# Operating Fluids and Materials are Key Technologies for Efficient Combustion Engines

High power density is key for further increasing the efficiency of internal combustion engines. It can be reached by aligning operating fluids (fuels, coolants and lubricants) and materials to pair long service life and high fatigue strength with optimized friction. The projects initiated by the Research Association for Combustion Engines (FVV) bridge the gap between basic research and industrial applications.

## 1 OBJECTIVE

The efficient use of ecological resources is one of the top tasks of modern engine development. The further development of all operating fluids – including fluids with caloric, lubricating and power-transmitting functions but also coolants – is often neglected but no less relevant. Not only do these fluids affect the operation of all engine subsystems; they directly influence the design of the overall engine, as high power density can only be reached when operating fluids and materials are combined to achieve both low frictional or power loss and high reliability. High power density, in turn, does not only lead to lower fuel consumption but also to improved resource efficiency by reducing the overall vehicle mass through the intelligent use of materials.

The focus of collective industrial research as coordinated by FVV is not on the operating fluids as such but the interaction of such fluids with the materials


© Aral

## VOICES OF THE FVV

© FVV

**Dr.-Ing. Dieter Eppinger heads the Testing and Reliability Department at SEG Automotive. He has been coordinating Planning Group 4 "Strength and Tribology" in the FVV research area of engines for many years.**
"To design future drives as resource-efficiently as possible, it is crucial for us to understand the interactions between operating fluids, materials and operating conditions as best as we can."

© LVK

**Prof. Dr.-Ing. Bert Buchholz holds the Chair for Reciprocating Engines and Internal Combustion Engines at the University of Rostock.**
"With the new test methods such as the diesel fuel thermal oxidation test, we are laying the foundations for the use of alternative fuels."

© FVV

**Martin Nitsche is Deputy Managing Director of the Research Association for Combustion Engines and is in charge of joint industrial research on issues of tribology, material strength and (static) friction.**
"Modern surface technology makes it possible to set exact friction values. They can, however, only be used in industrial practice if we have suitable simulation models."

FVV **http://www.fvv-net.de/en**

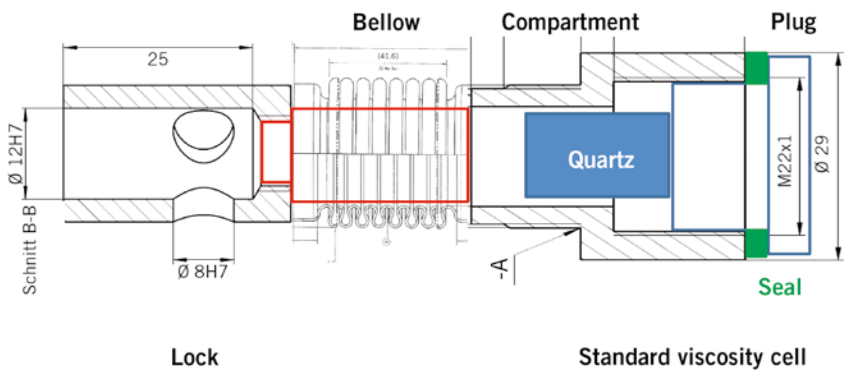


**FIGURE 1** Test bench concept for shock-pressure measurements (© ITR Clausthal)

used in vehicle powertrains. The primary goal is not always to minimise friction, as often published, but to obtain ideal friction on a "by-case" basis. In shaft-hub connections, for example, this may result in a targeted increase in friction force. Broad industrial use of the results obtained from research in these areas requires suitable simulation tools. The modelling methods developed within the framework of FVV projects lay the foundations for this.

New challenges in researching the interfaces between operating fluids and materials exist, primarily, because of the introduction of biogenic or synthetic fuels. They directly impact material strength and with it also engine service life as various mechanisms take effect. The interaction between fuels and lubricants is not negligible in this context.

## 2 TRIBOLOGICAL DESIGN

### 2.1 OPTIMIZED SURFACES UNDER FRICTION

Modern engines and components with high power density require the transmission of high forces and torques. In this context, not only the materials themselves but also the force-transmitting interfaces between components are decisive. To render the best possible layout results, the forces (loads) that occur during engine operation need to be well predicted, and the forces that are transmitted (load carrying capacity) need to be exactly known. Both, mean values and occurring dispersion need to be considered as a reduction of the often-large dispersion leads to a significant increase in joint performance, even with an unchanged mean value. A layout based solely on the usual parameters, such as the roughness of a surface, would render inaccurate results given the high loads imposed on modern engines. Identifying suitable parameters for this is an important field of activity for collective industrial research, as the supplier structure in engine design is characterized by many small and medium-sized enterprises (SMEs). The so-called "GECKO" cluster, a project which was funded by the German Research Foundation (DFG) and the Federal Ministry for Economic Affairs and Energy (BMWi) via the Association of Industrial Research Associations (AiF) and jointly implemented with the Research Association for Drive Technology (FVA) [1], systematically investigated, for example, new technical solutions for the surface treatment of frictional connections. Studies of physical vapour deposition, thermal spray coatings and laser structuring showed that significant increases in friction coefficients are possible with all three methods. In one of the subprojects, a three-dimensional contact model was developed, with which the solid-state friction of metallic materials can be simulated after calibration.

Another project focused on the transferability of model-based static friction coefficients as determined in GECKO to real components [2], for which the Chemnitz University of Technology (TU Chemnitz) carried out comparative investigations on model test benches, using typical connections, such as transverse press-fit, frontal press-fit and flange joint connections. The researchers proved that the majority of these model tests could be directly transferred to real applications, but they also identified other significant parameters that need to be taken into account in practice. The project resulted in a guideline for cost-effective model tests based on real components.

### 2.2 TRIBOLOGICAL FLUID MODELS

It is not the first time that the development of engines has been going hand-in-hand with optimizing fuels through simulations. Increased computing capacity of modern computer systems and new findings in physical chemistry are opening up options for further increasing power density. Tribologically optimised auxiliary units, and pumps, in particular, can significantly reduce power dissipation, whereby new load collectives in electrified powertrains pose a challenge. A research project that was completed in 2015 and carried out collectively with the FVA laid the foundations for a tribological fluid model that is especially suitable for designing auxiliary drive units in electric and hybrid vehicles [3]. Three research institutes collaborated and conducted numerous bench tests, some of them with new measuring methods. They identified two fluid models that are also suitable for peak fluid loads. The still ongoing follow-up project [4] focuses on closely investigating all those physical effects that occur in the very thin lubrication gap under transient loads. This requires further developing the measurement technology in a first step. **FIGURE 1** shows a possible setup for testing thrust-like impact. The results will then be observed in a fluid model which will consider the pressure dependence of viscosity as it exists under real conditions. This model will ultimately be optimized so that it can easily be used in commercial CFD programs by a wide range of users.

## 3 THE IMPACT OF NEW FUELS

Fuel combustion can always cause the formation of deposits in high-performance diesel injection systems and thus negatively impact long-term combustion stability and emissions. The increased sensitivity of modern injectors, the continuously growing variety of diesel fuels and the admixture of different blends exacerbate the deposition problem and must be given increased attention in the future. In particular, higher injection pressures and the associated higher system temperatures place high demands on thermal and oxidative fuel stability and additive resistance.

### 3.1 TEST METHODS FOR DIESEL FUELS

Two consecutive projects were called into life to establish and validate a method suitable for determining in practice how diesel-like fuels affect deposit-formation in the fuel injection system in the long term. The method is essentially based on a test procedure which was originally developed for testing aviation fuels and adapted to diesel-like fuels at the University of Rostock, **FIGURE 2**. During the test, the fuel under investigation is moderately pressurized at 34 bar and flows along a heated aluminium tube (test specimen). The layer thicknesses of the coatings produced on the test specimen surface are measured using an ellipsometer and evaluated as a function of temperature. The first project [5] has already been completed and showed that the deposit types were the same as those found inside common-rail injectors. Also, numerous new findings on the thermal stability of various fuels and the effectiveness of certain additive groups were gained. The second project [6] is still running and aims at finding a method to quickly and cost-effectively classify diesel fuels and their tendency to form deposits when carrying out Diesel Deposit Formation Tests (DDFT) in practice. This requires finding an entirely new evaluation method. The findings of this project are highly relevant not only for designing of injection components but also for screening commercially used fuels as well as analysing field failures. A reduction in engine endurance tests would, moreover, allow for considerable cost and $CO_2$ savings.

### 3.2 FATIGUE CAUSED BY CORROSIVE FUELS

Many years of practical experience have shown the effects of cyclic wear of metallic materials when in contact with fossil fuels that are free of water and virtually free of contaminants during engine operation. Such an experience cannot simply be transferred to other media and materials without further systematic studies. Biogenic fuel mixtures present as a potentially corrosive ambient medium which may lead to crack formation in metallic components as a result of vibrating mechanical loads. The University of Technology Darmstadt took the lead and set up a project [7] in which three Research and Technology (RTD) Performers developed a method that now permits the safer use of components through new protection and design concepts. Long-term exposure tests and electrochemical measurement methods were some of the methods used to clarify essential damage mechanisms as well as the interactions between fatigue and corrosion.

### 3.3 OIL AGING WITH NEW FUELS

The long-term operating behavior of engines is partly influenced by fuel ingress (unburnt fuel and combustion products) into the engine oil. The use of new petrol blends may likely change this behavior. As intermediate products of alcohol fuel oxidation, short-chain organic acids, such as acetic acid and formic acid in particular, are suspected of accelerating oil aging and having a highly corrosive effect on engine components. The influence of bioalcohol fuel blends (bio-methanol and ethanol) on the lubrication system of a modern Euro-6 passenger car engine with direct petrol injection was investigated for the first time; the project was run in cooperation with the Federal Ministry of Food and Agriculture (BMEL) via the Agency for Renewable Resources (FNR), conducted at the University of Rostock and completed this year [8]. One crucial part was to analyse the real-life blow-by gas composition as an important ingress route in engine tests as. Endurance tests were carried out and determined the ageing of lubricating oil and numerous other parameters. This was followed by analysing the wear and surface quality of the key engine components. The tests showed that the wear of the researched fuel mixtures and fossil fuels hardly differed.


**FIGURE 2** Laboratory setup for the Diesel Deposit Formation Test (DDFT) (© LVK Rostock)

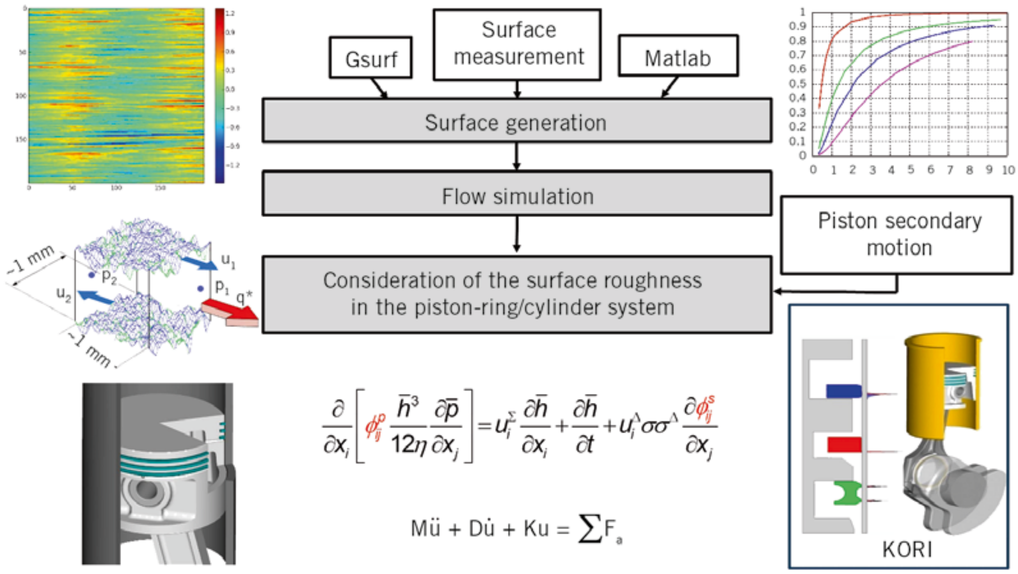


**FIGURE 3** Simulation chain for piston ring oil transport (© iaf-mt Kassel)

## 4 PISTON RING OIL TRANSPORT

The oil transport caused by the movement of the piston rings in grooves and on the cylinder wall significantly influences emission behaviour and the condition of engine oil of internal combustion engines. The oil transport is also dependent on the load collectives that occur and that are changing with the introduction of hybridised drives. It is therefore extremely important to clearly understand the physics, and to mimic them in a model is extremely important when developing new powertrains. To measure and subsequently simulate oil transport, the FVV first established the required testing environment and then linked several projects using FVV own funds to create the test conditions. The complex simulation models developed on this basis enable an understanding of the secondary piston movement, the piston ring movement, the gas flow in the ring pack and the oil transport in the ring pack [9], **FIGURE 3**. The software is capable of calculating ring movements and positions, gas flow and gas pressure as well as lubricant film heights and power loss.

## 5 TRANSFERABILITY TO NEW DRIVES

In principle, the tasks for research into operating fluids and strength of materials in internal combustion engines should also be applied to electrified drives. Because of the often-higher speeds and smaller sizes of the mechanical components, the power density and the service life of electrical drives are even more dependent on tribology and durability than internal combustion engines. Collective industrial research of electric powertrain systems would normally fall within the competence of the FVA, the Research Association of Drive Technology. Since hybrid powertrains can, however, also be optimized on a system level, which constitutes an important part of FVV's activities, both associations closely cooperate in many projects and programs.

The ongoing development of hybrid electric powertrains with fuel cells requires in-depth and proven scientific knowledge of material fatigue phenomena that occur under contact with operating fluids. The long-term strength of metallic components continuously exposed to hydrogen is a particularly important field of research.

The challenges engine developers will face with the introduction of synthetic fuels are probably comparable to those posed by biogenic fuel blends in the past. Given the sheer variety of synthetic fuels and the possible admixture ratios that are currently on the table, it is essential to investigate in detail how they interact with other operating fluids, how they behave during operation and what effect they have on the service life of engine components.

### REFERENCES

**[1]** IGF research cluster "Design and identification of characteristic data of friction contact-optimized surfaces". Funding organisations: BMWi/AiF, DFG (17229 N). Project coordination: Dr.-Ing. Anton Stich (Audi AG), RTD performer: Prof. Dr.-Ing. Erhard Leidich (Institute of Construction and Drive Technology, TU Chemnitz)

**[2]** IGF Research project "Investigations into the transferability of model-based static friction coefficients and friction characteristics based on joined components". Funding organisation: BMWi/AiF (18500 BR). Project coordination: Dr.-Ing. Anton Stich (Audi AG), RTD performer: Prof. Dr.-Ing. Erhard Leidich (Institute of Construction and Drive Technology, TU Chemnitz)

**[3]** IGF Research project "Tribological models of fluids used for auxiliary powertrain pumps in electric and hybrid electric vehicles". Funding organisations: BMWi/AiF, FVA, FVV (17699 BG). Project coordination: Dipl.-Ing. Klaus Meyer (Robert Bosch GmbH), RTD performer: Prof. Dr.-Ing. Hubert Schwarze (Institute of Tribology and Energy Conversion Machinery), TU Clausthal

**[4]** IGF Research project "Tribological models of fluids used for auxiliary powertrain pumps". Funding organisation: BMWi/AiF (19427 BG). Project coordination: Dipl.-Ing. Klaus Meyer (Robert Bosch GmbH), RTD performer: Prof. Dr.-Ing. Hubert Schwarze (Institut für Tribologie und Energiewandlungsmaschinen, TU Clausthal)

**[5]** IGF Research project "Laboratory test development to assess internal diesel injector deposit formation (IDID) by diesel additives". Funding organisation: FVV (1198). Project coordination: Dr.-Ing. Alexander von Stockhausen (Robert Bosch GmbH), RTD performer: Prof. Dr.-Ing. Bert Buchholz (Chair of Piston Machines and Internal Combustion Engines, University of Rostock)

**[6]** IGF Research project "Application and validation of a lab-test method for classification of diesel fuels according to their tendency for deposit formation in injection systems as a function of temperature". Funding organisation: FVV (1285). Project coordination: Dr.-Ing. Alexander von Stockhausen (Robert Bosch GmbH), RTD performer: Prof. Dr.-Ing. Bert Buchholz (Chair of Piston Machines and Internal Combustion Engines, University of Rostock)

**[7]** IGF Research project "Development and experimental verification of a fatigue assessment method for highly loaded engine components in corrosive fuels". Funding organisations: DFG, FVV (OE 558/9-1). Project coordination: Dipl.-Ing. Hendrik Lindl (Robert Bosch GmbH), RTD performer: Prof. Dr.-Ing. Matthias Oechsner (Institute for Materials Science/Centre for Structural Materials, TU Darmstadt)
**[8]** IGF Research project "Effects of new gasoline fuels on the aging of lubricants and resulting effects on tribology of engine components". Funding organisations: FNR, FVV (22021315). Project coordination: Dr. Peter Berlet (IAVF Antriebstechnik GmbH), RTD performer: Prof. Dr.-Ing. Bert Buchholz (Chair of Piston Machines and Internal Combustion Engines, University of Rostock)
**[9]** IGF Research project "Piston ring oil transport". Funding organisation: BMWi/AiF, FVV (17553 N). Project coordination: Dr.-Ing. Arnim Robota (Federal Mogul Burscheid GmbH), RTD performer: Prof. Dr.-Ing. Georg Wachtmeister (Institute of Internal Combustion Engines, TU Munich) and Prof. Dr.-Ing. Adrian Rienäcker (Chair of Machine Elements and Tribology, University of Kassel)

## THANKS

The Research Association for Combustion Engines would like to express its gratitude to public funding bodies and all FVV members for their generous support of the research activities mentioned in this paper. Our special thanks goes to the research institutions, project managers and members of working groups and project user committees for their trustworthy and excellent cooperation.