. Dr.-Ing. Peter Mertens, Senior Vice President Research & Development at Volvo Car Corporation, looked ahead and described in his plenary speech Volvo’s way to reach Zero Emissions.

In the future the varied topics of automobile and engine technology will continue to be of high significance for research and industry. In 2015 participants from about 30 countries will again experience technical innovations and exciting discussions about latest developments in the automotive industry.
Open Day
at the Institute for Combustion Engines
for the employees and their families
June 28th, 2014