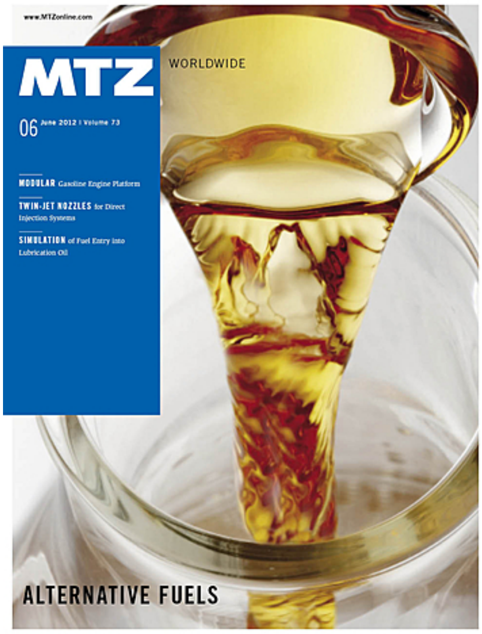


MTZ worldwide 6/2012
http://www.mtz-worldwide.com

www.MTZonline.com

MTZ

WORLDWIDE

06 June 2012 | Volume 73

MODULAR Gasoline Engine Platform

TWIN-JET NOZZLES for Direct Injection Systems

SIMULATION of Fuel Entry into Lubrication Oil

ALTERNATIVE FUELS

CONTENTS

COVER STORY

ALTERNATIVE FUELS

4, 12 | After a period of great euphoria, little was heard for a long time about the development of alternative fuels from sustainable resources. Now, however, fuel research seems to be experiencing a renaissance. Emitec has addressed fundamental issues of the future energy supply with the aim of anticipating sustainable mobility and possible future technologies. In order to examine the interaction between biogenic fuels and components, Oel-Waerme-Institut (OWI) has developed a hardware-in-the-loop test stand.

COVER FIGURE © Jim Barber / shutterstock
FIGURE ABOVE © iQoncept / shutterstock

RESOLVING CONFLICTS

Dear Reader,

Are conflicts a part of our everyday working life? Indeed they are, and there is certainly no benefit in the long term in simply evading or concealing everyday conflicts instead of trying to resolve them in an appropriate manner. Pretending for a while that everything is harmonious is also a dubious strategy, as it poisons the atmosphere even if people are not actually aware of it. Teamwork, which plays such a key role today, poses a challenge in this respect in every aspect of our work, but it is one that also offers many opportunities for resolving conflicts. Even though conflicts are an inevitable part of a professional environment, some people still see them as negative and destructive. Without question, there are always two sides to a conflict; there is no denying that there are dangers and risks. But isn't every risk also an opportunity? An opportunity to find new agreement after a period of conflict and tension. Such a chance does not come automatically. But there is a lot we can do to take advantage of it.

Is it possible to learn how to resolve conflicts? I think so, and addressing conflicts can even be enjoyable. One possibility takes the form of an argument. Yes, even though the word "argument" has negative connotations for many people. But if one understands it simply as a difference of opinion, an argument is neither good nor bad. The fact that there are no arguments is by no means a sign that a relationship is working well.

Does that mean that it is impossible to avoid arguments? What is decisive is how one argues. Arguments can be mature, fair and constructive, but they can also be destructive, hurtful and immature. Learning how to argue fairly is an important prerequisite for successfully dealing with conflicts at work and under stressful conditions. Not only will senseless conflicts that have no deeper background be automatically alleviated, there will be a greater focus on unavoidable conflicts, which can then be duly addressed and resolved.

W. Siebenpfeiffer

WOLFGANG SIEBENPFEIFFER,
Editor in Chief and Editor in Charge
Stuttgart, April 2012

SUSTAINABLE FUEL A FANTASY?

Emitec has been committed to environmentally friendly mobility, including electrification, since 1986. The financial and technical implementation of the next stages toward this aim will entail optimum use of the company's resources. The following three key issues have to be subjected to scientific scrutiny to gain better insight into sustainable mobility and potential technologies: Is environmentally friendly or environmentally neutral mobility achievable? Will there be a sustainable and cheap supply of suitable fuels? And do we have to avoid carbon-based energy sources?

AUTHORS

DIPL.-ING. WOLFGANG MAUS
is Chairman of the Board of Management of Emitec Gesellschaft für Emissionstechnologie mbH in Lohmar (Germany).

DR. RER. NAT. EBERHARD JACOB
is Consultant for Emission Technologies at Emitec Gesellschaft für Emissionstechnologie mbH in Lohmar (Germany).

DIPL.-ING. ROLF BRÜCK
is Managing Director Research, Development and Application at Emitec Gesellschaft für Emissionstechnologie mbH in Lohmar (Germany).

DIPL.-CHEM.-ING. PETER HIRTH
is Head of Research, Development and Test Department at Emitec Gesellschaft für Emissionstechnologie mbH in Lohmar (Germany).

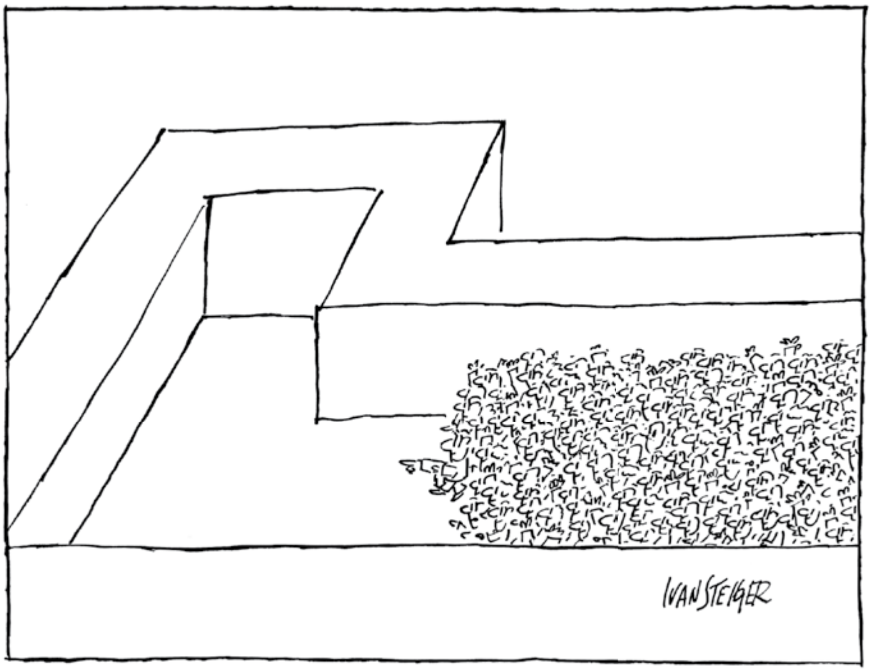
SUSTAINABILITY – INTRODUCTION AND OBJECTIVE

Sustainable management dates back to the 16th century and the aims of responsible forest management: The rate of deforestation should not exceed the rate of reforestation. This is biological sustainability. Today, there is a wider demand for "sustainability" that encompasses practically every part of life. Strictly speaking, the term sustainability still only makes sense when referring to that which will survive the remaining life span of the earth, that is, the constant forces of nature and renewables with an inherent biological agenda.
It does not apply to resources. Materials can only be recycled and matter can only be transmuted. Even energy cannot be sustainable because it follows the laws of thermodynamics [1]. There is one issue that is consistently ignored in the sustainability debate: When it comes to the consumption of various resources we are supposed to think in ethical categories, such as generational fairness. How many generations should we include to be politically correct? Would our good intentions not have to last until the end of the world, when the oceans boil in 900 million years [2]?

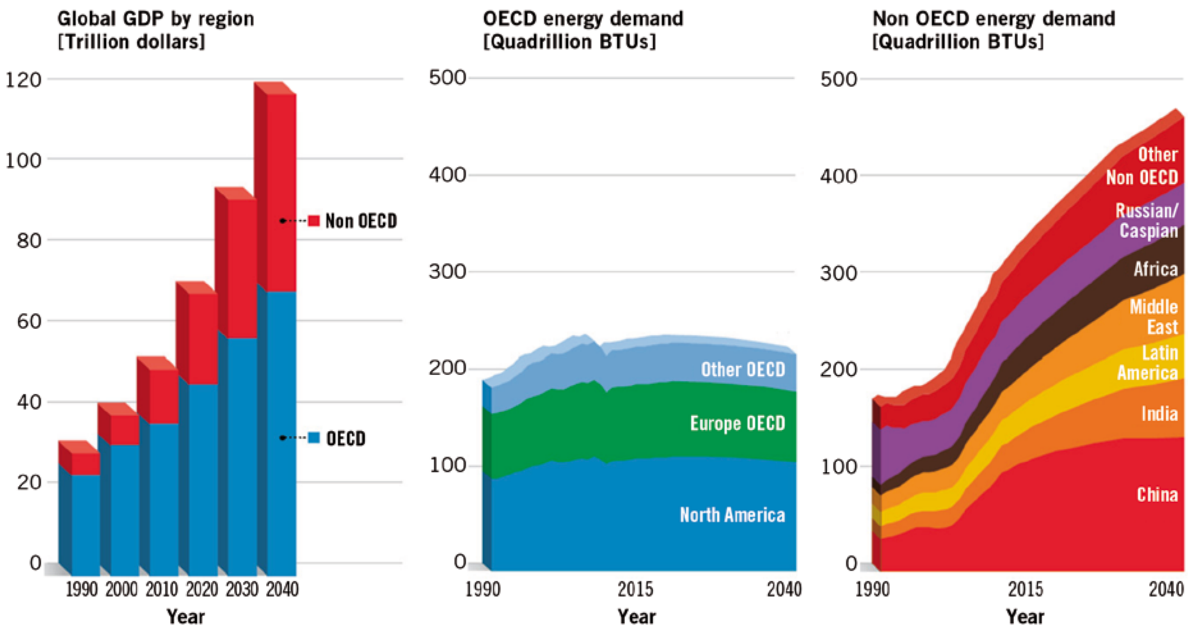
Fossil fuel reserves, including uranium, will be depleted within a few generations. The fast breeder reactor is the only remaining long-term option. However, wind, water, sun and nuclear fusion are the only truly sustainable energy sources. The green dictum on energy policy, ❶, requires more precise definition:

: Sustainability applies for <<900 million years.
: "Alternative" energy is in conflict with the first law of thermodynamics.
: "Renewable" energy contradicts the second law.
: "Energy reform": energy cannot be reformed.
: CO_2 causes climate change: CO_2 is only one part of the complex mix of factors that control our climate, the claim has not been verified.

This discussion should be rationalised by looking at what physics has to tell us. We will have to make more efficient use of energy and develop new technologies to largely replace our finite fossil fuel reserves. The, as yet unsubstantiated, damaging impact that rising CO_2 levels in the atmosphere have on our climate is leading to enormous changes in energy systems worldwide – with significant national variation.
The driving force behind these changes is a dramatic reduction of CO_2 emissions that are caused by the burning of fossil fuels. The fact that a disproportionately



❶ The green dictum on energy policy: CO_2 is a climate gas but the herd instinct takes us down a blind alley

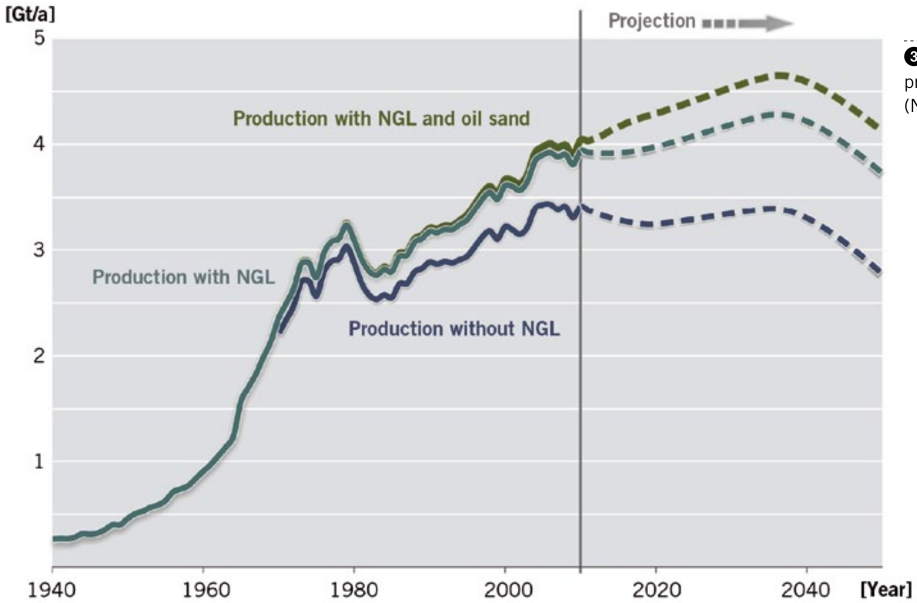


❷ Development of the global gross national product and energy demand until 2040 for different world regions [4]

high burden falls on the combustion engine is nothing short of disastrous. Combustion engines are associated with the highest CO_2 abatement costs compared to other emission sources and this is going to increase the cost of mobility accordingly.

It should first be noted that combustion engines powered by liquid fuels are going to maintain their dominant position in the vehicle powertrain, especially for long-distance journeys. There are two reasons for this, first the unrivalled volumetric energy storage density of gasoline and diesel, which is 9 to 10 kWh/l, and second the ability of the chemical industry to synthesise these liquid fuels from other carbon-based primary raw materials, including, in principle, CO_2. This makes it possible to gradually supplement and replace crude oil in case it has to be taken off the market because of rising prices, the security of supply or CO_2 emissions. The production of synthetic fuels is slowly becoming more cost-effective. The purpose of this article is to demonstrate that fuels will be cheaply available as long as energy is cheaply available.

In hybrid vehicles with electrified powertrains the combustion engine serves as a basic propulsion system. Fully electric vehicles will be a niche product for the next 20 to 25 years because of an inadequate battery storage density of maximal 0.5 kWh/l. Electric vehicles do not have



❸ Historical development of oil production and projection of potential development until 2050 (NGL = Natural Gas Liquid (condensate)) [5] sufficient range for long-distance traffic, especially goods traffic [3].

GLOBAL PROSPECTS UNTIL 2040: ENERGY SOURCES AND FUELS

In order to be able to develop a fuel scenario for the next few decades we first have to look at the economic development forecasts and future demand for primary energy sources at international and national level, ❷. The global economy is growing at different rates, ranging on average from 2 % (OECD countries) to 4.5 % (non-OECD countries and, particularly, BRIC countries) a year until 2040. If the relevant efficiency increases are implemented the energy demand of the OECD countries will level off until 2040, otherwise it will rise by 90 %. During this period the energy requirement, including any efficiency gains, of the non-OECD countries will rise by approximately 60 %, or to over 250 % if savings potentials are not utilised. However, the potential efficiency gains in the non-OECD countries are more than offset by the enormous increase in their energy demand [4].

Oil will continue to dominate the global supply of energy until 2040 because economic growth in the non-OECD countries is expected to reach 70 %. Natural gas is going to be the energy source with the fastest growing demand, which is likely to rise by approximately 60 % between 2010 and 2040. The number of passenger cars is going to double to 1.6 billion vehicles worldwide by 2040. Since passenger cars are steadily becoming more fuel-efficient, the substantial increase in demand for fuel worldwide will be due to goods traffic. Global fuel requirements for passenger cars and light-duty commercial vehicles are going to peak soon and will then subside slightly [4].

FOSSIL FUEL RESERVES

Oil currently accounts for 34 % of primary energy consumption, making it the most important energy source worldwide. It will continue to be a major force behind mobility. Oil production reached its highest levels in 2010 with a total of 3,937 Mt. However, the reserves of this fossil raw material are finite. All indications are that the global production of conventional crude oil will reach its peak (peak oil) in the next 15 to 20 years. This is the point at which, despite all efforts, it will no longer be possible to extract more oil because the production rate from existing deposits is limited by geological conditions and few new deposits are being discovered. This peak won't be very pronounced; it will be more like a gently sloping plateau. According to an updated projection by the German Mineral Resources Agency, ❸, global oil production could increase until 2036 when annual production could reach 4.6 Gt [5]. The International Energy Agency's growth scenario for crude oil states that demand is likely to be 4.8 Gt a year by 2035 [6]. As a result, crude oil will be the first energy source no longer able to meet rising demand [5].

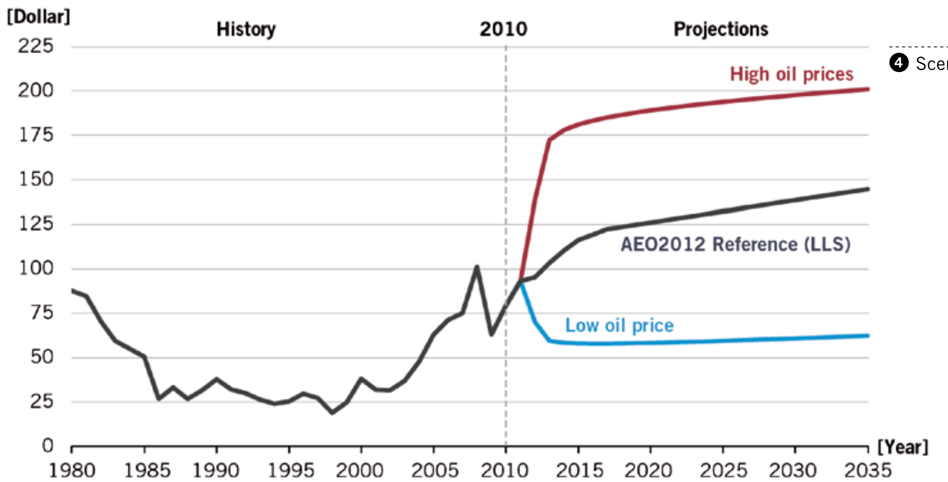
COST PROJECTIONS AND SUPPLIES

The era of fossil fuels is far from over, however, the era of cheap oil is. There are two reasons for this, first demand is expected to rise due to rapidly growing economies and the anticipated population growth and second the rising exploration and processing costs for crude oil of increasingly poor quality. The resulting disparity will lead to much higher prices in the long term. At this time, high oil prices appear to be the most likely scenario, ❹ [7].

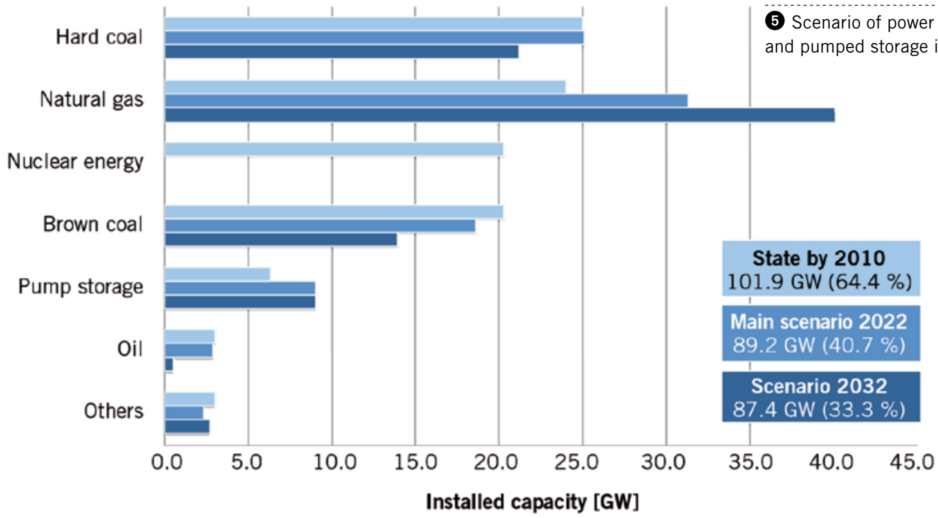
Coal is by far the most widely available fossil fuel reserve [5]. The dilemma we face is that we have to use an energy source that produces the highest CO_2 emissions. CO_2 separation and storage are frequently proposed as a solution to this problem.

EFFECTS OF ENERGY REFORM IN GERMANY

The German government's energy policy, which envisages an accelerated phase-out of nuclear power in Germany, forces a radical change in electricity supplies. The scenario developed by the Federal Network Agency shows what the energy mix might look like between 2022 and 2032 compared to 2010. ❺ shows that black and brown coal accounted for over half of primary energy sources in 2010; the rest is predominantly generated by nuclear power. The construction of new gas-fired and pumped-storage power stations can only make up for half of the shortfall in conventional power generation caused by the nuclear phase-out. The percentage of power generated by coal-fired power stations will remain constant until around 2022 and will not begin to decline (by 16 %) before 2032.



❹ Scenarios of crude oil price development [7]



❺ Scenario of power generation from fossil primary energy sources and pumped storage in Germany [8]

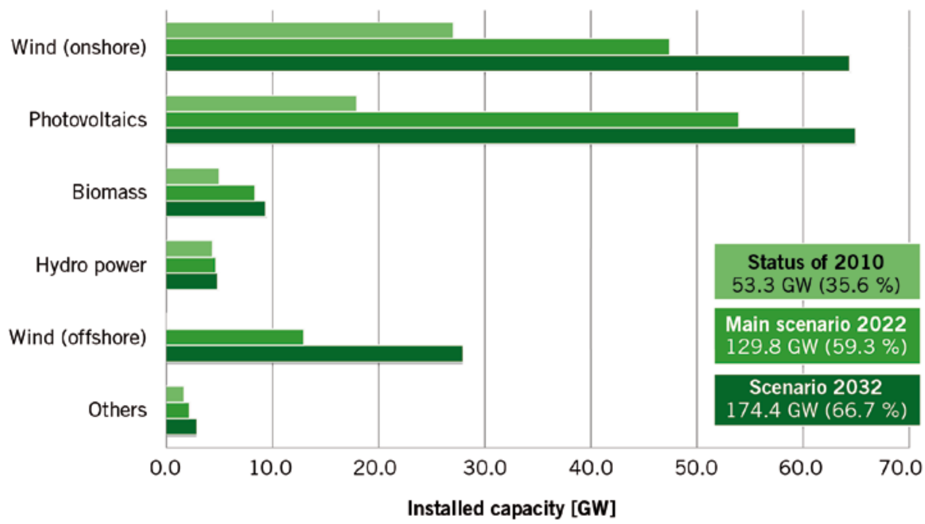
The installed capacity of power generation based on the conversion of non-fossil energy sources, ❻, is to be raised from 56.3 GW in 2010 to 175 GW in 2032 [8]. It should be noted that the capacity that is not continuously available is 94 % for wind turbines and 90 % for photovoltaic systems [9]. This imbalance between the supply of energy from non-fossil sources and the demand for energy necessitates the construction of physical energy storage systems since the moderating effect of "intelligent" electricity networks is insufficient. Even an accelerated expansion of wind power and photovoltaics could only partially replace nuclear energy [10].

COAL-FIRED POWER STATIONS AND CCS TECHNOLOGY

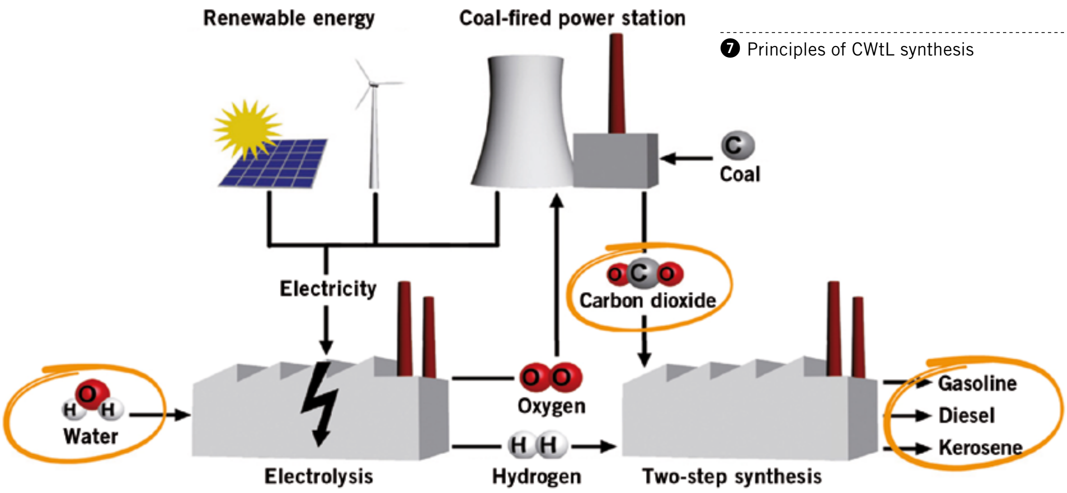
Unlike Germany, the rest of the world is going to see an increase in the amount of electricity that is generated by coal-fired power stations. One way of dramatically reducing the associated CO_2 emissions is by capturing and storing the CO_2 (carbon dioxide capture and sequestration, CCS). The great expansion of efficient coal-fired power station technologies and CCS technologies could significantly improve the prospects of the coal industry. Unless CCS technologies are widely introduced in the 2020s we will have to rely on other low-CO_2 technologies, which would be an extraordinarily difficult task [6]. However, CCS technology has not been widely tested yet and it is still unclear if and how this technology could be applied to the spectrum of energy systems. The German Upper House rightly stopped the German CCS Act in September 2011 despite this being a breach of the relevant EU directive. The separation of CO_2 is going to reduce the efficiency of coal-fired power stations from just below 50 % in the most efficient power stations to approximately 40 %.

FUTURE FUELS

There is still a significant development potential in combustion engines and vehicle technology. Smaller engines, more active catalytic converters and more efficient vehicles could increase overall efficiency by 35 to 40 %. The implementation of these developments relies on the availability of high-quality fuels and lubricants. In the last decade, the oil industry made huge advances in fuel quality, especially through the introduction of sulphur-free and low-aromatic fuels and low-ash engine oils. Unfortunately, this positive development



❻ Scenario of power generation from wind, run-of-river, photovoltaics and biomass in Germany [8]; only a small percentage is continuously available [9]



❼ Principles of CWtL synthesis

is compromised by the mandatory addition of biofuels. The admixture of fatty acid methyl esters (Fame, biodiesel), in particular, leads to a substantial deterioration in fuel quality and has no future [11]. Domestically produced biofuels are on average twice as expensive as oil-based fuels.

An EU study revealed that biodiesel increased CO_2 emissions by 9 to 20 % compared to oil-based diesel when the effects of indirect land use change (ILUC) were taken into consideration. The EU directives on the mandatory addition of biofuels are likely to be changed as a result of these findings [12].

According to forecasts by the Association of the German Petroleum Industry, Germany faces another substantial drop in sales of mineral oil products from 106 Mt in 2010 to 92 Mt by 2025. The sale of gasoline is going to fall to 12 Mt by 2025, a drop of 37 % compared to 2010 as a result of efficiency improvements in the powertrain [13].

SYNTHETIC FUELS

There are several different technologies for the production of synthetic hydrocarbons depending on the type of available process energy. When the primary energy is electricity the best solution would be to generate H_2 by electrolysis. This H_2 could then be used to convert CO_2 directly to CO by a reverse water gas reaction ($CO_2 + H_2 \leftrightarrows CO + H_2O$). The CO can be hydrogenated to form hydrocarbons either directly through various catalytic processes (Fischer-Tropsch) or via methanol (MtG, MtSynfuels).

FUEL PRODUCTION VIA METHANOL AS AN INTERMEDIATE

Between 1985 and 1996 New Zealand successfully produced gasoline from natural gas via methanol as an intermediate in a methanol-to-gasoline (MtG) process. The plant has since closed because oil-based gasoline is much cheaper [14]. Hydrocarbons are synthesised via dehydration of methanol on acidic zeolite catalysts at a temperature of 350 °C and a pressure of 20 bar. The resulting product mix consists of alkanes, aromatic compounds and olefins with fewer than 11 C atoms (C5-9 > 80 %). The amount of MtG products generated worldwide from coal and natural gas was less than 1 Mt a year [15]. By contrast, the prospects for the methanol-to-synfuel process (MtSynfuels) developed by Lurgi are far better because of the mild process conditions associated with multi-stage synthesis and the potential for producing diesel fuels [16].

FISCHER-TROPSCH PROCESS

The energy feedstock for Fischer-Tropsch processes includes coal (CtL), natural gas (GtL) or, to a very limited extent, biomass (BtL). During the Second World War the CtL process was used in Germany to synthesise gasoline. In South Africa a large percentage of fuel is produced by this process. Qatar uses a large number of GtL plants to exploit its vast natural gas fields. GtL production reached about 10 Mt a year in 2010 [15]. Until 2015 the production of GtL hydrocarbons is expected to rise to 30 Mt a year, of which 30 to 60 % will be diesel [17]. At present, value creation in GtL refineries is mostly based on engine base oil and wax.

Recent Fischer-Tropsch reactor developments have focused on micro-structured reactors. The integration of highly active catalysts is seen as a major technical advantage because they absorb the high heat flow density through excellent heat transfer properties. This improves the financial viability of smaller plants that can then be used to exploit smaller natural gas fields [18].

FUELS FROM ELECTRICAL ENERGY AND WATER

“Chemical charging”, which involves recycling the separated CO_2 and converting it to hydrocarbon fuels, is an alternative to CCS technologies. The principle of a carbon dioxide and water-to-liquid (CWtL) process [1] is shown in ❼. The associated chemical processes are summarised in ❽.

The CWtL synthesis of hydrocarbons can be divided into the steps below. The equations refer to the reaction enthalpy $\Delta_R H^0_{298}$ in simple terms as energy. Firstly combustion of coal with oxygen electrolytically generated according to Eq. 2 in a fluidised bed with flue gas circulation and power generation by a steam-power process and gas purification (oxyfuel power station [19]):

EQ. 1	$C + O_2 \rightarrow CO_2$ + **energy** (110 kWh/kmol)

A power generator with an efficiency of 40 % is able to produce 44 kWh of electrical energy/kmol of carbon.

Secondly generation of H_2 and O_2 by electrolysis, [20] and non-fossil electricity:

EQ. 2	$3\ H_2O$ + **electrical energy** (203 kWh/kmol) $\rightarrow 3\ H_2 + 1{,}5\ O_2$

Thirdly catalytic conversion of purified CO_2 with H_2 electrolytically generated according to Eq. 2 on Cu/ZnO catalysts to produce methanol:

EQ. 3	$CO_2 + 3H_2 \leftrightarrows CH_3OH + H_2O$ + **energy** (3,3 kWh/kmol)

And fourthly synthesis of hydrocarbons by catalytic conversion on zeolite catalyst to produce gasoline by a methanol-to-gasoline (MtG) process:

EQ. 4	$CH_3OH \rightarrow (\text{-}CH_2\text{-}) + H_2O$ + **energy** (26 kWh/kmol)

The Fischer-Tropsch synthesis of diesel fuels is another possibility to produce hydrocarbons by hydrogenation of CO_2, in which CO_2 is reduced with H_2 (reverse water gas reaction) according to Eq. 5:

EQ. 5	$CO_2 + H_2 \leftrightarrows CO + H_2O$ + **energy** (11,4 kWh/kmol)

at 800 °C and 20 bar before the synthesis process according to Eq. 6:

EQ. 6	$CO + 2\ H_2 \rightarrow (\text{-}CH_2\text{-}) + H_2O$ + **energy** (42,3 kWh/kmol)

The chemical charging process that forms the basis of both processes is:

EQ. 7	$CO_2 + H_2O$ + **electro-energy** (208 kWh/kmol) $\rightarrow (\text{-}CH_2\text{-}) + 1{,}5\ O_2$

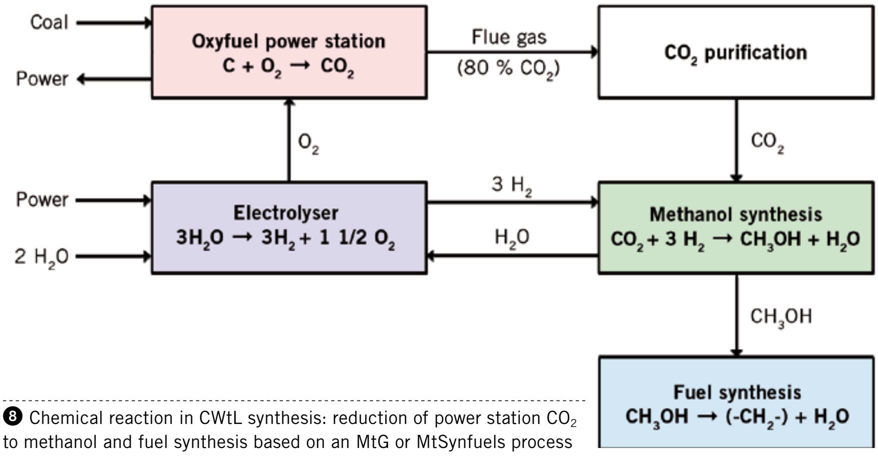
The two processes and their individual reactions, Eq. 1 to Eq. 6, are special forms of carbon capture and conversion (CCC). The oxygen generated as a by-product of electrolytic hydrogen production is used to burn coal. However, oxyfuel power stations currently rely on oxygen that has been produced in an energy-intensive process by an air separation plant, which generally wastes any incidental N_2. The air separation plant alone requires 14.5 % of the generator output of an oxyfuel power station [19].

A CWtL process, in which the power station operates with electrolysis O_2-rich air and CO_2 separation and in which gasoline is produced from CO_2 and electrolysis H_2 by an MtG process, was proposed in 2010. The efficiency of this process was calculated to be 50 % [1]. Gasoline production costs depend mainly on the type of power generation, ❾.

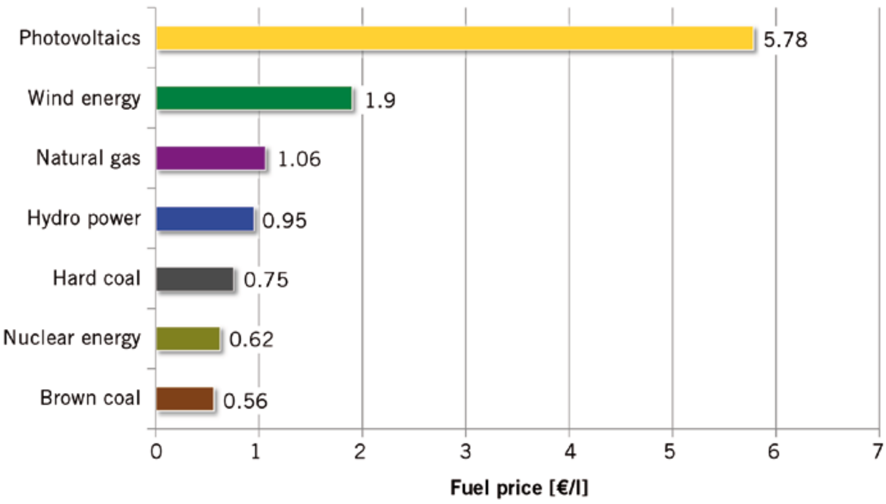
The efficiency of hydrocarbon production from CO_2, water and electrical energy depends on the CO_2 concentration in the feed gas, ❿. The efficiencies relating to the production of Fischer-Tropsch hydrocarbons from solar energy, water and CO_2 were calculated as a function of the CO_2 concentration in the feed gas. For almost pure CO_2, which accumulates in oxyfuel power stations, the efficiency is 66 %. In case of CO_2 scrubbing, as required for the use of flue gas in conventional power stations, efficiency drops to 62 %. If the CO_2 also has to be separated from the air the figure is as low as 56 % [16].

SUMMARY

The chemical energy of the fuel that is burned in a power station to form CO_2 and water can be converted to electrical energy with an efficiency of 35 to 50 %. What is not widely known is that the reverse, the transformation from electri-



❽ Chemical reaction in CWtL synthesis: reduction of power station CO_2 to methanol and fuel synthesis based on an MtG or MtSynfuels process

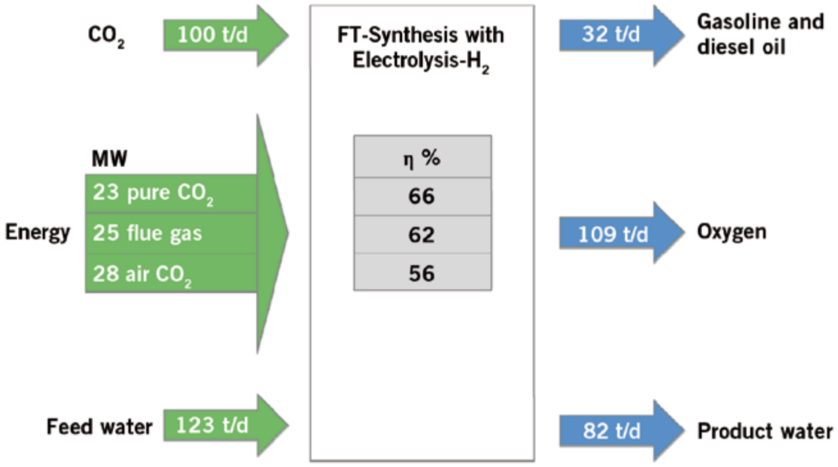


❾ Fuel costs depending on type of power generation [21] cal energy to chemical energy, can be performed with an even higher degree of efficiency (50 to 66 %), for instance, by converting CO_2 and water to fuel. The highest levels of efficiency are achieved with pure CO_2 as the raw material and incidental product of oxyfuel coal-fired power stations. Hydrogen (for CO_2 reduction) and oxygen (for coal combustion/CO_2 generation) are generated by electrolysis. Fuel can be produced by Fischer-Tropsch synthesis and a methanol-to-synfuel process.

Coal-fired power stations will continue to be an important source of power generation worldwide, and be part of the electricity mix in Germany, over the next few decades. As a result, CO_2 recycling must be recognised as the main challenge that needs to be addressed. Vehicles with combustion engines will have a future as long as cheap electricity is available.

REFERENCES

[1] Maus, W.: Saving the mobility- Politics and physics in contradiction? www.emitec.com/41/, 10/2010
[2] Wikipedia: Life cycle of the sun
[3] Schüth, F.; Jacob, E.: The Future of Energy beyond Oil and Gas. 32. International Vienna Motor Symposium 2011, VDI-Fortschritt-Berichte, Line 12, No. 735, Band 1, pp. 174-193
[4] 2012 The Outlook for Energy: A View to 2040. exxonmobil.com/energyoutlook
[5] Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen. DERA Kurzstudie, www.bgr.bund.de/DERA_Rohstoffinformationen, Hannover, November 2011
[6] IEA World Energy Outlook 2011. p. 639, Paris, www.worldenergyoutlook.org
[7] Gruenspecht, H.: Annual Energy Outlook 2012, www.eia.gov
[8] Bundesnetzagentur, Genehmigung des Szenariorahmens für die Netzentwicklungsplanung, December 20, 2011, p. 2
[9] Auswirkungen des KK-Moratoriums auf das Übertragungsnetz und die Versorgungssicherheit. April 4, 2011, www.bundesnetzagentur.de
[10] Schlögl, R.: Die Rolle der Chemie bei der Energiewende. In: Angew. Chem. 123 (2011), pp. 6550-6553
[11] Jacob, E.: Diesel Fuels in Technological Transition to the Post-fossil Age. 33. International Vienna Motor Symposium 2012. VDI Fortschritt-Berichte, Line 12, No. 749, Band 1, pp. 274-293
[12] Thielicke, R.: Trübe Brühe. In: Focus 8/2012, p. 72
[13] MWV-Prognose 2025 für die Bundesrepublik Deutschland. www.mwv.de, Berlin, June 2011
[14] Hartmann, M.: Production of Synthetic Fuels from Natural Gas or Biomass – Status of Commercial Realization. In: Erdöl, Erdgas, Kohle 123 (2007), pp. 363-369
[15] Schaub, G.; Edzang, R.: Erzeugung synthetischer Kraftstoffe aus Erdgas und Biomasse-Stand und Perspektiven. In: Chemie Ingenieur Technik 83 (2011), pp. 1912-1924
[16] www.volkswagen.com/..../mtsynfuels_proc
[17] Jess, A.; Kaiser, P.; Kern, C.; Unde, R.B.; v. Olshausen, C.: Considerations concerning the Energy Demand and Energy Mix for Global Welfare and Stable Ecosystems. In: Chemie Ingenieur Technik 83 (2011), pp. 1777-1791
[18] McDaniel, J.: The Microchannel Advantage. CWC World XTL Summit, www.oxfordcatalysts.com/press/ppt/, 2011
[19] Altmann, H.; Jentsch, N.: Das Oxyfuel-Verfahren in Braunkohlekraftwerken. Kooperationsforum Innovation konventionelle Kraftwerke, Vattenfall, Nuremberg 2005
[20] Bräuninger, S.; Schindler, G.; Schwab, E.; Weck, A.: What will it take to make hydrogen an energy carrier for transportation? GDCh-Wissenschaftsforum Bremen, September 2011
[21] Calculation according to **[1]**. Costs of electricity from: Wikipedia „Kraftwerke“, March 2, 2012



⑩ Mass and energy balance of Fischer-Tropsch synthesis of fuels from CO_2 and electrolysis H_2; efficiencies and energy input depend on the degree of CO_2 enrichment [17]

STABILITY OF FUELS CONTAINING CURRENT AND FUTURE BIOFUELS

Oel-Waerme-Institut GmbH, an affiliated research institute of RWTH Aachen University, has developed a hardware-in-the-loop test facility to investigate the interaction between biofuels and the components that come into contact with them. An analysis of the measurements shows that significant technical modifications will need to be made to independent vehicle heaters and in-tank pumps in order to enable a high proportion of biofuel to be used.

AUTHORS

DR.-ING. OLIVER VAN RHEINBERG
is Head of Energy Sources Department and authorised Representative of the Oel-Waerme-Institut GmbH Herzogenrath (Germany).

DIPL.-ING. HAJO HOFFMANN
is Project Engineer and Vice Leader of the Fuels Workgroup of the Oel-Waerme-Institut GmbH in Herzogenrath (Germany).

DIPL.-ING. CHRISTIAN JASCHINSKI
is Project Engineer within the Fuels Workgroup of the Oel-Waerme-Institut GmbH in Herzogenrath (Germany).

M.SC. WINFRIED KOCH
is Scholarship Holder affiliated to the Fuels Workgroup at Oel-Waerme-Institut GmbH in Herzogenrath (Germany).

DEVELOPMENT OF LIQUID FUELS

The main development in the field of liquid fuels in the past decades was the continuing decrease of the organic sulfur content of the fuel [1]. The sulfur content of diesel fuels and gasoline decreased to less than 10 mg/kg in Europe and 15 mg/kg in North America due to technical developments such as catalytic exhaust gas treatment and due to emission and immission regulations. The hydrogenating desulfurisation process also catalyses additional reactions, which especially have an impact on the stability of the products. Amongst others, this is the conversion of naturally occurring primary and secondary antioxidants. Important primary antioxidants are phenols, important secondary antioxidants are sulfur and nitrogen compounds. Depending on the crude oil and the extent of hydrogenation, these are removed from the fuel down to the low ppm range [2]. Despite these side reactions, the fossil fuels show a very good stability.

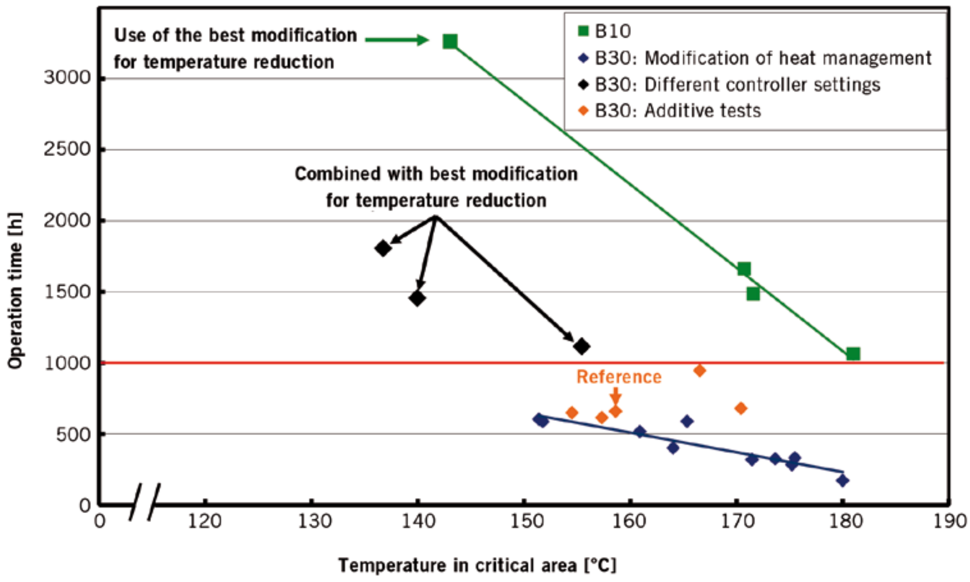
Due to the rising number of diesel engines in transportation, the quantity of sales shifted from gasoline towards diesel fuels in Europe in the past years. In order to compensate the resulting surplus of gasoline respectively the shortage of diesel fuel, as much of the light end is added to the diesel fuel as possible without passing the threshold of 55 °C flash point. Thus, the use of gasoline components in diesel fuels postulated by the Dena survey already is maxed out within the feasibility [1].

Prognoses regarding the future production and use of fossil fuels in Germany suggest sales in 2025 of 31.7 million t/a diesel (-1 % compared to 2011), 14.8 million t/a gasoline (-35 %) and 13.6 million t/a light heating oil (-31 %) [1, 3, 4]. Therefore, the main use of fossil fuels in the future will remain within the traffic sector with a share of 58 to 84 %, depending on the prognosis referred to. Due to an increased efficiency and diversification of the used energy carriers, a slight decrease in the use of fossil fuels for passenger transportation is expected. Due to the requirement of a high energy density, the transport of goods will remain the main use of fossil fuels, the demand in this sector therefore is expected to stagnate rather than decline [3].

SUBSTITUTION BY BIOGENOUS PRODUCTS

Considering the expected development of the future use of fossil fuels, especially the substitution of middle distillates should be pursued by technical development and political guidance. The integration of biofuels may bear great potential in short-term and medium-term with low investment and long-term impact.

Biodiesel is used as a substitute for diesel fuel and domestic heating oil. In Germany, fatty acid methyl ester (Fame) is available as biodiesel. In transportation, it is used mandatorily to comply with the so-called Biokraftstoffquotengesetz, a German law which sets a mandatory use of biofuels in transportation. In domestic heating, the local Erneuerbare-Energien-Wärmegesetze (EEWärmeG, “renewable energies in heating laws”) is the basis for the use of Fame. The surplus of Fame in Europe is significant. The production capacity of 21 million t is much larger than the actual production of 9 million t in 2011 [5]. Fame contributed to the fulfilment of demand in fuels in transportation in 2011 with 7.2 % respectively 2.4 million t in Germany [5]. This is a very low share compared to the production capacity of 8 million t. The currently commercially available biofuels etha-



❶ Influence of the temperature of the critical area on deposit formation and durability

nol and Fame substitute 10 % of the gasoline respectively 7 % of the diesel fuel. This is also the blending limit for the use in the existing vehicles [1]. In domestic heating the current limit for the installed units is the blending of domestic heating oil with 10 % by vol. Fame. The necessary storage stabilities as well as the lack of a release by the manufacturers of the already installed units prohibits the use of up to 20 % by vol. Fame, which would still be compliant to the alternative heating oil standard DIN SPEC 51603-6.

Thus, new biofuels other than the ones of the so-called first generation, e.g. ethanol and Fame, are necessary in order to fulfil the legislative mandatory substitution of fuels in transportation as well as in domestic heating. Particularly, the mandatory reduction of GHG by the use of biofuels by 35 % in 2013, 50 % in 2017 and 60 % in 2018 makes the development of new processes as well as an increase in the efficiency of the existing processes necessary. The next step is expected to be the use of hydrogenated vegetable oil (HVO). HVO is currently produced with a capacity of approximately 2 million t/a [5]. The hydrogenation leads to an aliphatic product with physical and chemical properties very similar to those of mineral based fuels. Initial testing shows no challenges in the use of HVO even at high blending ratios [6, 7].

The development of certification criteria is pursued on a national and on an international basis to ensure a sustainable cultivation and use of the biomass. Several certification standards approved by the EU exist for the production of Fame, for example the so-called International Sustainability & Carbon Certification (ISCC). The hydrogenation of vegetable oils is considered by EL/2009/28/EG to be more efficient regarding the GHG reduction than the production of Fame. The sustainability of the HVO production in the newly built plant in Rotterdam is already ISCC certified [8], proving the ecological and sustainable production of HVO to be feasible. The GHG reduction can be improved further, if existing refineries are used for the production process and if the necessary hydrogen is derived from regenerative sources, for example from electrolysis using wind or solar energy. It is recommended to further merge the production of biofuels with the production of fossil fuels, which could be achieved by co processing of biomass in the refineries [1]. This highlights the co-hydrogenation of vegetable oil as an improvement of the economic use of biomass as well as a method to decrease CO_2 emissions. The crediting of the use of biomass, regardless the process utilised is therefore aspired.

Besides the use of HVO, the development of Biomass-to-Liquid (BtL) fuels is pursued using different approaches. The competition to the food production can be resolved by the use of whole plants and waste materials while providing fuels with a higher GHG reduction. BtL fuels are supposed to share the same beneficial properties as Gas-to-Liquid (GtL) fuels. The demonstration of the production on an industrial scale, however, is pending. Therefore, an estimation of the time frame until these fuels become commercially available is currently difficult.

REQUIREMENTS TO LIQUID FUELS

Several different investigations are conducted to advance the blending levels with biofuels as well as the introduction of new fuels. Exceeding the compliance of new fuels with the demands to the physical and chemical properties set by DIN EN 590 and DIN SPEC 51603-6, the compatibility of the new fuels with the technical components and the storage stability has to be ensured. A stable fuel is characterised by not changing its properties during the use. Oxidation stability is defined as the stability against the reaction with oxygen, forming soluble or insoluble oxidation products. Thermal stability is defined as the stability against the change of properties under increased thermal stress of the fuel, for example in the injector. Lastly, storage stability is defined as the stability against the change of properties if the fuel during storage caused, for example, by light, heat and catalytic active metals. The technological advances and the increasing energy density within the technical systems constantly increase the demands on the thermo-oxidative stability of the fuels.

TESTING METHOD HARDWARE-IN-THE-LOOP

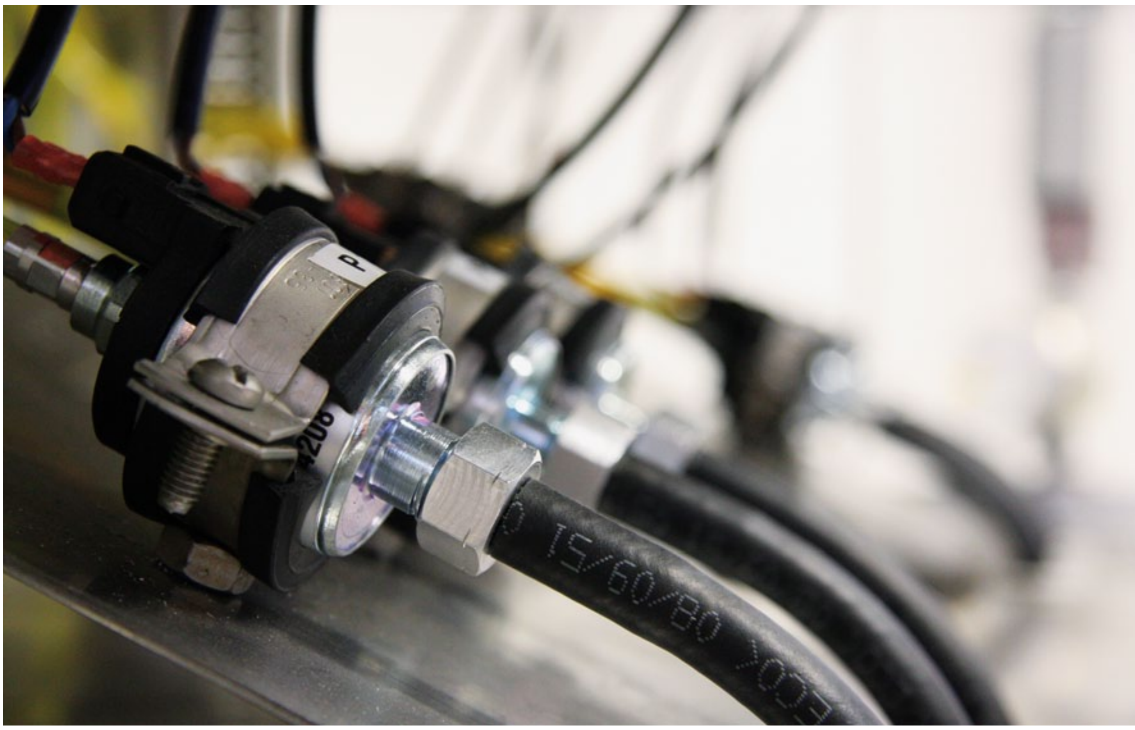
Within the joint research project called GoBio – Gezielte Optimierung kraftstoffführender Komponenten für biogene Kraftstoffe in mobilen Applikationen (targeted optimisation of fuel bearing components for the use of biogenous fuels in mobile applications), several hardware-in-the-loop tests for different components regarding their compatibility with biogenous fuels were developed, Cover Figure. In-tank fuel feed pumps as well as independent vehicle heaters were tested using a test method which increases the impact on the components, leading to an accelerated production of results regarding the lifetime expectancy. Two different approaches were applied to enable the use of biofuels with the tested components. The first approach was to adjust the fuel properties to minimise their potentially existing negative impacts to a tolerable level by adding suitable additives. The second approach aimed at the enhancement of the components. Fundamental knowledge was gained and substantial enhancements achieved by the systematic development of the components. Tested fuels were summer- and winter diesel, two different Fame, hydrogenated vegetable oil and butanol. These fuels were tested in different blends with 5, 10, 30 and 100 % by vol. bio component.

INDEPENDENT VEHICLE HEATERS

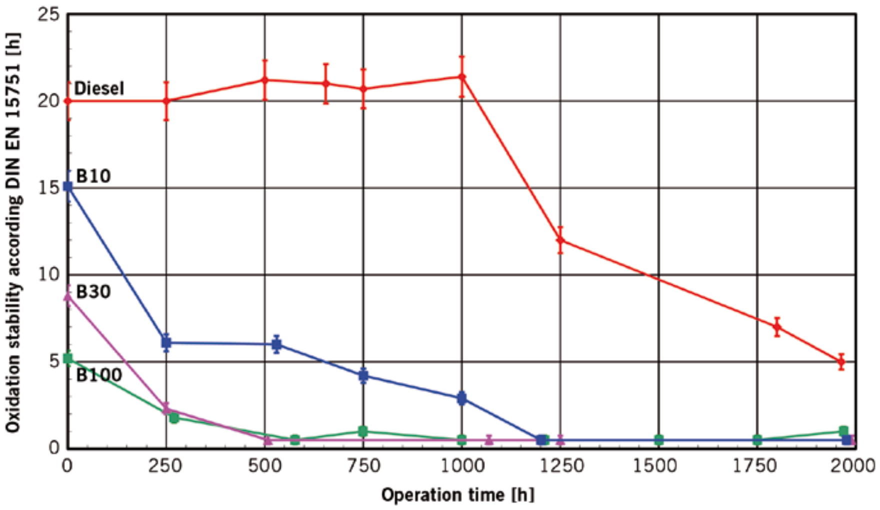
The independent vehicle heaters are not cleared for the use with more than 10 % by vol. Fame by the manufacturer. If operated with high Fame contents, the heaters failed due to deposit formation in critical areas. This deposit formation does not occur if mineral diesel is used and is caused by an increased polymerisation of Fame in the temperature range between 160 and 300 °C. The design life could be safely guaranteed for B10 by adjustments to the thermal management of the heaters. Using B30, the durability was improved from 300 h without adaptations to a maximum of 1850 h by a combination of adjustments to the thermal management and changes to the heater control, ❶. For the fuel supply of the independent vehicle heaters, piston pumps are used, ❷. The piston pumps were analysed in another hardware-in-the-loop test. During these tests no failures at all occurred within the design life. However, the use of fuels containing significantly more than 10 % Fame for the operation of these commercially available vehicle heaters is not recommended. A significant difference between the different diesel fuels and Fame regarding their behaviour during operation was not observed, although differences in the analytics were present. The use of fuels not prone to polymerisation, such as 10 % by vol. butanol and 30 % by vol. HVO did not lead to the failures observed when using Fame. Thus, the vehicle heaters can be operated with these fuels without any modifications. However, even if the fuel contains only 1 % by vol. butanol, its flashpoint drops below the flash point of 55 °C demanded by DIN EN 590. The marketability of blends containing butanol therefore is questionable.

IN-TANK PUMPS

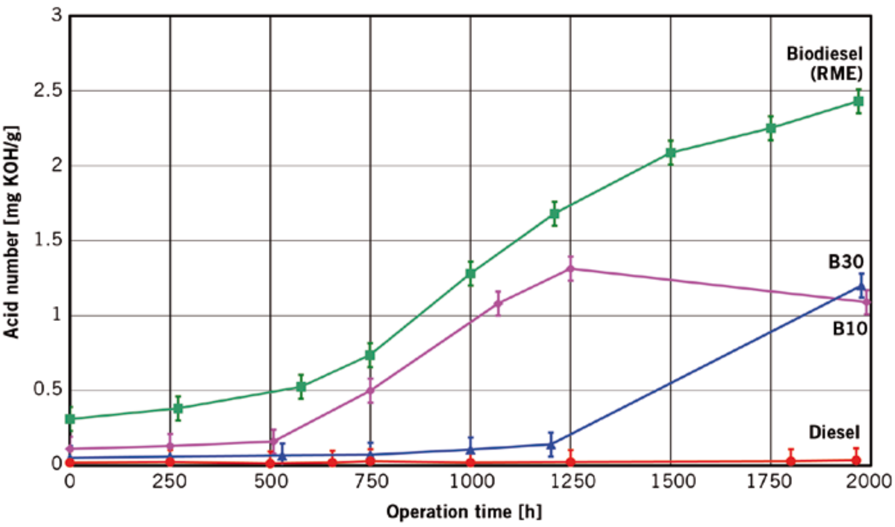
The use of Fame-blended fuels showed a significant influence on the durability of the in-tank pumps as well. Fuels with low Fame levels have no or at least insignificant influences on the pump durability. Fuels containing 30 % by vol. Fame, however, had a strong negative effect on the durability of the pumps, which in this case dropped below the design life. Furthermore, the wear varied significantly, making lifetime expectancy cal-



❷ Piston pumps of the independent vehicle heaters, analysed in a hardware-in-the-loop test



❸ Decrease of the oxidation stability in the hardware-in-the-loop test rig

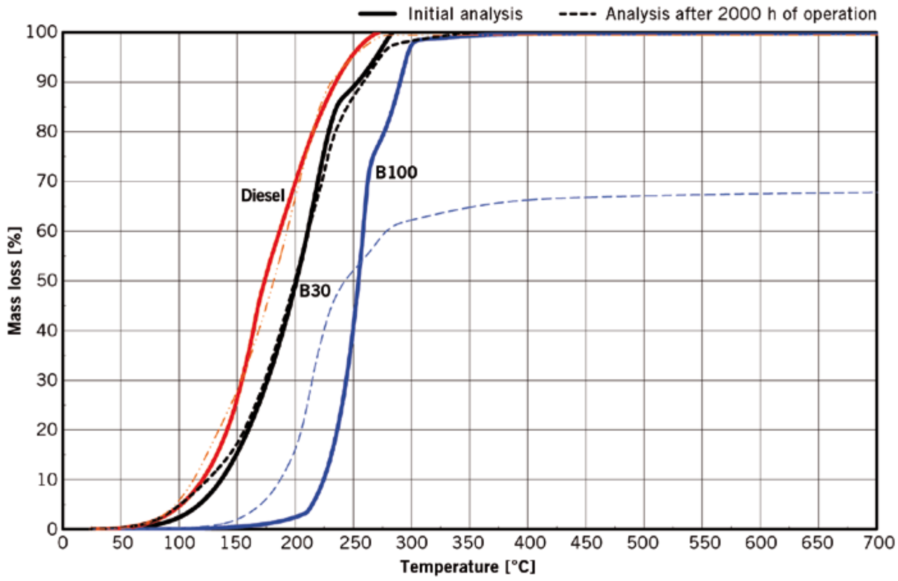


❹ Influence of the Fame concentration on the degradation in the hardware-in-the-loop test rig

culations very difficult. Pure Fame (B100), however, showed almost no influence on pump operation and lead to a sufficient durability. Corrosion due to unsuitable materials in the pumps was not observed.

The fuels were operated for 2000 h in the hardware-in-the-loop tests, which would result in an extreme thermo-oxidative degradation of the fuel and an accentuated interaction between fuel and materials. The extreme degradation could be proven by several parameters of the accompanying fuel analysis. Examples are the decreasing oxidation stability, ❸, and the increasing acid number, ❹. The ageing mainly led to the formation of polymer products which contained oxygen. As these products are polar, they sedimented quickly and became visible within the pumps as highly viscous mass, ❺. Pure diesel showed no increase of the analysed parameters, while pure biodiesel, on the other hand, showed an extreme increase. However, sedimentation of the deposits, as observed when using blends, did not occur when using pure biodiesel. The oxidation products remained solved in the biodiesel, which was proven via thermo gravimetric analysis (TGA), ❻. While the distillation curve of pure diesel and B30 hardly changes, the biodiesel obviously contains components with boiling points up to 700 °C. These components continuously cleaned the material surface. Thus, at the end of the testing the pumps were optically not distinguishable from new ones.

❺ Deposit formation of fuels containing Fame



❻ Thermo gravimetric analysis of fuels degraded in the hardware-in-the-loop test rig

The abrasion of the electrical contacts between the carbon pencils and the collector is the major damage pattern. Due to the combination of the blends' fuel properties and the continuous electrical supply, voltage peaks occurred, which damaged the material. A technical solution was an intermittent power supply, mitigating the voltage peaks. By this, the drop in durability could be diminished far enough to enable the pumps for the use of B10 fuels.

The basic findings are that the use of fuels containing significantly more than 10 % by vol. Fame in vehicles and fuel pumps not cleared for the use of fuels with more than 10 % by vol. Fame is not feasible without significant technical modifications.

ENSURING THE STABILITY

Due to differences in the application technique, the thermo-oxidative stress is much lower in domestic heating. Thus, the focus in this field rather lies on the storage- and the oxidation stability, as storage of the fuels for several years must be possible without any fuel quality issues. The results for fuels in the heating sector are also valid for fuels in transportation, as their properties are very similar.

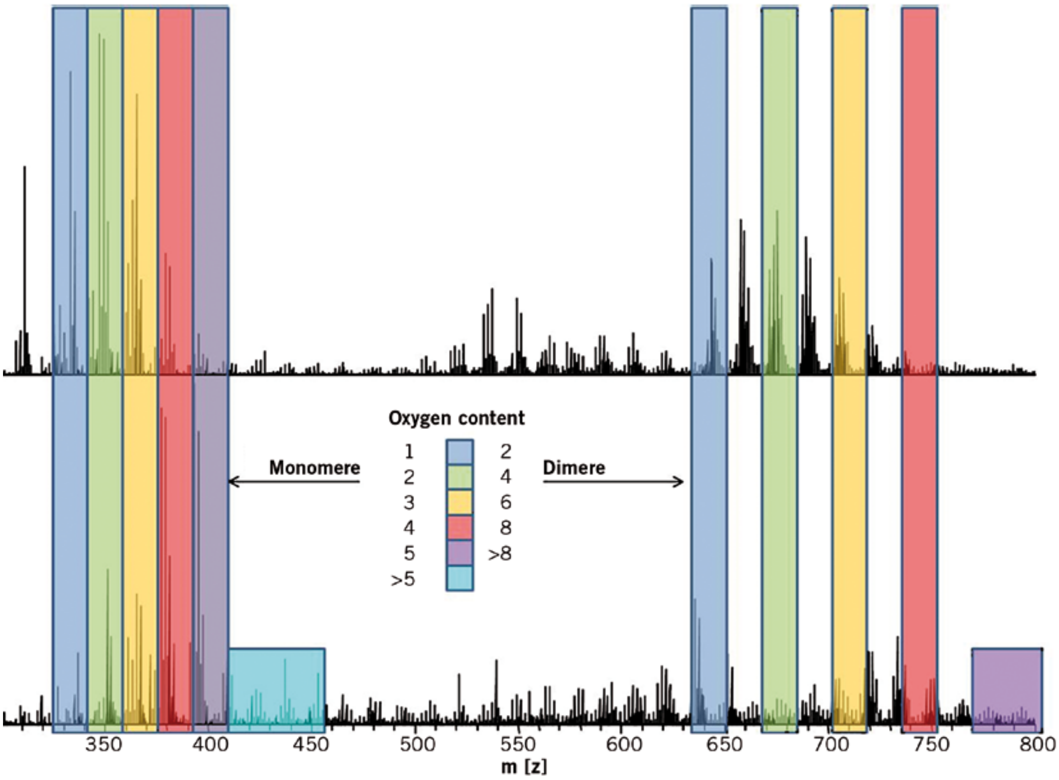
Fuels are tested by the storage of fuel samples in heating cabinets and the use in hardware-in-the-loop test rigs. Additionally, there is an ongoing development of new analytic lab test methods with the aim to enable a distinct prediction of fuel stability. For example, a test method based on the PetroOxy test for the determination of the oxidation stability under defined thermo-oxidative stress was developed. The test consists of a sealed pressure chamber, in which the pressure loss is measured and interpreted as the assimilation of oxygen, which can be interpreted into a measure for the oxidation stability of the fuel. Furthermore, the oxidation stability of fuels in the presence of metals containing copper can be determined with this testing method. This is important, as the autoxidation reactions of hydrocarbons are catalytically accelerated by metals containing copper on the one hand, while they are used in domestic heating in various applications on the other hand. Another advantage of this testing method in comparison to the ones suggested in the fuel standard is the larger amount of fuel for testing, which allows additional chemical and physical analysis of the fuel samples. The detected products of the reaction can be used to determine the possible reaction mechanisms of the thermo-oxidative degradation. The understanding of these reactions enables the identification of chemical compounds contributing to the ageing processes.

After validation of the influences of temperature, pressure and Fame content, the effectiveness of different antioxidants in the fuels was investigated. It was concluded, that the composition of the mineral fuel, the composition of fatty acids and the content of natural antioxidants have great influence on the effectiveness of the tested antioxidants. ❼ shows ESI-Orbitrab-MS measurements of differently aged fuel blends [9]. Monomers, dimers, and most likely also trimers and their total formulas could be identified. Up to eight oxygen atoms were detected. While the oxidation advances, the detected signal groups are shifting to higher masses. The further determination of the structure of the oxidation products is subject of current investigations.

USE OF ANTIOXIDANTS

The validation of antioxidants proved especially phenolic, aminic and selected aliphatic polyamines to be very effective, ❽. Furthermore, a combinatorial examination showed that synergistic effects may occur, especially between sterically hindered phenols and aromatic polyamines.

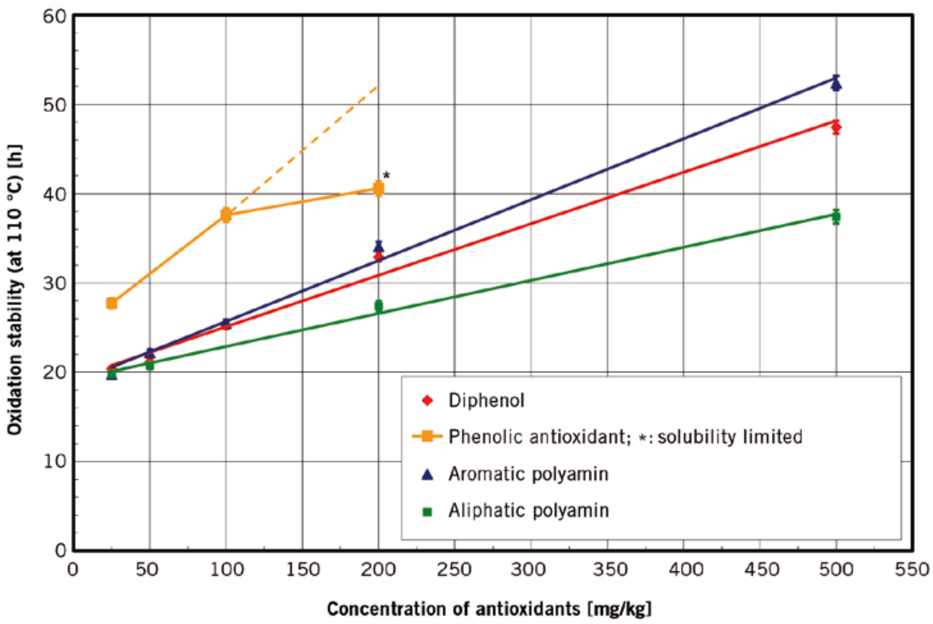
The effectiveness of antioxidants in fuels with high Fame content generally decreases significantly in the presence of copper. Some of the antioxidants showed complexing properties, the oxidation stability therefore did not decrease significantly in the presence of copper. This means that the oxidation products of the antioxidants can react as metal deactivators by forming stable metal complexes with the solved metal ions. These complexes are not able to accelerate the autoxidation reactions catalytically anymore.



❼ ESI-Orbitrab-MS measurements of oxidation products during the degradation of fuels containing Fame [9]

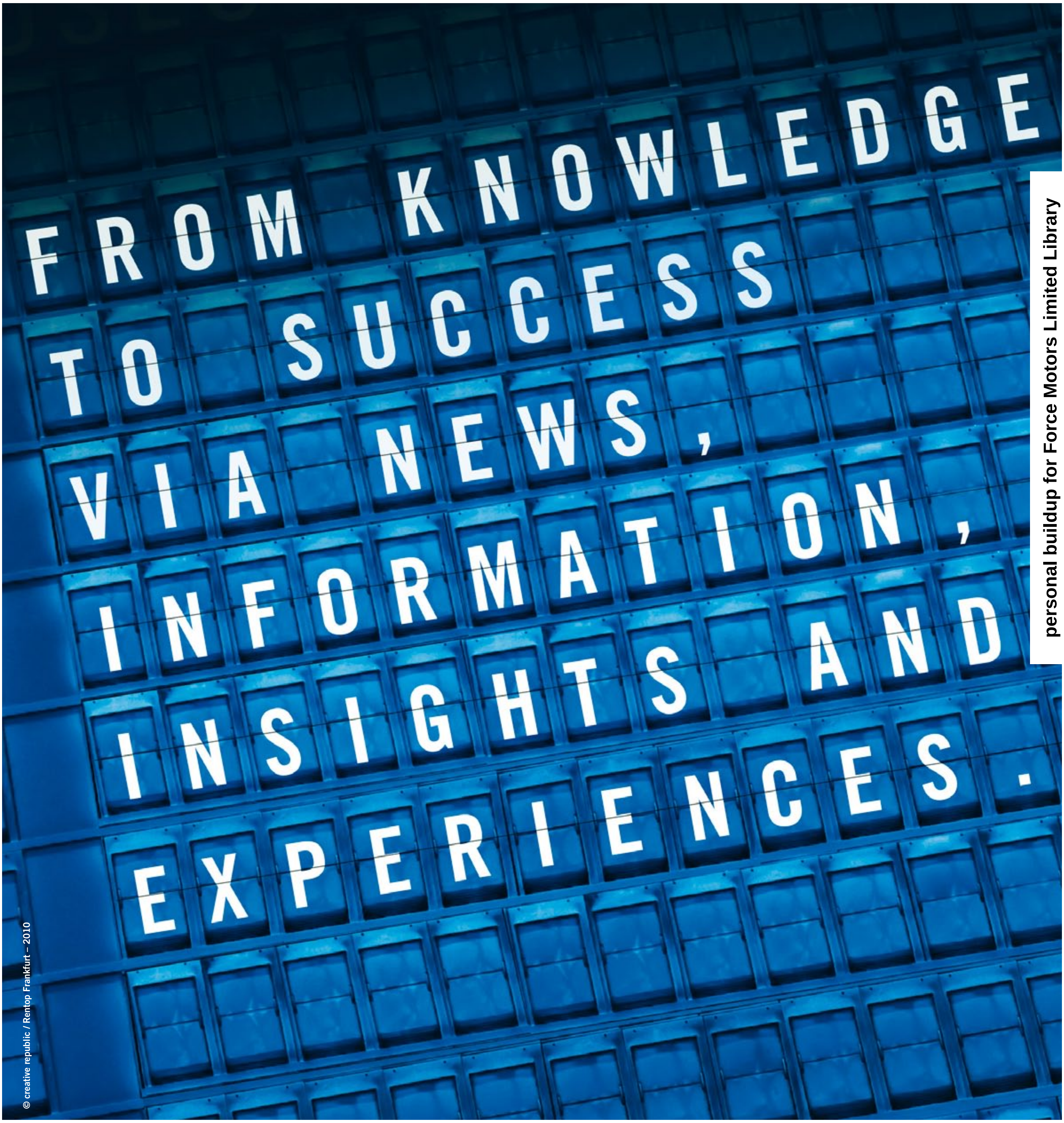
SUMMARY AND CONCLUSION

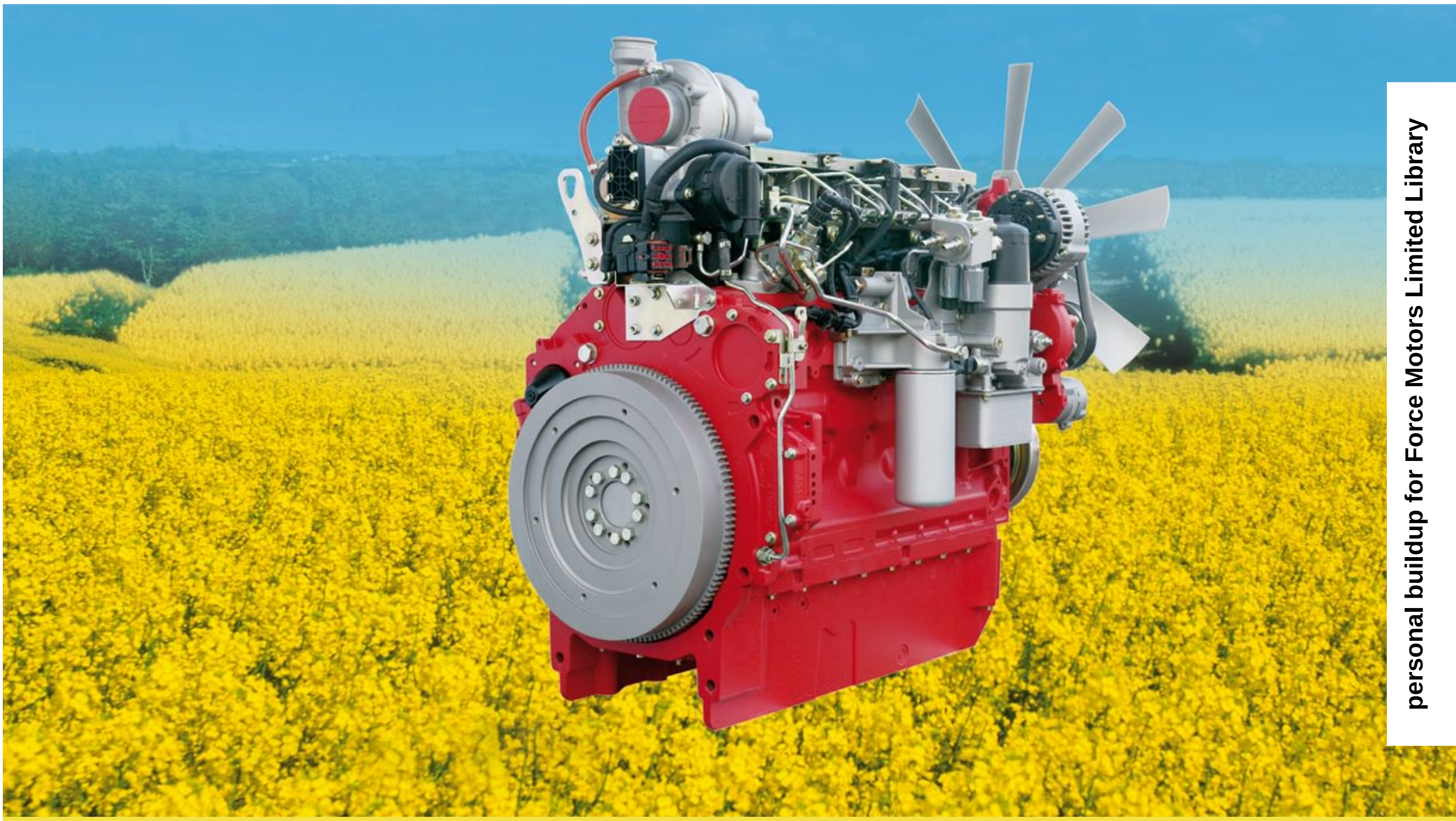
It may be concluded, that liquid fuels will dominate transportation in the future, although the development of engines powered by natural gas and electricity is promoted and their share therefore will steadily increase. Due to legal requirements, the blending of mineral fuels with bio fuels will further increase, which will lead to a diversification of the fuels used. Stability will be an important fuel parameter to ensure failure-free operation. The targeted use of additives therefore will be an important measurement to adjust the fuel properties to the components in which the fuel is used in.



❽ Influence of different antioxidants on the oxidation stability

REFERENCES
[1] Haendschke, S.; Schuster, M.; Rumpke, C.: Unbeliebt, aber unentbehrlich. Bedarf und Produktion von Mineralöl im künftigen Energiemix. Deutsche Energie-Agentur GmbH, 2011
[2] Kolbe, N.; van Rheinberg, O.; Andersson, J. T.: Influence of desulfurization methods on the phenol content and pattern in gasoil and diesel fuel. In: Energy & Fuels 23 (2009), No. 6, pp. 3024-3031
[3] Shell-Lkw-Studie, 2010
[4] MWV-Prognose 2025, 2011
[5] Biodiesel/min. Diesel. In: UFOP-Marktinformation Ölsaaten und Biokraftstoffe, Issue March 2012, p. 3
[6] Mikkonen, S.: Second generation renewable diesel offers advantages. In: Hydrocarbon processing 87,2 (2008), pp. 63-66
[7] Krahl, J.: Erfahrungen mit Biokraftstoffen unterschiedlicher Generation. Uniti-Mineralöltechnologie-Forum 2011
[8] UFOP-Marktinformation: Neue HVO-Produktionsanlage in Rotterdam in Betrieb genommen. Issue January, p. 4, 2012
[9] Hildebrandt, S.; Luftmann, H.; Andersson, J.T.: Products from the Oxidation of Biodiesel Blends. Conference Anakon, Switzerland, 2011


FROM KNOWLEDGE
TO SUCCESS
VIA NEWS,
INFORMATION,
INSIGHTS AND
EXPERIENCES.



ELEMENT POLLUTION OF EXHAUST AFTERTREATMENT SYSTEMS BY USING BIODIESEL

Biodiesel is a particularly attractive fuel for agricultural machinery. However, the introduction of new emission standards has made the use of exhaust gas treatment systems in agricultural vehicles essential. The combination of biodiesel and exhaust gas treatment causes problems, because the biodiesel contains traces of inorganic elements. These turn into ash during the combustion process in the engine, which can result in permanent damage to the components of the exhaust gas treatment system. Deutz and ASG have investigated the impact of current grades of biodiesel on the systems in real-life operation.

AUTHORS

DR.-ING. HANS-WALTER KNUTH
is former Team Leader of Exhaust and Fuels at the Deutz AG in Cologne (Germany).

DR. RER. NAT. HENDRIK STEIN
is Head of Process Development and Deputy Head of the Laboratory at ASG Analytik-Service Gesellschaft mbH in Neusäß (Germany).

DR. RER. NAT. THOMAS WILHARM
is Director of ASG Analytik-Service Gesellschaft mbH in Neusäß (Germany).

DIPL.-ING. MARKUS WINKLER
is responsible for the Fuel Analysis and Fuel Approvals at the Deutz AG in Cologne (Germany).

MOTIVATION

The substitution of fuels based on mineral oils with biofuels is a method to achieve political goals, considerably reduce CO_2 emissions and save fossil fuels. The EU Commission is pursuing a specific goal in the transport sector, namely that at least 10 % of the conventional fuels used in Europe should be replaced by fuels from renewable sources by the year 2020. This plan is entitled Renewable Energy Action Plan. It is supported by the European Community Law through the Fuel Quality Directive (2003/30/EC) and the Renewable Energy Directive (2009/28/EC). These directives are part of the European climate and energy package that the European Council decided upon in December 2008. The EU member states have recognised that this goal can primarily only be reached with biofuels; as such, they have submitted their national action plans to the Commission accordingly [1].

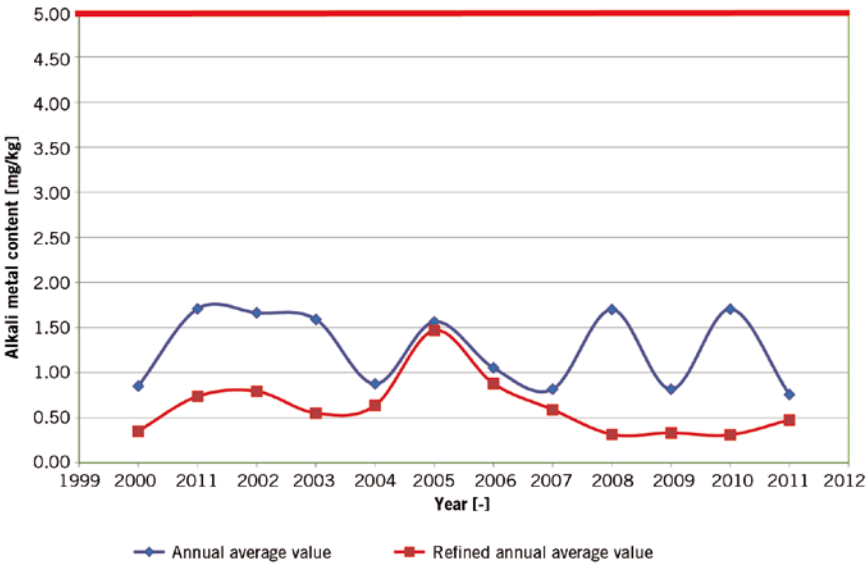
From the point of view of the engine manufacturer Deutz, biodiesel possesses certain fuel characteristics that are associated with negative effects in both the engine's injection system and lubricant system. If certain precautionary measures are observed, engines can still be reliably operated with pure biodiesel. For example, Deutz has approved various engine series for use with biodiesel [2]. Especially in the area of agricultural engineering, biodiesel approvals could be attractive due to the tax advantages associated with the fuel.

The ever-tightening exhaust gas limits for heavy duty diesel engines can only comply with these requirements if exhaust aftertreatment measures are used (e.g. diesel particle filters and/or selective catalytic reduction (SCR)). Using biodiesel in combination with these aftertreatment technologies is afflicted by additional problems, as biodiesel contains traces of inorganic elements such as sodium, potassium, calcium and magnesium. When combusted in the engine, inorganic elements generate ashes (e.g. oxides) which are partially transferred into the aftertreatment components, thereby inhibiting their efficiency on a long-term basis.

The limits for inorganic elements specified in the European Norm for Biodiesel DIN EN 14214 [3] are as follows: maximal 5 mg/kg of Na+K, maximal

5 mg/kg of Ca+Mg. If these limits really do reflect the actual biodiesel quality that can be seen in the field today, they are at a level that would cause irreversible damage to the aftertreatment components at their current level of technological development.

As part of a study supported by the Union zur Förderung der Oel- und Proteinpflanzen e.V. (UFOP) [4], analysis results of market-relevant biodiesel specimens from the years 2000 to 2011 were evaluated. This was done to provide developers of engines and exhaust aftertreatment systems with realistic data with which they could estimate the potential carriers of ash-forming substances and catalyst contaminants. This data was based on the databases of the Arbeitsgemeinschaft Qualitätsmanagement Biodiesel e.V. (AGQM) and Analytik-Service GmbH (ASG).



❶ Annual average values and refined annual average values for the total concentration of alkali metals in biodiesel

STATUS OF CURRENT ENGINE AND AFTERTREATMENT TECHNOLOGY

The exhaust legislation has been drastically tightened up in Europe throughout the last 20 years. This has caused the limits for nitrous oxide (NO_x) to be reduced by 97 % and the limit for particle mass has been reduced by approximately 98.5 %. The introduction of the exhaust class Euro IV has led to SCR technology coming out on top as the leading exhaust aftertreatment technology for heavy commercial vehicles. A limit for the number of particles is to be introduced from Euro VI onwards; adhering to this will only be possible by means of a combination of the SCR system and the particle filter.

Emission stage IIIA has been in force since January 2006 and working mobile machines have been able to comply with it solely by measures that affect the inside of the engine. These include charge air cooling, exhaust gas return and increasing the injection pressure. However, since 2011, the introduction of exhaust class IIIB has made the use of exhaust aftertreatment inevitable. To this end, Deutz has decided on the following technological courses:

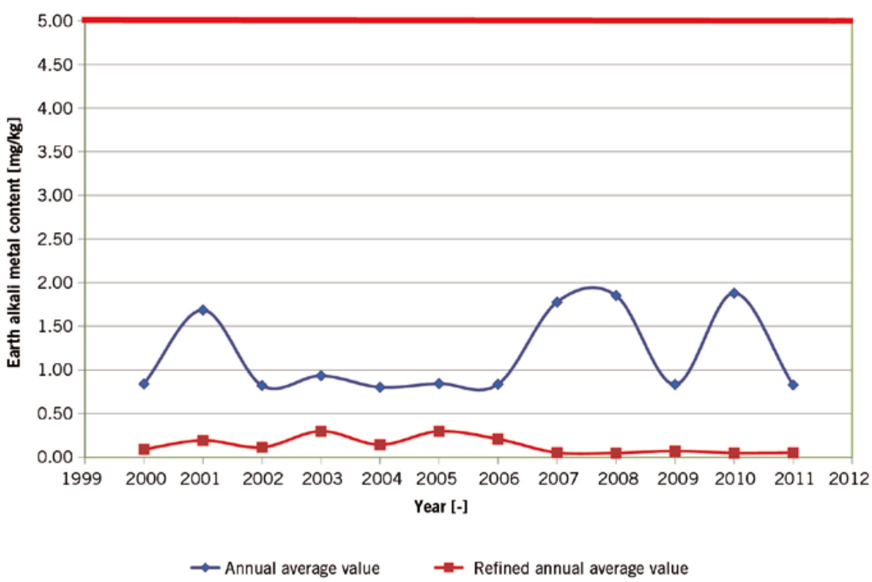
: particle filter in combination with exhaust gas return for construction equipment and other industrial purposes
: SCR (vanadium-tungsten titanium dioxide VWT) without exhaust gas return for agricultural purposes.

SCR technology was selected for agricultural purposes as a particularly low level of fuel consumption is required for this market. As nitrous oxide can be effectively reduced through aftertreatment using SCR technology, the engine can be set up for optimal consumption by selecting an earlier fuel injection point.

BIODIESEL SURVEY

In the last 11 years, AGQM has gathered more than 8000 analytical data containing phosphorous and metallic content from unannounced inspections of biodiesel manufacturers. The method of choice for determining element contents is the ICP OES method (inductively coupled plasma optical emission spectrometry). Alkali and alkaline earth metals are measured with the testing method DIN EN 14538 [5] and the phosphorous content is measured with the DIN EN 14107 [6] method.

In the first stage, the annual average value was calculated; this meant that all



❷ Annual average values and refined annual average values for the total concentration of alkaline earth metals in biodiesel

BIODIESEL FIELD TEST 2008/2009 (UFOP PROJECT 540/80)				
ENGINE	PERFORMANCE / TORQUE	DISPLACEMENT	EXHAUST CLASS	OIL QUALITY
TDC2013 L04 4V	158 kW bei 2300 rpm / MDmax: 800 Nm	4.8 l	Euro IV/V with VWT-SCR	ACEA E7 DQC III-10 Element contents for contamination calculation: Ca: 3.350 mg/kg Mg: 10 mg/kg P: 1.300 mg/kg Zn: 1.400 mg/kg
TDC2013 L06 4V	235 kW bei 2300 rpm / MDmax: 1200 Nm	7.2 l		
BIODIESEL FIELD TEST 2010/2011 (UFOP PROJECT 540/103)				
ENGINE	**PERFORMANCE / TORQUE**	**DISPLACEMENT**	**EXHAUST CLASS**	
TDC 7.8 L6	238 kW at 2200 rpm / MDmax: 1500 Nm, CR: 2000 bar	7.8 l	Class COM IIIB with VWT-SCR	
TDC 6.1 L6	203 kW at 2100 rpm / MDmax: 1200 Nm, CR: 2000 bar	6.1 l		
TDC 6.1 L6	174 kW at 2100 rpm / MDmax: 1070 Nm, CR: 1600 bar	6.1 l		

❸ Engines, exhaust aftertreatment systems and lubricating oils from both the biodiesel field tests as the basis for the calculations

the test results that were under the lower limit of determination (e.g. <0.5 mg/kg) were not considered. This data was also integrated in the second stage. This took place on the basis of the re-evaluations of the raw data and made the annual average value more precise. ❶ and ❷ show the results that were calculated for the total concentration of alkalis and alkaline earth metals for the years 2000 to 2011. At the upper end of the scale, the highest permissible value (in accordance with DIN EN 14214) is shown as 5 mg/kg; this is the total concentration of alkali or alkaline earth metals.

Alkaline metals like sodium and potassium are brought into the fuel via the transesterification catalysts during the process of biodiesel manufacturing. In contrast, the alkaline earth metals Calcium and Magnesium mostly enter the fuel via the vegetable oil that is used during manufacturing or they can be brought in via the washing water that is used when the biodiesel is washed. Basically, the annual average values calculated are considerably lower than the associated limit values. There tends to be more alkali and alkaline earth metals in biodiesel. The refined average values always undercut the associated annual average values.

EFFECT OF ASH ACCUMULATION ON AFTERTREATMENT SYSTEMS

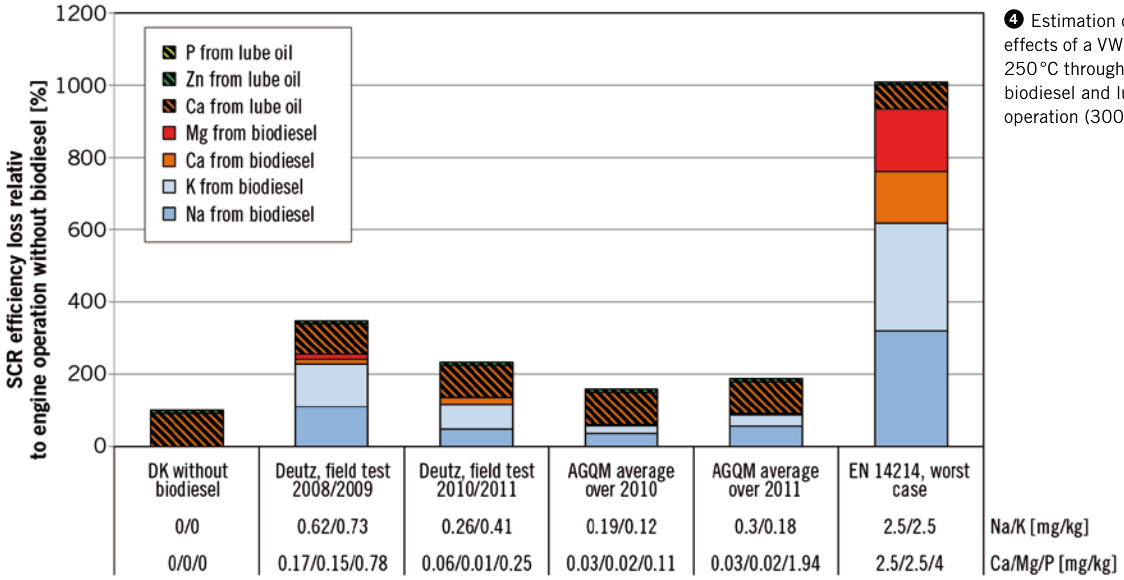
Contamination of SCR catalysts by metals has been comprehensively described in the literature and basic elements such as potassium and sodium show an especially high contaminative effect [7-10]. The contamination is based on the fact that the acid reaction centres of the SCR catalyst are neutralised and as such, are no longer available to take up the ammonia, which is also alkaline in nature. The result is a drop in effectiveness right up to complete deactivation. According to the investigation results of a FVV project [7], as much as 0.1 % mass of potassium in the washcoat of a vanadium-SCR catalyst led to a drop in effectiveness of approximately 20 %. Sodium is a similarly strong contaminant, the alkaline earth metals calcium and magnesium usually have a lower, but still considerable contaminant effect.

On the basis of the contaminant data available in the literature, a calculative method has been developed to estimate the contamination of a VWT-SCR catalyst as it would be expected to occur when biodiesel with defined element contents is burned. Contamination through elements that result from the lubricant due to the oil consumption are also considered. Oil consumption makes up just 0.05 % of fuel consumption, but the risk of contamination through lubricant components should not be neglected, as higher element concentrations are present in them. This is a short description of the manner in which SCR contamination is calculated:

: calculation of the element emissions from fuel consumption and oil consumption as well as the element content in biodiesel and lubricant (data from ❸, assumption that 30 % of the oil consumption will occur due to evaporation – i.e. without elements being emitted)
: calculation of element concentrations in the washcoat as a function of the lifespan. Assumption of a defined deposition rate (2.5 %, determined on the basis of washcoat analyses from the field test project)
: calculation of the contamination caused by the use of element-specific contamination rates through the FVV project [7] and summation of all the elements.

❹ shows the calculated VWT-SCR reductions in efficiency for various biodiesel qualities in terms of element contaminations (100 % relates to diesel without biodiesel). If the biodiesel producers were to actually manufacture a marginal biodiesel in accordance with DIN EN 14214, a nine-fold contamination effect would occur; this level of contamination would be far too high. This would make using biodiesel in engines with SCR exhaust aftertreatment technology impossible. In contrast, on the basis of the 2010 AGQM data as well as the Deutz field test data as part of UFOP project 540/103 of 2010/11, contamination through biodiesel is possible where this biodiesel is itself only just above contamination through lubricant. When the effectiveness of the SCR catalysts were measured again in both field tests, a lower reduction of effectiveness was found in comparison with the calculations [11, 12]. Due to the results that are at hand, Deutz has decided to approve class IIIB engines with SCR exhaust aftertreatment systems for operation with B100. This approval is given under the proviso that the SCR catalyst always be replaced after 3000 h of biodiesel operation.

A similar calculation procedure was used for the accumulation of ashes in particle filters. A retention rate of 100 % is assumed here. ❺ shows the results of this calculation for the same application as above. Here, too, 100 % relates to diesel without biodiesel. The relation of the damaging effects of the various fuel qualities is very similar for both the ash



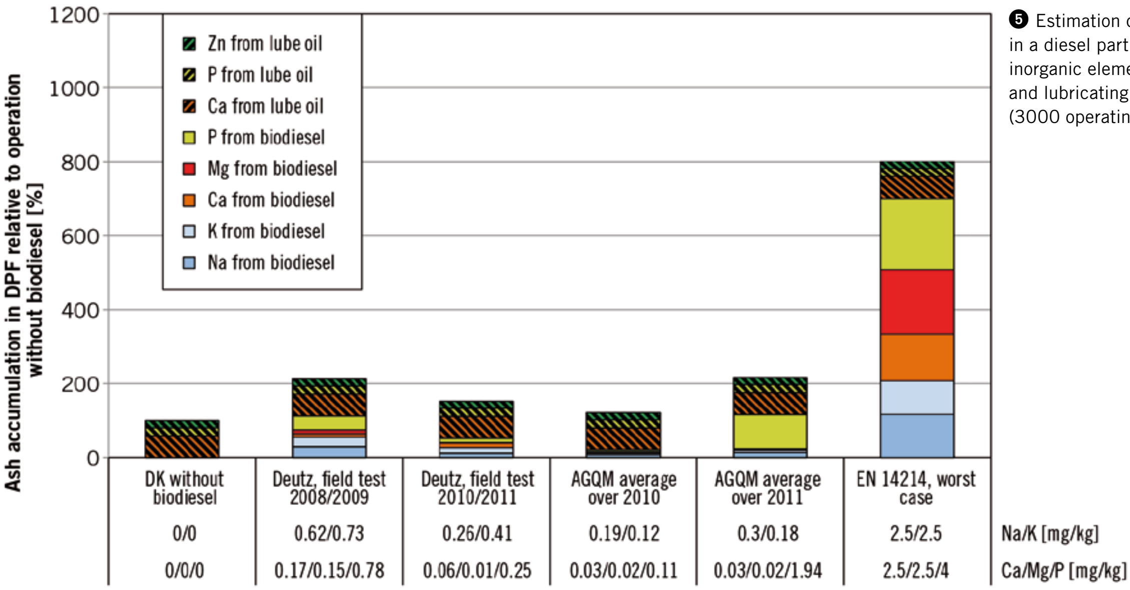
❹ Estimation of the contaminant effects of a VWT-SCR coated catalyst at 250 °C through inorganic elements from biodiesel and lubricating oil at tractor operation (3000 operating hours)

contaminant and the SCR contamination. A (hypothetical) marginal biodiesel in accordance with DIN EN 14214 would have a eleven-fold greater level of ash accumulation than a biodiesel-free diesel fuel and would clog the filter in less than 500 h. This will become relevant from the introduction of the EU class VI in 2014, as both particle filters and SCR catalysts will be used. This will also be the case for agricultural machinery. In terms of the ash accumulation, it must be stated that the real biodiesel qualities deliver a considerably better image than a worst case quality that exhausts the specification limits.

SUMMARY AND OUTLOOK

The evaluation of the AQGM and field test data shows that the quality of biodiesel is considerably better in the field than the associated limit values permit. Two studies from the USA delivered similar results [13, 14]. In this context, it is appreciated that AGQM now publishes the results of their unannounced quality inspection on an annual basis. The low concentrations of elements are an important factor for the approval of EU class IIIB Deutz agricultural engines.

A fundamental re-evaluation of biodiesel approvals is necessary for future EU class IV engine concepts and the use of exhaust aftertreatment technologies that is associated with them (Fe-Zeolith-SCR-Substrate, DOC). Due to the contamination problems, the engine manufacturer is of the opinion that urgent action must be taken to considerably reduce the limit values of EN 14214 and develop the analytical methods that are associated with it. Measures to reduce the element content in lubricating oil have already been implemented. The measures implemented by the engine manufacturers to reduce lubricating oil consumption have also been largely exhausted.



❺ Estimation of ash contaminant in a diesel particle filter caused by inorganic elements from biodiesel and lubricating oil at tractor operation (3000 operating hours)

REFERENCES

[1] http://ec.europa.eu/energy/renewables/transparency_platform/doc/national_ renewable_energy_action_plan_germany_de.pdf

[2] Technical circular Fuels. TR 0199-99-1218, Deutz AG, Cologne

[3] DIN EN 14214: Automotive fuels – Fatty acid methyl esters (FAME) for diesel engines – Requirements and test methods. Beuth: Berlin, April 2010

[4] Wilharm, T.; Stein, H.: Kurzstudie zur Evaluierung der Metall-, Phosphor- und Schwefelgehalte in Biodiesel. UFOP project No. 540/104, Neusäß, 2011

[5] DIN EN 14538: Fat and oil derivatives – Fatty acid methyl ester – Determination of Ca, K, Mg and Na content by optical emission spectral analysis with inductively coupled plasma (ICP OES). Beuth: Berlin, September 2006

[6] DIN EN 14107: Fat and oil derivatives – Fatty acid methylesters (FAME) – Determination of phosphorous content by inductively coupled plasma (ICP) emission spectrometry. Beuth: Berlin, October 2003

[7] Kern, P.; Klimczak, M.; Lucas, M.: Dieselkatalysatordesaktivierung I + II. FVV concluding report No. 878, Frankfurt, 2009

[8] Klimczak, M. et al: High-throughput study of the effects of inorganic additives and poisons on NH3-SCR catalysts. Part I: V2O5–WO3/TiO2 catalysts. In Applied Catalysis B: Environmental 95 (2010), pp. 39-47

[9] Kern, P. et al: High-throughput study of the effects of inorganic additives and poisons on NH3-SCR catalysts. Part II: Fe–Zeolite catalysts. In: Applied Catalysis B: Environmental 95 (2010), pp. 48-56

[10] Guo, X.: Poisoning and sulfation on vanadia SCR catalyst. Brigham Young University, August 2006

[11] Winkler, M.; Knuth, H.W.: Durchführung eines Prüfstandsdauerlaufs über 500 Stunden sowie Feldtesterprobung zur Freigabe von Deutz-Common-Rail-Motoren in Nutzfahrzeugen Euro IV für Biodiesel. UFOP project No. 540/080, concluding report, 2009

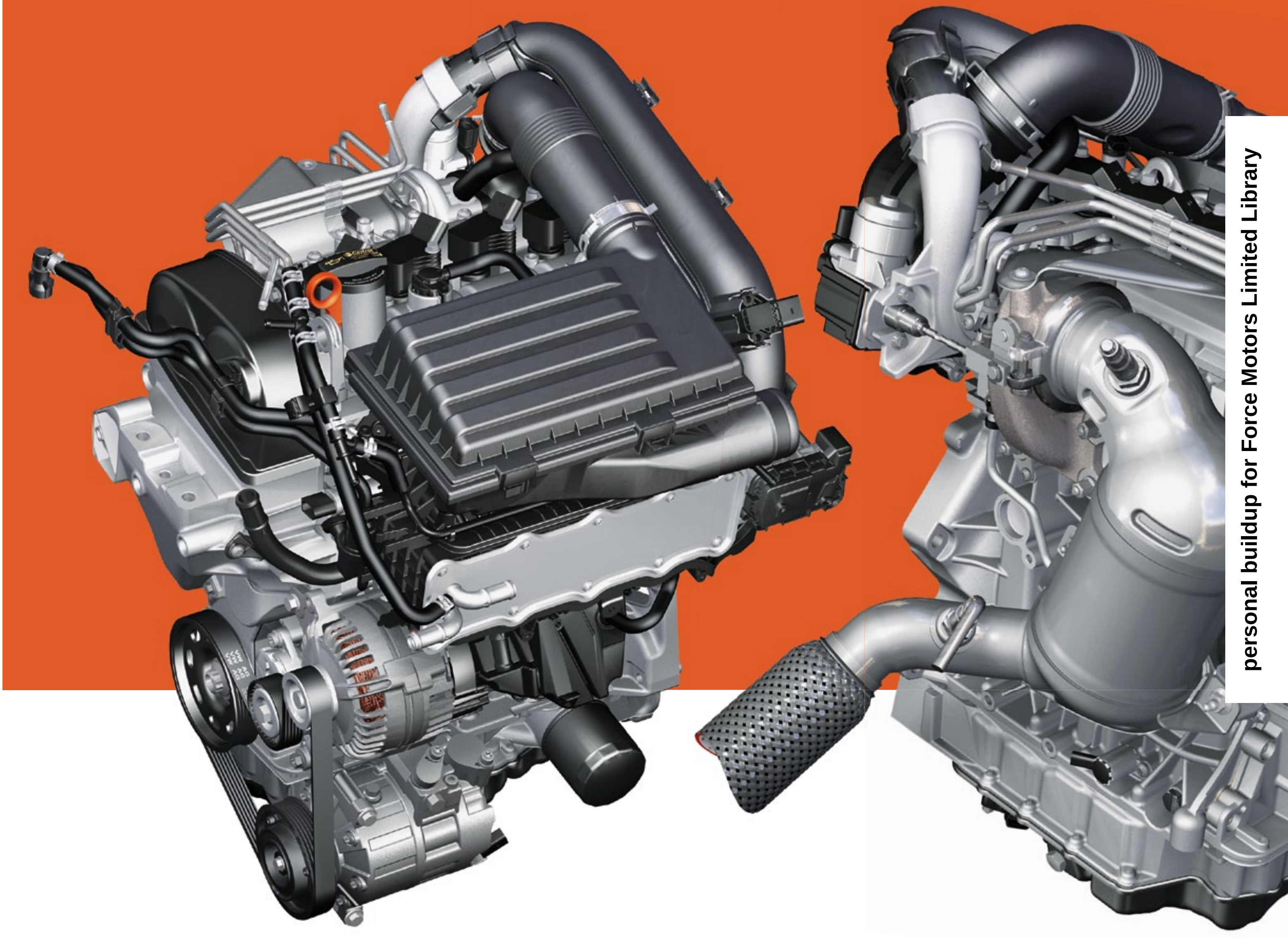
[12] Winkler. M.: Dauerhaltbarkeitsuntersuchungen an Deutz-Agripower-Motoren der Emissionsstufe IIIB mit SCR-Systemen zur Freigabe von Biodiesel. UFOP project No. 540/103, UFOP specialist panel Bio-fuels, Berlin, 2011

[13] http://www.ufop.de/downloads/20110825_Abschlussbericht_ENG_red.pdf

[14] http://www.ufop.de/downloads/Abschlussbericht_englisch_Sep09.pdf

THANKS

The results of this work have been made possible with the generous support of the Union zur Förderung der Oel- und Proteinpflanzen e.V. (UFOP). We would like to thank the Arbeitsgemeinschaft Qualitätsmanagement Biodiesel e.V. (AGQM) for making the analysed data available.



MOTIVATION

The development of the new engine generation internally labelled EA211 is closely integrated with the construction of the Volkswagen Group's new modular transverse platform (MQB in German). The MQB covers the A0, A and B passenger car segments for all brands of Volkswagen AG. All of them make use of standardised components and modules. A major motivating factor for the development of the modular transverse platform and thus the new EA211 engine range was the Volkswagen drive and fuel strategy. Its primary aim is the significant reduction of fuel consumption. The group already reacted some years ago to this demand with its Blue Motion Technology strategy. It is within this context that the decision was made to replace the proven EA111 engine range and the TSI engines based on it with a new design bearing the reference EA211. The following objectives were formulated in the design specification:

: modular construction to facilitate production worldwide, standardisation of installation orientation with other group engines
: compact construction in order to realise short front overhangs on the vehicle
: reduction of engine weight by up to 30 %
: reduction of fuel consumption and CO_2 emissions by 10 to 20 %
: fulfilment of the future Euro 6 emission standard.

BASIC ARCHITECTURE

In order to make full use of the synergy potential presented by the modular transverse platform, the decision was taken to standardise the base engine architecture within the vehicle. Installation orientation plays a major role here. Previously, the gasoline engines from the EA111 range were tilted forwards with their exhaust side facing towards the radiator. In contrast, all other engines, including the diesel engines labelled TDI, were tilted backwards with their hot side facing towards the rear, ❶. Changing the installation orientation for the EA211 engines presented significant challenges. On the one hand, it called for the redesign of the engine peripherals such as cooling and exhaust system and, on the other, for changeover throughout the Volkswagen Group factories worldwide. However, the new layout delivers substantial synergies, including the application of a universal engine/transmission flange.

A further, important objective in the development of the EA211 was the compact layout of the auxiliary units. The air

THE NEW MODULAR GASOLINE ENGINE PLATFORM FROM VOLKSWAGEN

Volkswagen has developed a new generation of three- and four-cylinder in-line gasoline engines. The new engine family, known internally as EA211, has been produced to meet the requirements of the new modular transverse platform design from the Volkswagen Group. In comparison with previous generations, the new engines will be more compact and up to 30 % lighter in weight. In addition, their fuel consumption will be between 10 and 20 % lower.

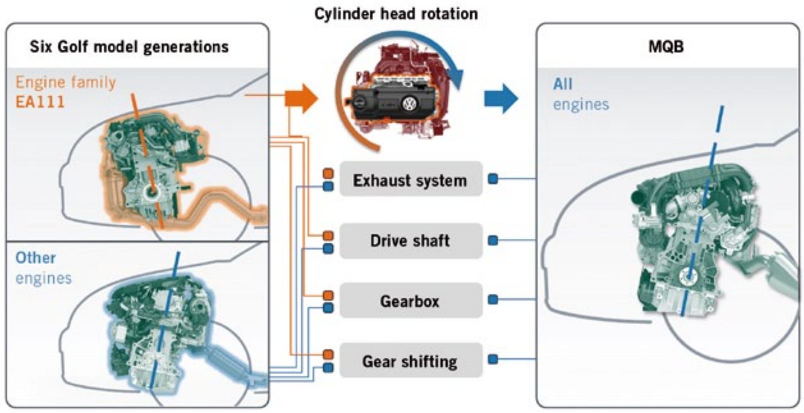
AUTHORS

DR.-ING. RÜDIGER SZENGEL
is Head of Development Gasoline Engines at Volkswagen AG in Wolfsburg (Germany).

DR.-ING. HERMANN MIDDENDORF
is Head of Development EA111/EA211 Gasoline Engines at Volkswagen AG in Wolfsburg (Germany).

DIPL.-ING. NIELS MÖLLER
is Technical Project Manager EA211 at Volkswagen AG in Wolfsburg (Germany).

DIPL.-ING. HANS BENNECKE
is Test Engineer Mechanical Testing EA211 at Volkswagen AG in Wolfsburg (Germany).



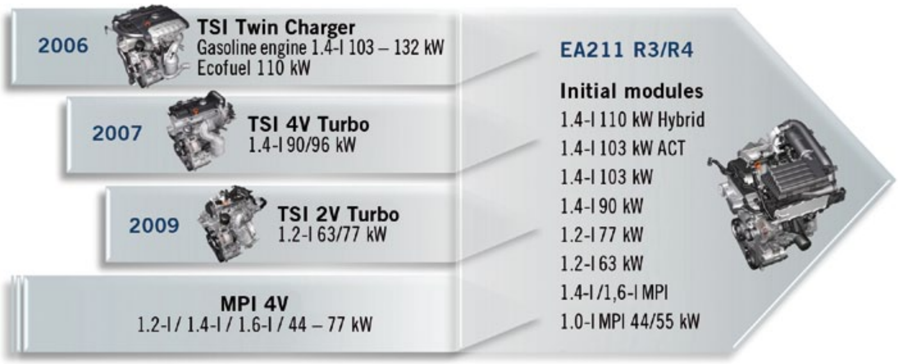
❶ Unified powertrain-assembly position in the modular transvers platform (MQB)

conditioning compressor and the generator on the new TSI are fixed directly to the oil sump and the engine block respectively without additional supports. In order to achieve such a compact layout and to run it with a simple toothed belt arrangement, the water pump was positioned on the clutch side of the engine on the front face of the cylinder head. It is driven via toothed belt by the camshaft.

As a consequence of the new mounting position tilted 12° rearward and the compact layout of the EA211 engines, the installed length is shortened by 50 mm, equating to 18 % compared with the previous engines. In the MQB, this means the front axle can be positioned 40 mm further forward. The front overhangs are thus shortened, benefiting impact characteristics, exterior design and axle load distribution.

REDUCTION OF FUEL CONSUMPTION

The reduction in fuel consumption laid down in the specification document – the second most important development objective – was achieved, on the one hand, through the application of new technologies and, on the other, through the painstaking analysis and optimisa-



❷ The new EA211 range (top) and engine data for the EA211 TSI platform (bottom)

	1.2-l 63 kW TSI	1.2-l 77 kW TSI	1.4-l 90 kW TSI	1.4-l 103 kW TSI	1.4-l 110 kW TSI HYBRID
TORQUE	160 Nm at 1400 rpm	175 Nm at 1400 rpm	200 Nm at 1400 rpm	250 Nm at 1500 rpm	250 Nm at 1500 rpm
NOM. ENGINE SPEED	4800 rpm	5000 rpm	5000 rpm	5000 rpm	5000 rpm
DISPLACEMENT	1197 cm³	1197 cm³	1395 cm³	1395 cm³	1395 cm³
BORE	71 mm	71 mm	74.5 mm	74.5 mm	74.5 mm
STROKE	75.6 mm	75.6 mm	80 mm	80 mm	80 mm
COMPRESSION RATIO	10.5	10.5	10.5	10.5	10.5
FUEL	RON95	RON95	RON95	RON95	US / "regular"
ENGINE WEIGHT	97 kg	97 kg	104 kg	106 kg	93 kg

tion of all friction sources in the base engines. All bearing diameters were reduced to the maximum required size, while the width and surfaces of the bearings were further developed from a topological standpoint.

The respective requirements for cooling and lubrication were calculated by means of simulation and testing. The circulation of oil and coolant was dethrottled with the help of CFD calculations.

1.4-L ENGINE WITH ACTIVE CYLINDER MANAGEMENT

The 1.4-l TSI engine with 103 kW in a special offer comes with a technical highlight that contributes to further reduction in fuel consumption. Its valve train module with active cylinder management (ACT) enables it to switch cylinders 2 and 3 on and off in accordance with requirements using electromagnetic actuators [1]. The still active cylinders 1 and 4 operate at a higher load point and, thus, more efficiently.

The 1.4-l TSI with robust ACT technology proves that it is possible, within the TSI strategy framework, to combine ambitious consumption targets with high power output and high torque. In the NEDC, the fuel consumption of the engine has been reduced by 0.4 l/100 km, equating to a drop in CO_2 emissions of 8 g/km. At moderate speeds in city traffic, as well as cross-country, savings of between 10 and 20 % are possible.

THE NEW ENGINE PLATFORM

Common characteristics of all engines in the EA211 range are:

- four-valve technology
- aluminium crankcase
- exhaust manifold integrated into the cylinder head
- camshaft drive via toothed belt.

The new platform has already celebrated its premiere in the Volkswagen model up! in the shape of the three-cylinder gasoline engine with a displacement of 999 cm³ and manifold injection. The core of the new engine family, however, is formed by the small, powerful and frugal four-cylinder TSI engines with 1.2-l and 1.4-l displacements.

All engines from the EA211 platform share cylinder spacing of 82 mm. The ideal stroke/bore ratio was selected for each displacement taking into account thermodynamics, acoustics and performance. The most desirable characteristics are derived from a long-stroke layout. In the case of the 1.2-l engine, bore/stroke is set at 71.0 mm/75.6 mm and, for the 1.4-l engine, at 74.5 mm/80.0 mm.

The spectrum of the new TSI family initially covers the well-known performance range of the Volkswagen line-up – it begins with 63 kW and extends to 110 kW for the engine used in the hybrid driveline, ❷. Alongside the TSI engines, four-cylinder MPI (multi point injection) variants with 1.4-l and 1.6-l displacements will also be derived from the platform for use on global markets.

CRANKCASE

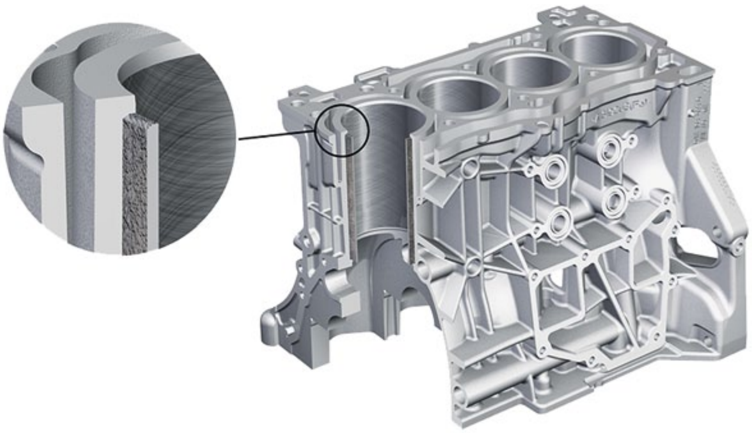
The crankcase of the EA211 is an ultra-stiff aluminium pressure die cast construction with cylinder liners in GJL 250 cast iron, ❸. The cylinder liners, which are fluid-spray honed in four stages, are fixed to the crankcase using rough-surface casting. The new crankcase weighs just 19 kg. Compared to the EA111 with 1.4-l displacement, which has a cast iron crankcase, this marks a weight reduction of 16 kg.

Crankcase ventilation is devised as block ventilation and is conducted largely inside the engine. This is an extremely robust layout because external pipe connections and transfer points are avoided almost entirely. In terms of cooling water circulation, the block layout is based on the proven two-circuit system from the small TSI engines. Supply to the oil cooler, which is screwed onto the side of the crankcase is likewise fully integrated within the crankcase.

CYLINDER HEAD

When it came to the redesign of the cylinder head, the focus was on intelligent thermal management and the expanded use of exhaust energy for rapid warm-up. The concept of the four-valve rolling cam follower head has been retained due to its low friction characteristics.

The exhaust manifold is fully integrated into the cylinder head, where it forms a highly effective exhaust heat exchanger, ❹. It is used to heat the engine quickly during warm-up, while also providing plenty of heat for a comfortable vehicle interior. Under full load, on the other hand, the exhaust is cooled by approximately 100 K, which reduces fuel consumption by up to 2.0 l/100 km. Compared to conventional, external manifolds, the exhaust flow paths with an integrated manifold are



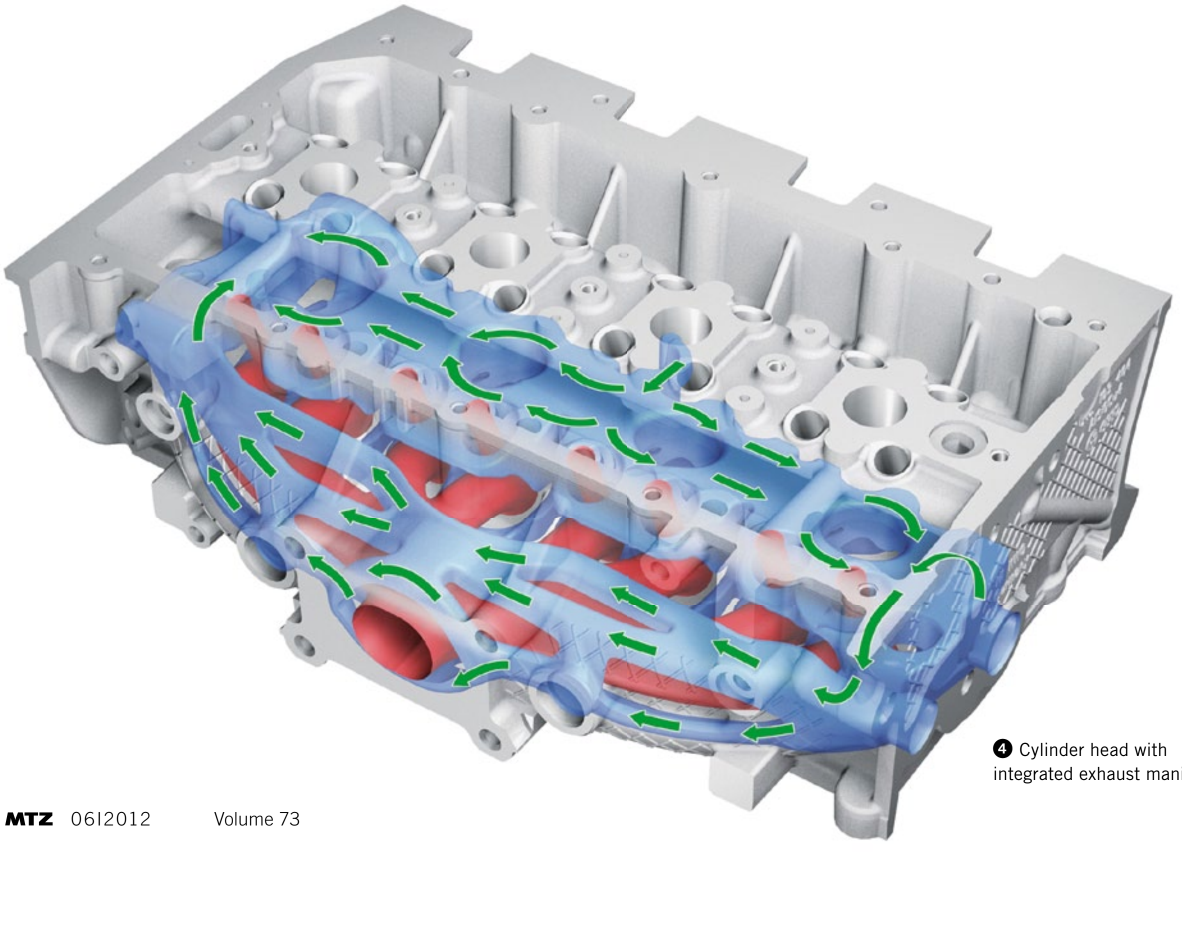
❸ The new alloy crankcase

considerably shorter, maintaining heat loss through the walls in the transient case at an acceptable level.

The valve angle has been increased to 120°, with the aim of increasing wear resistance – particularly when it comes to the use of alternative fuels and fuels of mid-range quality on global markets. The valve shaft diameter has been reduced to 5 mm to optimise the dynamics of the valve gear through lower mass and reduce friction as a result of lower valve spring force. The spark plugs have been specified with M12 threads to achieve optimum wall-thickness between the spark plugs and valve seats. Intensive finite element analysis work meant that the weight of the cylinder head increased by less than 1.2 kg, despite its considerably more complex geometry. The four-valve cylinder head of the EA211 is produced as an aluminium die casting at Volkswagen Group foundries using heat-treated AlSi10Mg(Cu) alloy. The sand cores are made entirely from inorganic material using environmentally friendly methods.

CRANKSHAFT DRIVE AND PISTON GROUP

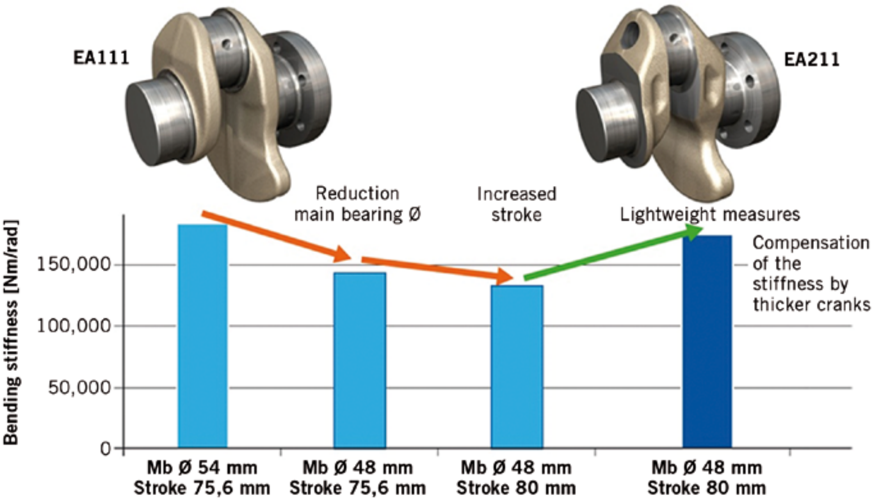
Friction reduction took high priority during the development of the EA211. One of the most important initiatives was the reduction of the main bearing diameter from 54 mm on the EA111 to between 42 and 48 mm in the different variants across the new engine platform. The axial location of the con rods is handled by the big-end bearing in order to facilitate thicker crank arms. They compensate for the loss in stiffness caused by the smaller bearing diameter. The higher elastic deformation and reduced friction deliver even crankshaft acoustics. As in the preceding engine, the crankshaft and conrods are made from forged steel. By using the latest FEA and NVH calculation methods, it was possible to reduce



❹ Cylinder head with integrated exhaust manifold the weight of the crankshaft by 20 %, ❺, and the weight of the conrods by up to 30 %, ❻. The conrod bearing spindles on the crankshaft are hollow bored.

At the small-end bearing, the conrod does not have the conventional trapezoidal shape. Rather, in the forging die, a geometry is formed that is optimised for weight in line with component loading. During the intake stroke, a very slim upper link pulls the piston downwards, as the forces at play here are relatively low. Accordingly, the geometry for transferring the working pressure is more robust in its design.

The aluminium pistons have been completely redesigned. The piston crown has a virtually flat form, as the wall-guidance for internal mix formation used in previous concepts is not applied here. This enabled reduction of piston weight and led to more homogeneous temperatures at the piston crown. The piston ring package was intensively validated in order to optimise friction and oil consumption. Installation clearance was increased in order to reduce friction. This also facilitated further improvements to acoustics through a slightly increased piston pin offset and refined piston crown geometry.



❺ Development in stiffness of the weight-optimised crankshaft

COOLING CIRCUIT

All TSI engines in the EA211 engine range have a high-temperature circuit for engine cooling and a low temperature circuit for indirect charge air cooling, ❼. The low-temperature circuit is driven via an electric coolant pump and can be controlled completely flexibly in line with requirements. In trailing throttle conditions, it also provides cooling for the turbocharger.

Engine cooling is handled by the high-temperature circuit. It is driven by a mechanical pump configured as a coolant pump module with integrated coolant temperature regulator. The module is mounted directly to the cylinder head on the transmission side of the engine. An expanding-wax thermostat for block cooling ensures that the cylinder liners remain at a constantly high temperature independent from the main cooling circuit. A further thermostat regulates the switching of the vehicle radiator. With a regulated temperature of 87 °C, it represents the best possible compromise between friction reduction and efficiency-optimised ignition. The overall efficiency of the coolant pump module was increased to more than 50 %, representing an improvement of up to 40 % over pumps currently found in series production. Moreover, the entire cooling circuit has been optimised for throttling losses.

❻ The weight-optimised conrod

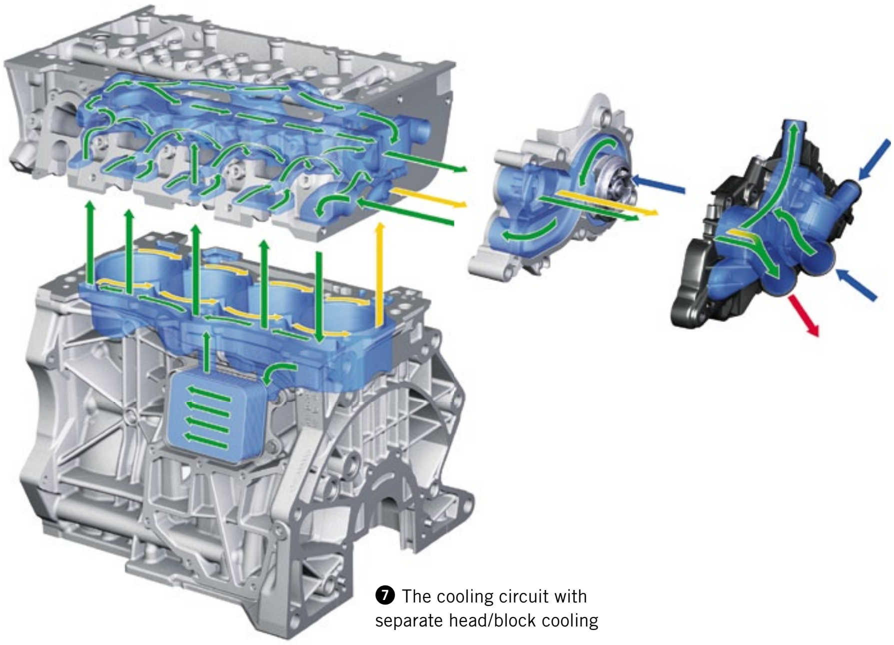
EXHAUST GAS TURBOCHARGER

All versions of the EA211 feature a fully redeveloped exhaust gas turbocharger with a single-scroll turbine. The integration of the exhaust manifold into the cylinder head and the resulting specific airflow characteristics represented the most important development parameters. The turbocharger has been specifically optimised for low-end torque and good transient characteristics with well-rounded torque curves. The 1.4-l TSI with 103 kW output, for instance, has a maximum torque of 250 Nm available from 1500 rpm. This marks an improvement of 25 % compared with the previous engine, ❽. A turbocharger was conceived and optimised for each of the three power outputs (1.2-l

TSI, 1.4-l TSI 90 kW and 1.4-l TSI 103/110 kW). In all derivatives, the mechanism is designed for a maximum exhaust gas temperature of 950 °C and is notable for its small rotor diameter and accordingly low moments of inertia with a high degree of efficiency.

The control of the wastegate is operated by a newly developed electric actuator. In contrast to conventional excess pressure control systems, the wastegate can be adjusted to the desired setting at any time and independently from the momentary charge pressure. The new actuator functions quickly and precisely, which has a positive effect on the acoustics of the turbocharger and on the responsiveness of the engine. The adjustment time between the two end stops is just 110 ms.

The interface between the turbocharger and the engine periphery is identical in all cases, allowing the use of the same cylinder heads, exhaust systems and oil and coolant lines. Thanks to the integration of the exhaust manifold into the cylinder head, it was possible to configure the turbine casing as a slim and lightweight four-hole flange unit. Thus, the weight of the turbocharger has been reduced by more than 2 kg compared with a conventional configuration.



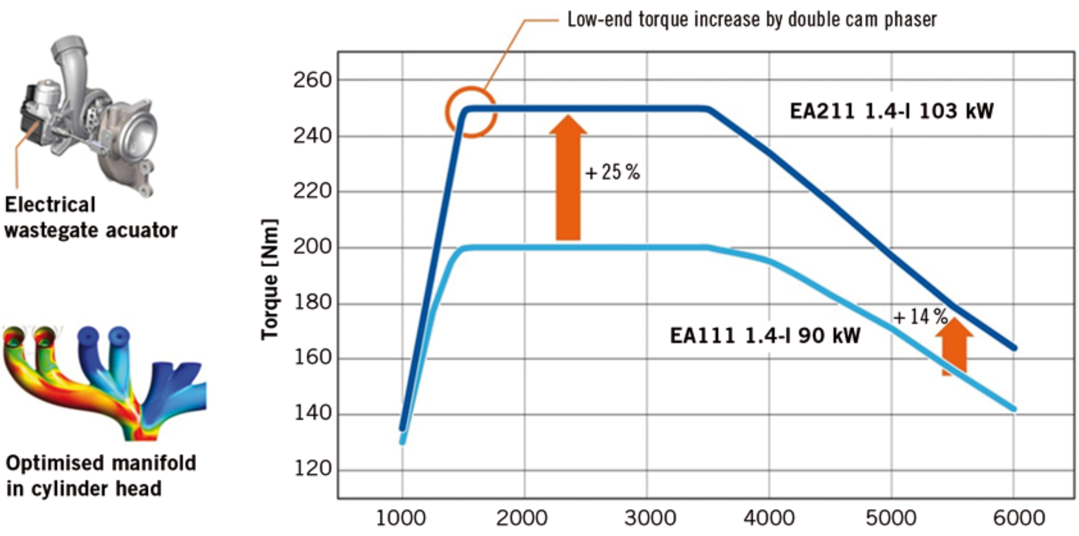
❼ The cooling circuit with separate head/block cooling

DEVELOPMENT OF THE INTAKE PORTS

The so-called Automatic Component Optimisation from Volkswagen proved to be the perfect tool for the development of the intake ports. The starting point for port development was the intake port on the 1.4-l TSI EA111. Based on this, the flow coefficient and tumble value for the EA211 TSI were derived using CFD calculations, with the objective of finding the best compromise between high flow rate and intensive charge movement. From the mathematical models, five ports were selected and evaluated using 3D simulations. Three of these ports were cast as physical models. Their measurement on the flow test rig confirmed the initial selection and they were subsequently tested on the full engine on the engine test stand. The optimum port variant delivered the best results in terms of fuel consumption, running smoothness and emissions. Its tumble value is considerably higher than that of the EA111 TSI, while its flow coefficient is only insignificantly lower.

OPTIMISATION OF THE COMBUSTION PROCESS

This optimum port variant formed the basis for the optimisation of the TSI combustion process for the EA211 range,



❽ Torque increase for the EA211 TSI engines which was aided by CFD. A major focal point was the matching of the spray pattern to the flow within the cylinder.

Due to the high specific loads of a small-displacement TSI engine, the optimum compromise for mixture formation with the smallest quantities of fuel, as well as under full load, is a multi-orifice valve (MOV) in combination with increased injection pressure. With the simulation methods used, it was possible to optimise in detail the MOV spray pattern and injector timing, as well as their adaptation for flow inside the cylinder.

Up to three injections per cycle are possible. These multiple injections occur from idle all the way to full load in the rev range up to 4000 rpm. Injection pressure is up to 200 bar. The stable tumble flow generated by the new intake port in combination with the non rotationally symmetrical five-orifice spray meant that a piston recess for mix formation under low load and special conditions like catalyst heating was not necessary.

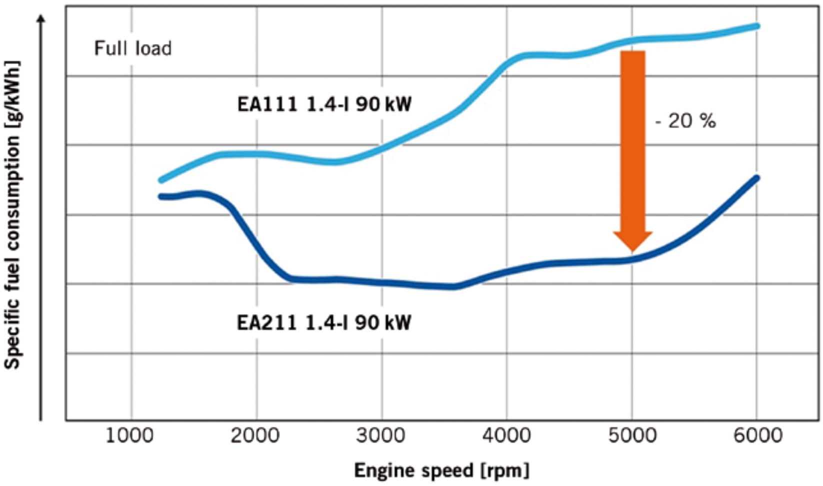
Moving outwards from the spark plug, the flame front is able to expand evenly, ensuring that no voids that might induce knock form at the edges. The compact combustion chamber design with consistently short flame paths and a recessed spark position, as well as the increased turbulent kinetic energy in the combustion chamber result in

- improved tolerance to residual gas under partial load
- reduced knocking tendency
- increased combustion efficiency.

INFLUENCE ON CONSUMPTION OF KNOCK LIMIT AND COMBUSTION SPEED

The combustion process developed for the EA211 TSI with its high combustion speed and resulting reduced knock tendency has a very positive effect on fuel consumption. Across the entire full-load curve, combustion duration has been shortened by circa 10° of crank angle, enabling mixture enrichment to be significantly reduced. Despite an increase in compression from 10.0 to 10.5 (in a configuration with super grade RON 95 gasoline), the combustion point is earlier. Peak pressure is likewise earlier and is also higher than for the EA111. Overall, the specific consumption of the EA211 under full load was reduced by up to 20 %, ❾.

❾ Fuel consumption at full load



Under partial load, too, the combustion process leads to a reduction in consumption. The main contributing factors in this instance are the higher compression ratio and increased residual gas tolerance. Because wall wetting is largely avoided, the mix can also be run leaner even when the engine is very cold.

FUEL CONSUMPTION AND EMISSIONS

With the new EA211 engines, it has been possible to achieve a further impressive reduction in fuel consumption. In the NEDC, consumption figures for the 1.4-l TSI engines have been reduced in comparison with the EA111 engines by around 8 to 10 %. In combination with extensive optimisation of the MQB vehicle, the average consumption in the compact class (Golf or Audi A3) will lie in the ballpark of around 5.0 to 5.2 l/100 km, which equates to CO_2 emissions of around 120 to 125 g/km. For the 1.4-l TSI with 103 kW and cylinder deactivation, the reduction measures up to 20 %. The new active cylinder management (ACT) alone reduces consumption by circa 0.4 l/100 km or around 8 g CO_2/km. Under low loads and at low vehicle speeds in particular, the potential for fuel savings is even greater.

SUMMARY

With the new EA211 series of gasoline engines, the demanding targets for the Volkswagen Group's future high-volume engines have been successfully realised. Through the shortening of the block by up to 18 % and the modular construction, the new engines are ideally suited for use in the Volkswagen Group's new modular transverse platform (MQB). They are also fully suitable for implementation in its other vehicles.

Fuel consumption in the NEDC drops by up to 10 % with the new EA211 TSI engines, and by as much as 20 % in combination with the new active cylinder management. And similar consumption benefits can be expected in real-life customer usage. Customers who drive their vehicles largely over short distances and a low temperatures will profit from the new intelligent thermal management. Sporty customers and regular motorway drivers who frequently run the engine at high load experience particularly substantial benefits from the reduced full-load consumption resulting from the exhaust manifold being integrated into the cylinder head. A further effect of this new concept is significantly improved heating of the occupant cabin.

Last but not least, the new solutions for the EA211 range also have a very positive impact on conventinal mixed operation. The smaller bearing diameters, the developments to the pistons and valve train, the new toothed belt and the regulated oil pump reduce base friction by up to 30 %. The painstaking weight optimisation of the engine design also delivers a major contribution within the overall vehicle to the achievement of weight and CO_2 targets.

REFERENCE

[1] Middendorf, H.; Theobald, J.; Lang, L.; Hartel, K.: Der 1,4-l-TSI-Ottomotor mit Zylinderabschaltung. In: MTZ 73 (2012), No. 3, pp. 186-197


IT'S TIME FOR EXPERT KNOWLEDGE
WITH NEW FLEXIBILITY. MTZ eMAGAZINE.
© creativea republic / Rentop Frankfurt – 2010

TWIN-JET NOZZLE INJECTORS FOR GASOLINE ENGINES

Twin-jet nozzles are recommended for gasoline motor injectors because they allow an almost tailor-made drop generation that controls the injected mass of fuel and also the penetration depth. All of these spray characteristics can be adjusted independently of each other, i.e. the spray characteristics requirements specified by the combustion process are easily attainable with twin-jet injectors. In the following, FMP Technology, Geiger Fertigungs-technologie and KW Technologie present practical implementations of twin-jet nozzles for gasoline engines.

AUTHORS

PROF. DR. DR. H. C. FRANZ DURST
is Founder and Managing Director of the FMP Technology GmbH in Erlangen (Germany).

ARTHUR HANDTMANN
is Chairman of the Board of the Arthur Handtmann Holding GmbH & Co. KG in Biberach (Germany).

MATTHIAS WEBER
is Development Engineer for gasoline injection systems, responsible for the design and construction of spray nozzles as well as the implementation of functional tests, at the FMP Technology GmbH in Erlangen (Germany).

FRANK SCHMID
is Head of the Department for Tool Making at the Geiger Fertigungstechnologie GmbH in Pretzfeld (Germany).

MOTIVATION

There is a strong belief in the field of gasoline engine development that improvements can still be made in internal combustion engines to reduce emissions without any loss of motor performance. Apart from further developing the engines, however, this necessitates new developments of the major components that can be used to facilitate combustion and, above all, to control it. In particular, there is a need for improved fuel-injection systems that allow jets of droplets with smaller Sauter mean diameters to be produced and that, at the same time, ensure that the pressure pulses generated by the injection are reduced, so that they permit systematic multiple injections and no further interaction effects occur between the individual injectors. FMP Technology, Geiger Fertigungstechnologie and KW Technologie have developed such a fuel injection system, and its characteristics are summarised in this publication. It shows outstanding properties for the employment of a novel injector system for gasoline engines.

Injectors with conventional round-hole nozzles cannot provide the advanced spray qualities indicated above, already because of the mechanism used to generate the spray. This is due to the influence of turbulent velocity fluctuations on the periphery of the jet, which cause the jet to disaggregate. This disintegration action is good for small nozzles, i.e. small Reynolds numbers, but not effective enough to cause good disaggregation at high Reynolds numbers. This is revealed by the diagram proposed by Ohnesorge et al. [1] and Reitz [2], ❶. The figure also shows that the required small drops in a spray are only produced in region IV and only in this region the turbulent velocity fluctuations are strong enough to disintegrate the fuel jet. Very good sprays usable for gasoline engines can only be generated in region V. The Reynolds number Re and Ohnesorge number Oh are defined as follows:

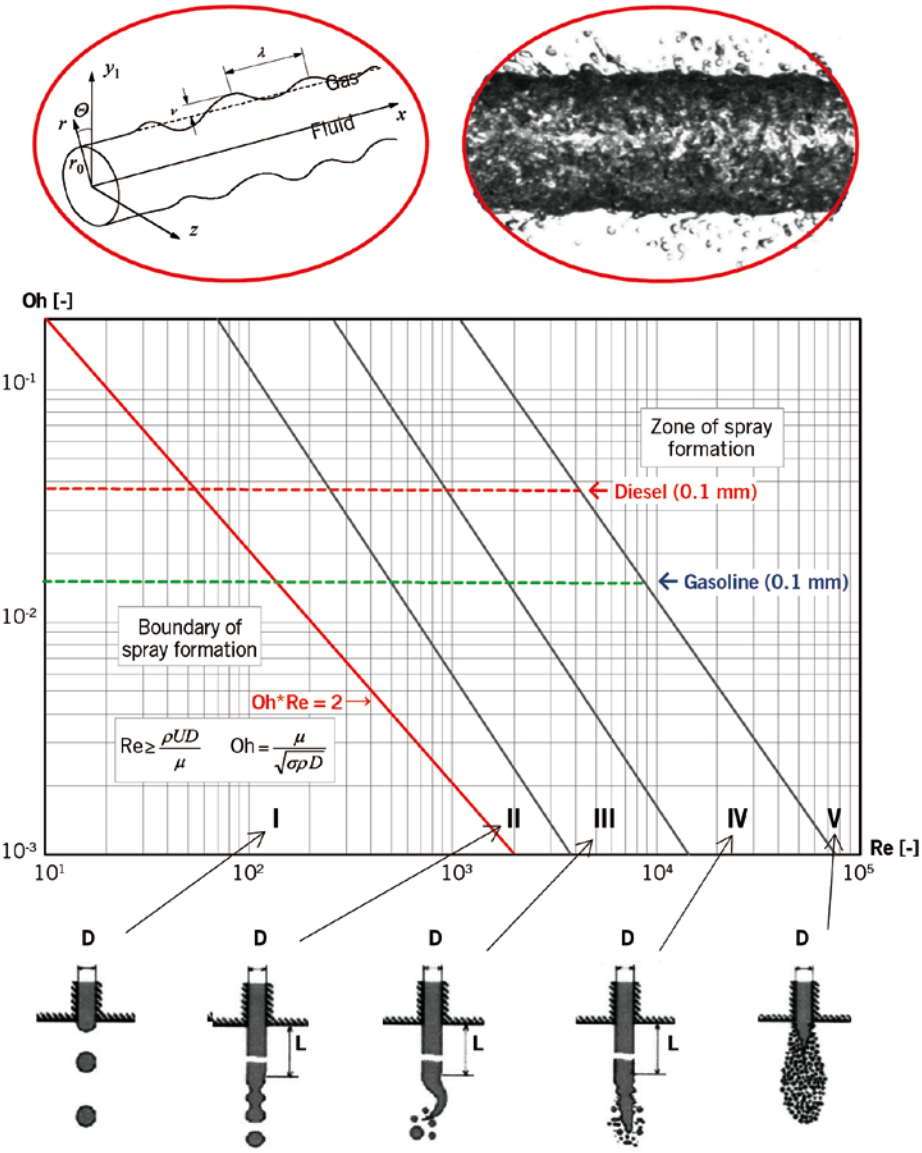
EQ. 1

$$Re = \frac{\rho U D}{\mu} \qquad Oh = \frac{\mu}{\sqrt{\sigma \rho D}}$$

DEVELOPMENT OF NOVEL SPRAY NOZZLES

Various mechanisms can be used to produce sprays for internal combustion engines. Controllable sprays can be gener-

❶ Properties of liquid jets



ated by a twin-jet spray mechanism, as investigated by Dombrowski and Johns [3] and Dombrowski and Hooper [4]. This type of spray formation is based on two intersecting liquid jets that interact in their cross section and lead to the formation of a small droplet contouring spray. This is outlined in ❷, which shows the two intersecting liquid jets, which already produce the spray at the lowest operating pressure in the injectors.

Based on the work of Dombrowski and colleagues, Couto et al. [5] developed a mathematical model to determine the resulting droplet-size distributions. This model analytical describes a thin liquid lamella, which is formed by the collision of two jets, and the following treatment of its disaggregation. The entire Couto-treatment allows the resulting droplet-size distribution to be calculated. This model requires, however, the disintegration of the liquid lamella to occur by air flows on both sides of the lamella. In the lamella shown in ②, these currents are absent. Own theoretical calculations for droplet formation in twin-jet sprays had therefore to be derived, and they produce the Sauter diameter:

EQ. 2	$\frac{d_{32}}{D} = const.\ f(\theta)\ f(Oh,Re)$

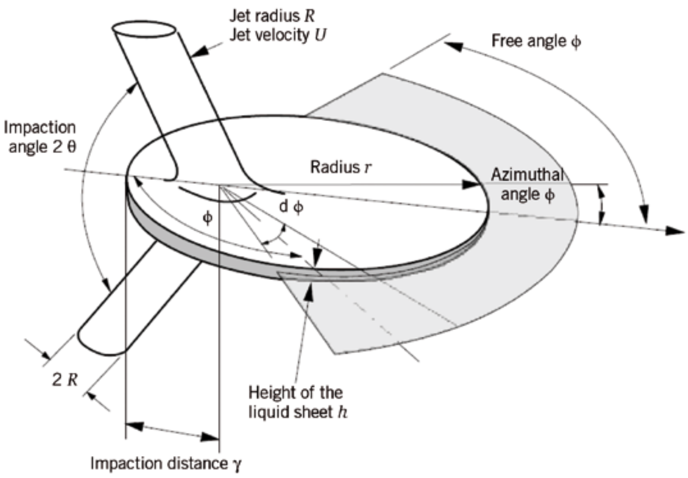
The calculations result in the specified distributions of the droplet sizes for liquid water, gasoline and diesel given in ❸. Good agreements between theoretical by derived results and experimental values was achieved. Own theoretical considerations have also revealed that for large angles θ, ②, the lamella portion with reverse flow can be prevented due to the surface tension of the fluid. For the limit angle α= 2 θ g the following relationship was derived:

EQ. 3	$\sin \alpha = 1 - \frac{8\sigma}{D\rho U^2}$

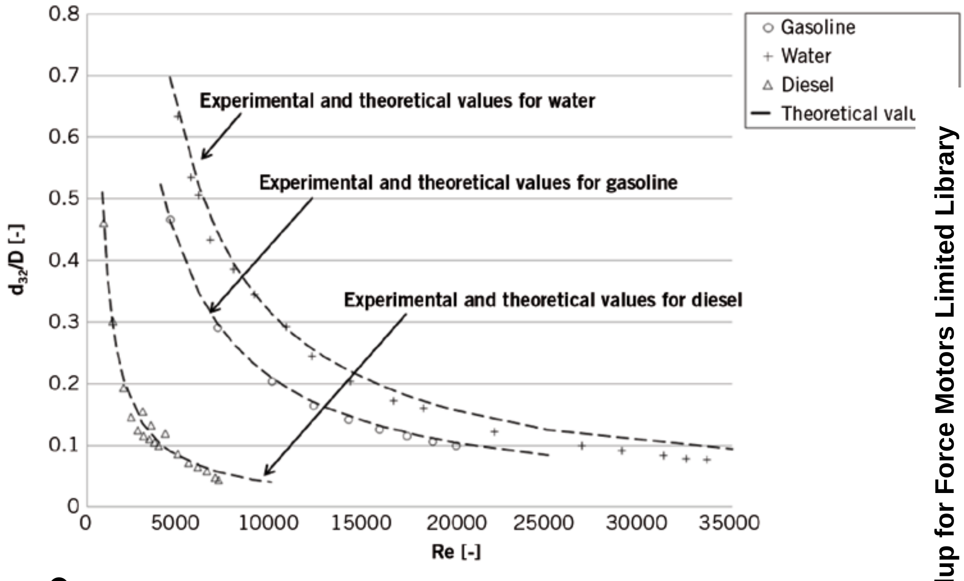
For liquid jets of gasoline, there one can thus calculate:

EQ. 4	$\theta \leq \theta_g = 44°$

❷ Interacting liquid jets in generating liquid sprays



This result meant that all the experimental studies carried out were far below $\theta = 44°$. This ensured that the meniscus formed between the jets that prevents lamella forming in the reverse direction thus also prevents the formation of drops emerging in this direction. The derived equation (Eq. 4) was an important result for manufacturing practical operational twin-jet sprays for gasoline engines.



❸ Comparison between experimental and theoretically calculated droplet sizes for twin-jet sprays

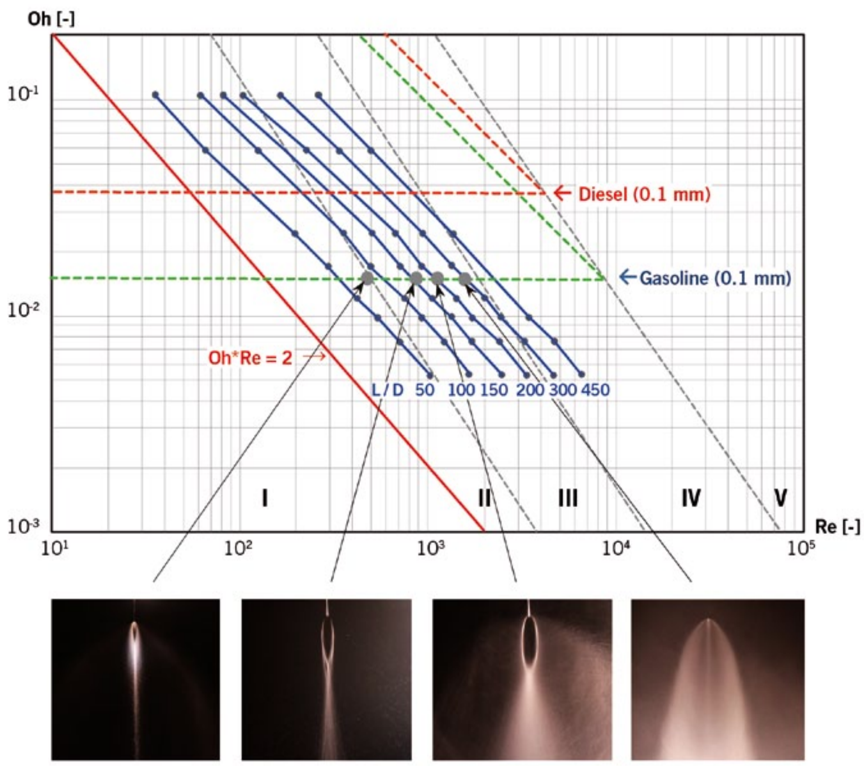
EXPERIMENTAL INVESTIGATION OF TWIN JETS

Representations of experimental results of spray formation by double jets in an Oh-Re graph make it clear that the spray formation already occurs at injection pressures for under one bar. With increasing pressure the spray formation improves, and even at pressures of $\Delta P<100$ bar there result very good spray characteristics for gasoline engines that far exceed the characteristics of sprays of round-hole nozzles at the same injection pressure, ❹. The analyses carried out in this context were conducted for nozzle diameters of 100 µm. To verify the findings derived from the analyses, experimental studies were undertaken and are summarised in the following. Drop formation in the double-jet spray begins much earlier, when opening the nozzles, than in round-hole nozzles.

BUILDING A TEST RIG

To investigate experimentally twin-jet nozzle properties, a test rig was set up in the FMP Technology GmbH spray laboratory, ❺. Displayed are two nozzles, each of which produces a circular jet. Both circular jets, i.e. the jets formed by the nozzles, are placed in x-y-z positioning systems that can be moved relative to one another and positioned such that they meet perfectly centred within a given distance from the exits of the nozzles and thus lead to an ideal double-jet spray. The properties of that spray depend on the diameter used for the two nozzles, on the equal jet velocities, the fluid properties and the angle between the jets. The diameters of both liquid jets were set as equal in the experiments in order to obtain stable configurations of twin-jet sprays. This stability is strictly guaranteed only when liquid jets with the same properties interact. Nonetheless, the spray production is very tolerant of small differences in the jet properties.

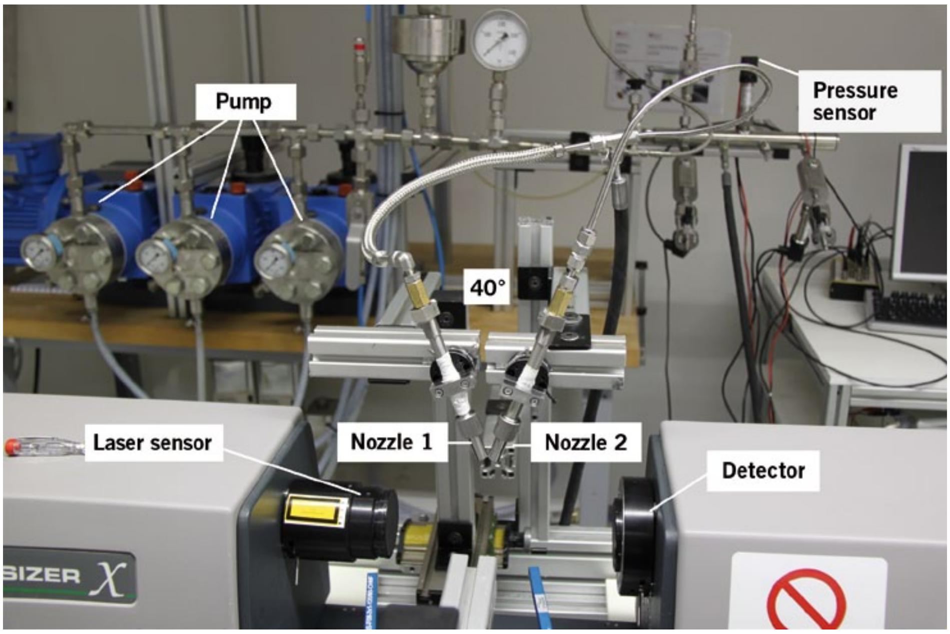
In order to measure the particle-size distributions in the twin-jet sprays generated, a so-called Malvern Mastersizer MS 2000 was employed. The associated measurement setup is also shown in ⑤. These representations show that the light diffraction employed in the Malvern particle sizer, was collected to measure the droplet-size distributions of sprays. From these measurements the corresponding mean values, such as the diameters d_{10} and d_{32} were deduced.



❹ Oh-Re graphs for twin-jet spray generators according to Y. Han et al. [6]

MEASUREMENT RESULTS

Detailed measurements of the properties of twin-jet sprays were carried out with



❺ Experimental setup in the spray laboratory

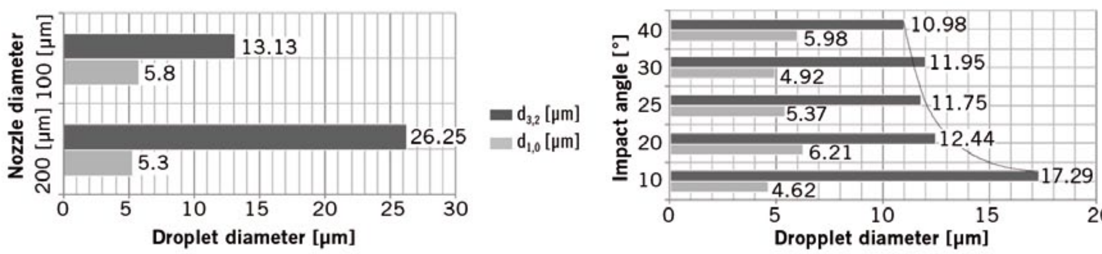
the measuring apparatus shown in ⑤. These showed that

- the Sauter mean diameter of the droplet distribution of the double beam is proportional to the spray nozzle diameter
- a dependency of the spray properties exists on the intersecting angle between the jets, but flat jets result at all angles that are only a few mm deep
- at high pressures, such as those in gasoline engines, there is only a minor dependence of the droplet size on the supply pressure.

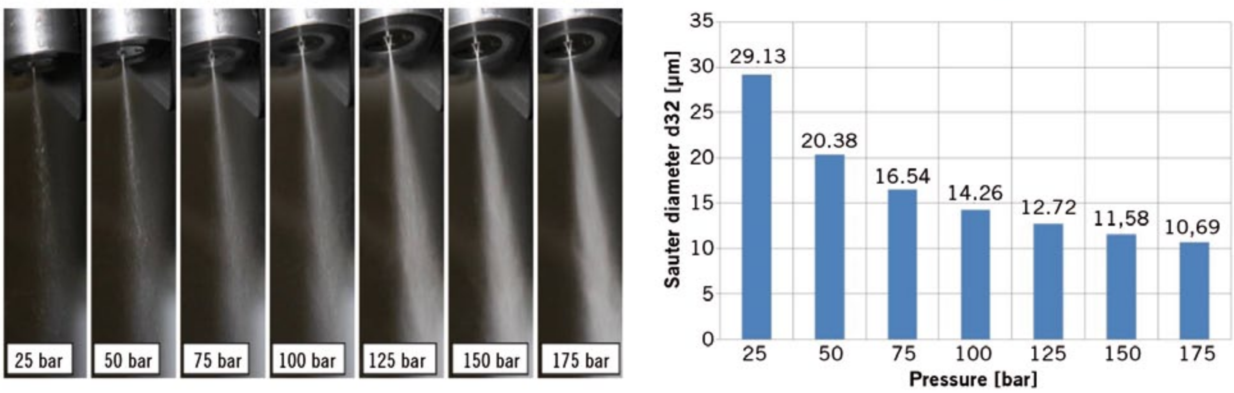
All the above results are shown in ❻.

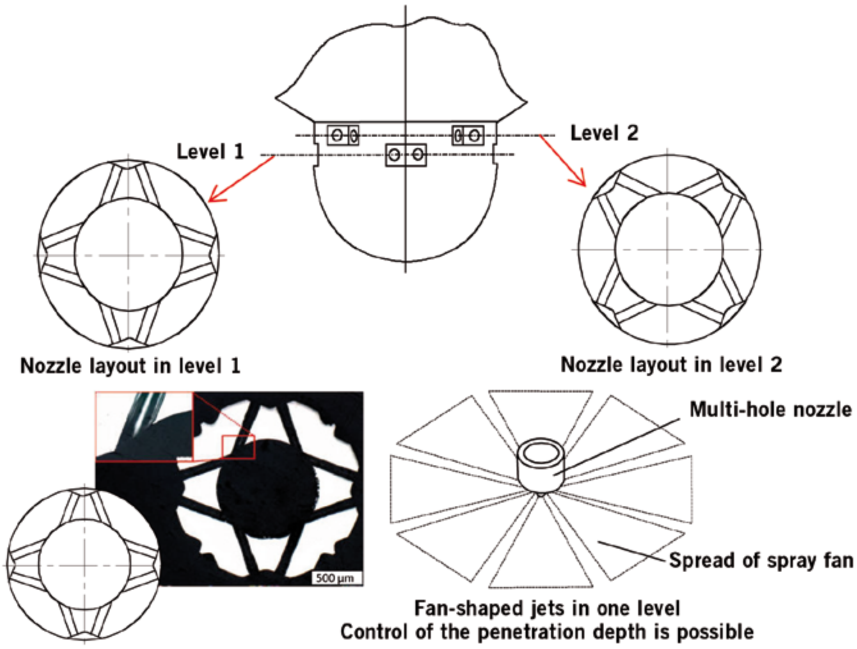
TWIN-JET SPRAY INJECTORS FOR GASOLINE ENGINES

To achieve the necessary mass flow needed for gasoline engine combustion and an even distribution of fuel in the combustion chamber, a special arrangement of twin jets, in the form of a multi-hole nozzle, was developed and patented. ❼ shows the chosen arrangement in the injector head of double jets for the first nozzle. A total of eight twin-jet nozzles were arranged radially, each having an angle of 40° between the two liquid jets. Due to the small size of the injector head only four twin-jet nozzles, each offset by 90°, could be opted for in one plane of the nozzle arrangements. For this reason, a further four twin-jet nozzles were mounted in a second bore-hole



❻ Measurement results for water sprays (to obtain values for gasoline, conversions can be made via the (1) Oh-Re relationship in Eq. 1)





❼ Representation of double-jet spray head of the developed injector

plane, offset by 0.5 mm. Moreover, the second plane with the inclined nozzle arrangement was rotated by 45° relative to the arrangement in the first nozzle plane. A total of eight twin-jet nozzles could thus be arranged at the injector, ⑦. The spatial coverage of eight twin-jet sprays is also outlined in the figure. Of course opportunities for further improvement of the design are available or can be thought of.

MEASURING SPRAY CHARACTERISTICS

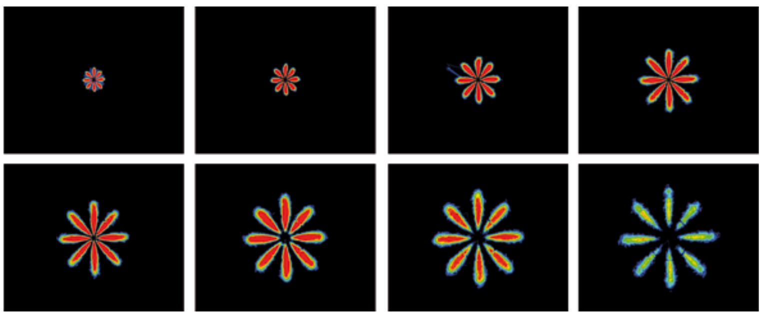
The investigations of the properties of the manufactured twin-jet-spray injectors, conducted in the laboratory of FMP Technology GmbH, were supplemented by measurements made by the Esytec GmbH Company in Erlangen in a special injection chamber set up for injector research. These measurements of the spray properties were carried out for different injection pressures in the pressurized chamber and for different temperatures of the injected fuel. Of the many series of measurements carried out, selected measurements obtained for 200 bar injection pressure at a fuel temperature of 60 °C, a chamber pressure of 15 bar and a chamber temperature of 155 °C are presented in ❽.

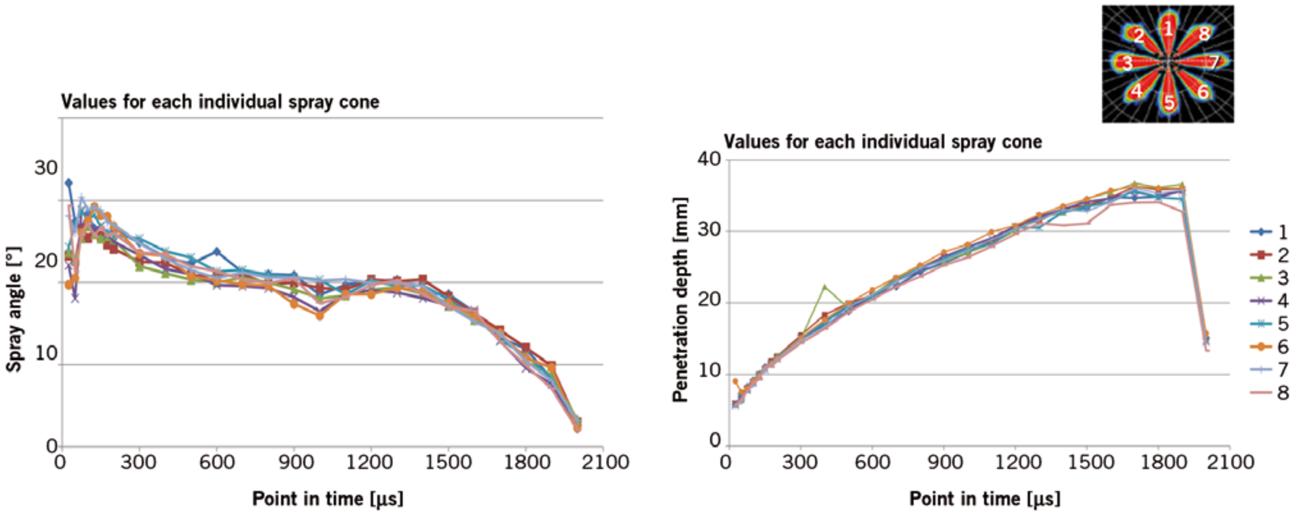
The presented results for the spray formation of the first 10 and 40 manufactured multiple twin-jet nozzles with eight nozzle pairs show a highly homogeneous dispersion with only minor variations in the spray patterns of the individual nozzle pairs. This uniformity of the spray formation of all twin spray cylinders could also be confirmed by measurements of the spray dispersion without counter pressure and at low chamber and fuel temperatures. In all measurements, uniform spray dispersion was evident. At high fuel and chamber temperatures homogeneous and rapid vaporisation behaviour of the spray was evidenced. This uniformity of the spray characteristics is shown in ❾. The high correlation of the measured penetration depth and the angle of the jets of the individual twin jets is worth emphasising here.

In addition to a uniform and large-area spray distribution in the combustion chamber, it is possible with the multiple arrangements of twin-jet nozzle, to produce droplets with a Sauter diameter of less than 10 µm for gasoline fuels. The developments have enabled a spray mechanism to be used that differs substantially from nowadays employed mechanisms, and moreover offers advantages with respect to the theoretical treatment of the resulting spray. Using the known properties of the spray, observations on vaporisation processes can be gathered, and, building up on the present work, calculations for the actual combustion can be achieved. Combustion engines became more theoretically treatable.

CONCLUSIONS AND OUTLOOK

This publication summarises work carried out to develop twin-jet-spray injectors for gasoline engines and to produce them in small batches as prototypes. The spray generation mechanism underlying twin-jet sprays differs significantly from that used with round-hole injector nozzles. The mechanism used with twin-jet spray injectors is theoretically treatable. It leads, with an appropriately selected nozzle diameter, to droplet size distributions with Sauter diameters under 10 µm for gasoline fuels, and in addition allows adjustable spray angles, thus allowing highly flexible spray patterns to be obtained with multiple twin-jet nozzles. The number and arrangement of the individual pairs of nozzles and their placements in the


❽ Temporal sequence of spray from the experiments in the Esytec injection chamber



❾ Measured properties of twin-jet sprays portraying the equivalence of the spray properties of the individual sprays (fuel: 200 bar, 60 °C; Combustion chamber: 15 bar, 150 °C)

respective combustion chambers as well as their adaptation to the combustion process allow requirements that can be simple and can be based on theory. A special flat spray contour, for example, makes it possible selectively to omit emission-critical areas in the combustion chamber. Wetting the open intake valves during the injection in the intake stroke can be avoided, and having a gap in the spray avoids direct wetting of the spark plug by the fuel. The number of pairs of nozzles can be adapted to the mass flow required by the engine manufacturer or the injection jets tilted as desired relative to the injection valve axis. This increases the flexibility of installation without sacrificing the performance of the motor. The developed injectors appear to allow novel combustion process to be realised for gasoline engines, with reduced emissions, reduced noise and without sacrificing performance.

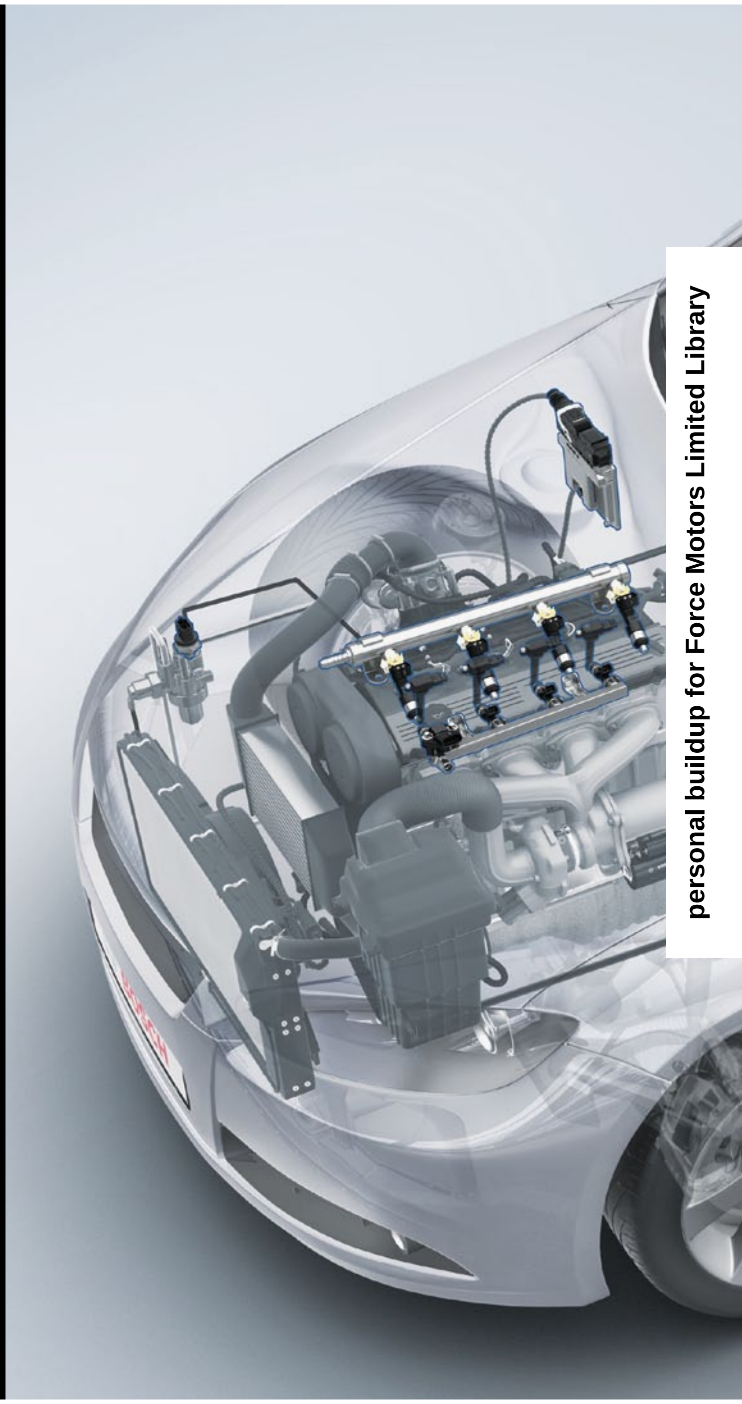
The results of the developments suggest that future injector systems for gasoline motors can be operated with injection pressures in the range of 70 to 80 bar for gasoline engines. This reduction in pressure lead to reductions in energy expenditure for injector systems, to reductions in system costs and are also associated with better control of the entire injection process. Appropriate fuel pumps can be developed or existing pumps adapted. Improving combustion in gasoline engines requires improvements of fuel injectors with regard to the pressure waves generated during opening and closing. This has also been achieved. The description of these developments and results is reserved for a future publication.

REFERENCES

[1] Ohnesorge, W.: Formation of Drops by Nozzles and the Breakup of Liquid Jets. In: Angew. Math. Mech. (1936), No. 16, pp. 355-258
[2] Reitz, R. D.: Atomization and Other Breakup Regimes of a Liquid Jet. Princeton University, Ph.D. thesis, 1987
[3] Dombrowski, N.; Johns, W. R.: The Aerodynamic Instability and Disintegration of Viscous Liquid Sheets. In: Chem. Eng. Sci. (1963), No. 18, pp. 203-214
[4] Dombrowski, N.; Hooper, P.C.: A study of the sprays formed by impinging jets in laminar and turbulent flow. In: Journal of Fluid Mechanics (1964), No. 18, pp. 392-400
[5] Couto, H. S.; Bastos-Netto, D.; Mugueis, C.E.: Modeling of the Initial Droplet Size Distribution Function in the Spray Formed by Impinging Jets. INPE-Brazilian Space Research Institute Cachoeira Paulista, 12630, Sao Paulo, Brazil, 1991
[6] Han, Y.: Private Communications. FMP Technology GmbH, Erlangen, July 2011

THANKS

The work described in this publication was supported by L. Schilling and D. Haspel from the FMP Technology GmbH and also by Mr Handtmann and Mr Wanner of Handtmann Systemtechnik GmbH & Co. KG. The developments have been funded by the companies KW Technologie GmbH & Co. KG, FMP Technology GmbH und Geiger Fertigungstechnologie GmbH as well as by a sponsored project of the Bundesministeriums für Wirtschaft und Technologie (ZIM-Projekt) (Federal Ministry of Economics and Technology). Our special thanks to Mr Y. Han of FAU Erlangen-Nuremberg for repeating some of the measurements to confirm the data.



FUTURE ENGINE CONTROL FOR SPARK-IGNITED CNG ENGINES

CNG as a fuel for internal combustion engines is a good alternative to conventional liquid fuels to reduce CO_2 emissions. Bosch offers an injection system for CNG which can be modularly combined with gasoline port fuel injection or direct injection. In the following an overview on the requirements and solutions for the system and the components as well as a global CNG market overview is presented.

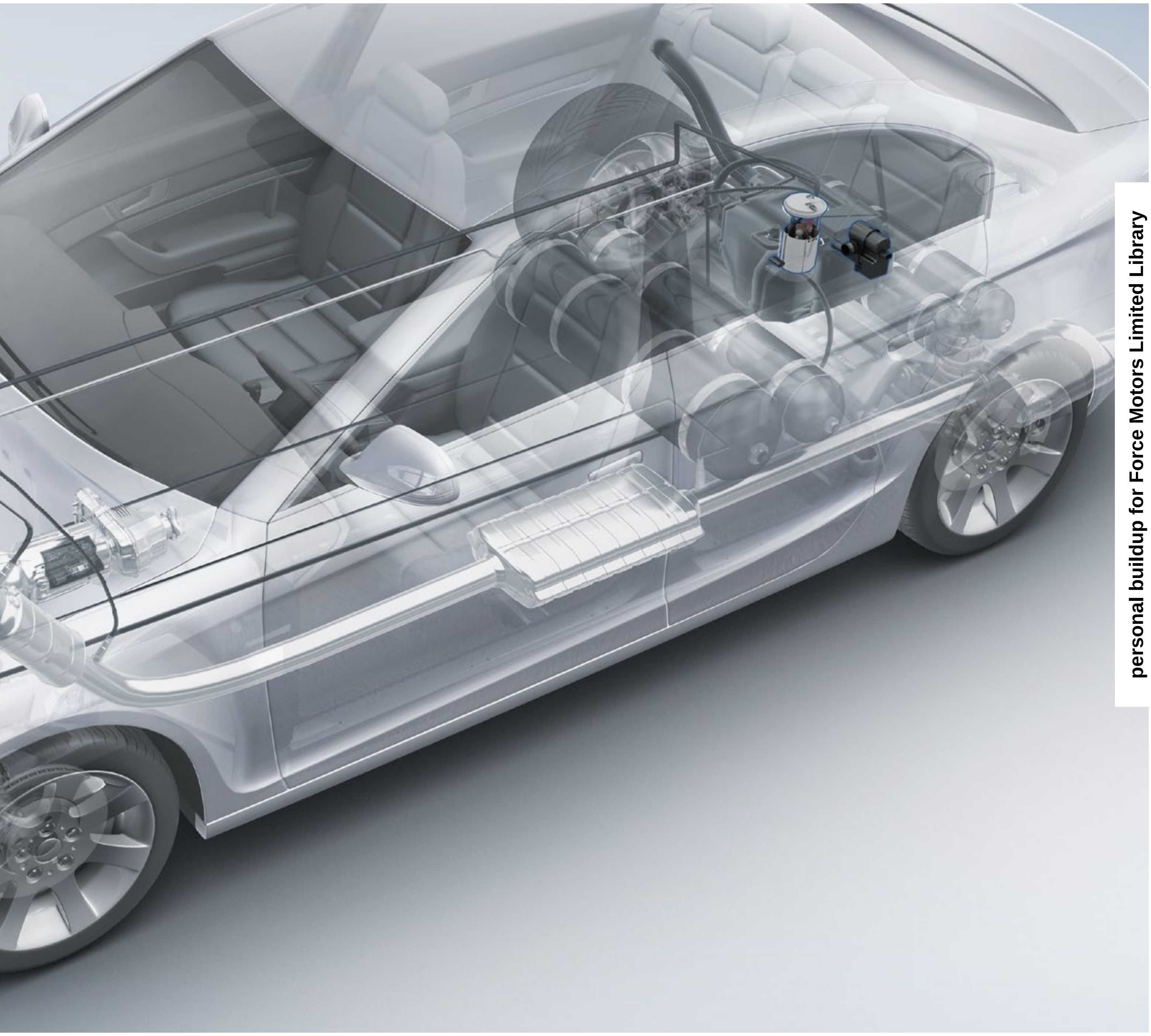
AUTHORS

DIPL.-ING. ROLAND HERYNEK
is Director System Engineering Platform in the Division Gasoline Systems at Robert Bosch GmbH in Stuttgart (Germany).

DIPL.-KAUFMANN HEIKO KAISER
is Senior Expert Product Management and Marketing Gas Technology in the Division Gasoline Systems at Robert Bosch GmbH in Stuttgart (Germany).

DR. RER. NAT. WINFRIED LANGER
is Senior Expert Head of Sub-System Gas in the Division Gasoline Systems at Robert Bosch GmbH in Stuttgart (Germany).

DIPL.-ING. (FH) FRANK MILLER
is Project Leader Customer Projects NGI2 in the Division Gasoline Systems at Robert Bosch GmbH in Stuttgart (Germany).

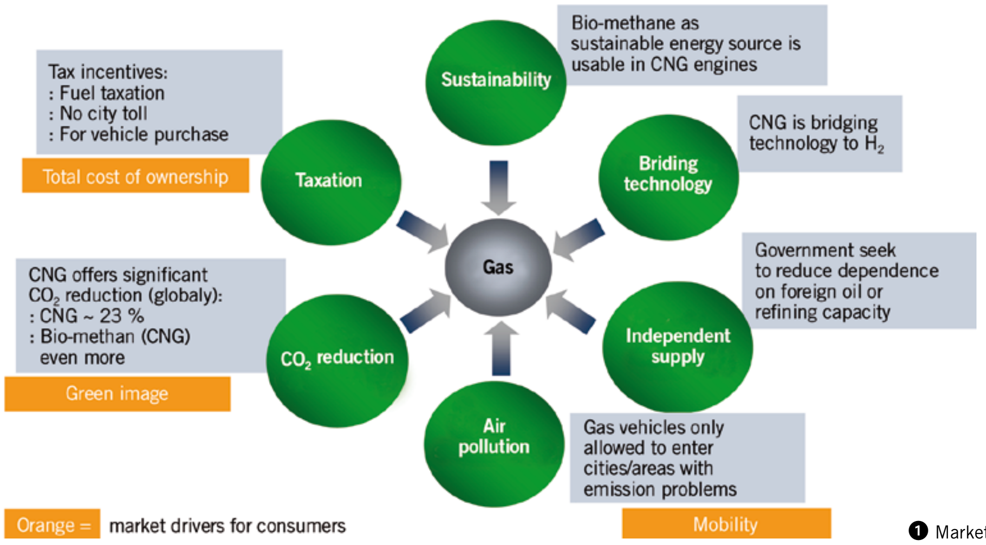


MARKET SITUATION, DRIVERS AND CHANCES

The market for CNG vehicles is growing rapidly worldwide. The CNG car fleet grew from approximately 1 million vehicles in 2000 to more than 12 million vehicles in 2010. This represents an annual growth rate (CAGR) of approximately 25 %. The major share of this growth took place in retrofit markets with focus on South America, Asia and Persia. Bosch is expecting that the CNG car market will grow further. Most important growth markets will be in Asia. But: overall CNG will remain a niche market. So, what is driving the CNG market? CNG offers a CO_2 reduction potential of about 25 % compared to gasoline. This reduction can be increased even further by the use of Bio CNG. In case the CNG is made from regeneratively produced electricity, the combustion engine can be powered CO_2 neutral. The drivers mentioned in ❶ can be summarised to a few major drivers:

: total cost of ownership and mobility for the end user
: independent supply and emission and CO_2 reduction for the law maker.

The market can be divided into three major segments: pure retrofit markets, markets moving towards OEM standard and classical OEM markets. In pure retrofit markets (more than 60 % of the global CNG fleet) a low price is the most important criterion. The requirements on technology and reliability of CNG components and systems are quite low. In markets moving towards OEM standard (approximately 30 % of the global CNG fleet) retrofit solutions, partly also used in OEM applications, are seen as state of the art. But OEMs are working more and more



❶ Market drivers CNG

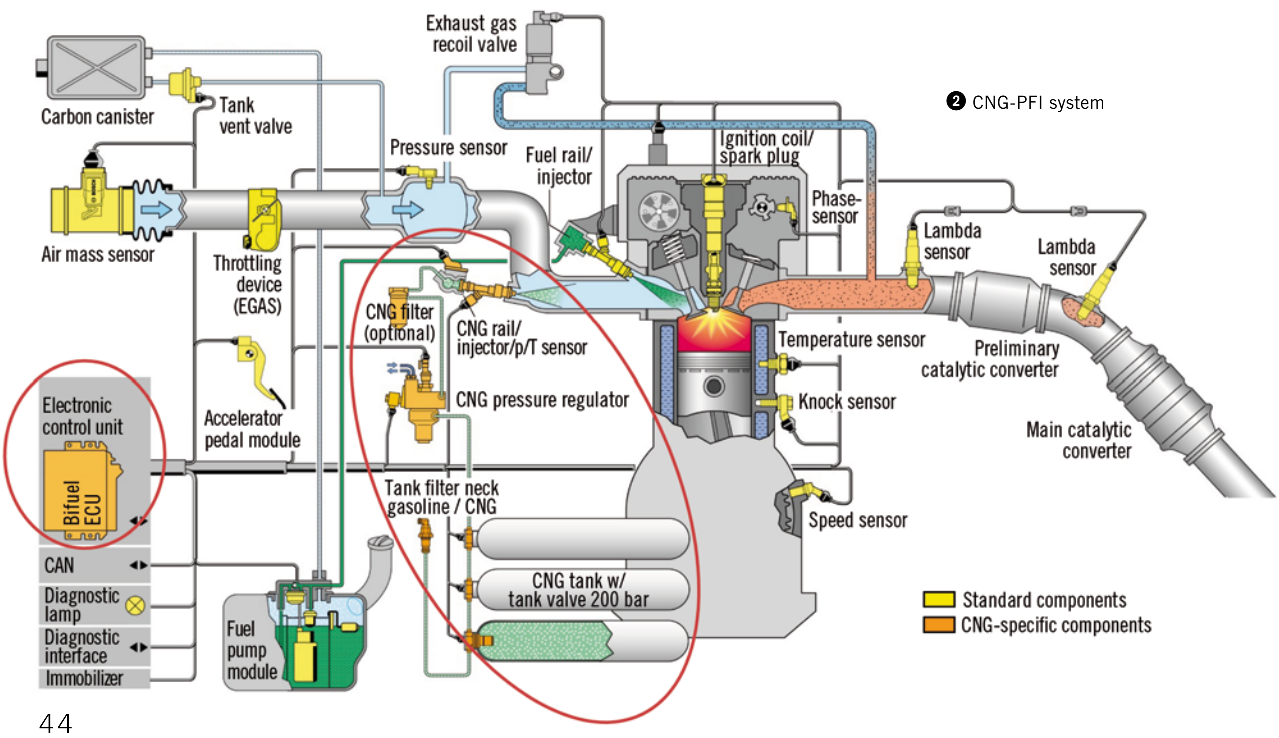
towards technical solutions which are in line with global OEM standards. In classical OEM markets (less than 10 % of the global CNG fleet) OEM technology is standard driven by the general high level of the whole automotive sector. The requirements on quality, robustness and durability of the CNG systems and components are high. Technology and performance are keys to market success.

Bosch has developed a CNG portfolio on an OEM level, which can be marketed via different sales channels. Bosch can offer harmonised systems and components for the heavy duty market, the passenger car segment and the retrofit market. This approach is key to be successful on a long term basis because the single niche markets cannot offer the necessary economies of scale.

CNG SYSTEMS

To realise bifuel systems, conventional gasoline engines are modified for CNG operation and enhanced by an additional CNG fuel system. For a flexible structure Bosch has developed a CNG-PFI injection system, which can be modularly integrated in existing gasoline port fuel injection or direct injection engines and it is also applicable to CNG monofuel systems, ❷ and ❸.

Gasoline direct injection engines usually have a higher compression ratio and could thereby use the advantage of methane's high knock resistance. By operating at an optimal ignition angle the improved level of efficiency leads to lower exhaust temperatures. Thereby additionally a stoichiometric mixture is possible. As a result there is a distinctly



❷ CNG-PFI system

decreased CNG consumption and CO_2 emissions when operating at full load.

During the CNG operation the fuel components of the gasoline system are only passive. The missing cooling effect of the flushing gasoline leads to higher temperature of direct injection valves and high-pressure pump. Because of the reactivity of the engine environment concerning the components, the temperature conditions have to be evaluated specifically for the particular customer project. If necessary, measures for decreasing the temperature have to be implemented.

SYSTEM REQUIREMENTS TIGHTNESS OF INJECTION VALVES

In contrast to gasoline systems the CNG does not decrease due to contraction of the fuel volume as the engine cools; thereby the pressure at the injection valve is present also if the vehicle is parked. In a system without leakage-optimised injectors the gas mass of the rail is escaping into the intake manifold. For example a mass of 70 mg HC is to be expected at a system pressure of 0.3 MPa and a rail volume of 50 cm^3. Based on the undefined fuel quantity the air-fuel mixture is to rich in the starting phase and will not be ignitable. This will lead to a delayed start and to an increase of HC emissions. Hence it is mandatory to use special injection valves without internal leakage for CNG applications. Thereby the vehicle starts immediately and has no initial HC emissions by leakage.

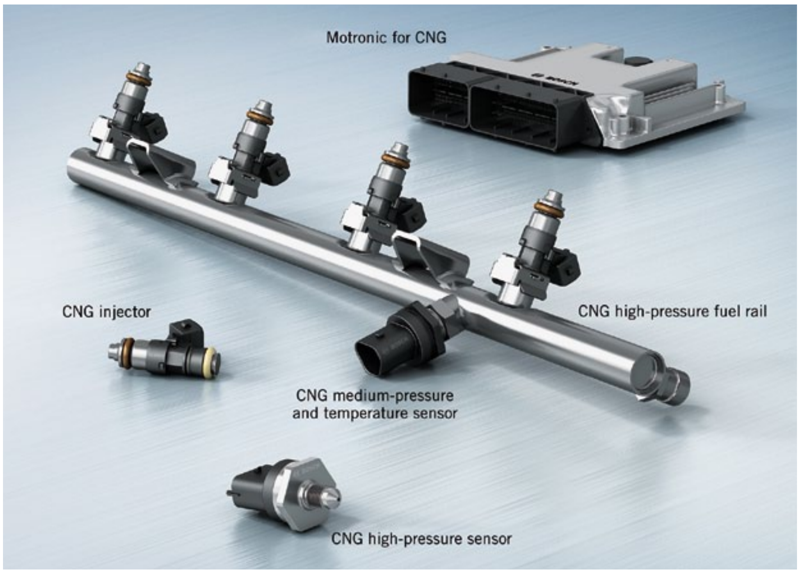
CNG DIRECT INJECTION

Corresponding to gasoline direct injection engines there is also the possibility of CNG direct injection (CNG-DI). When injecting the fuel after closing the inlet valve there is no air filling reduction by the CNG partial pressure of approximately 10 % compared to manifold injection. To realise a CNG-DI system it is required to develop a special direct injection valve, which also can be run with oil-free CNG. Additionally fulfilling the tightness requirements at the valve located in the temperature range of the combustion chamber is challenging. The low benefits of CNG-DI have to be compared to high costs and risks referring to a small market size. Furthermore, the disadvantage of filling by partial pressure can be compensated more easily and more cost-effectively by available components of air charging.

CNG direct injection is no option for series production due of its high development effort and risk combined with a small market volume. Thereby CNG-PFI systems offer a very good cost-benefit ratio at maximum variability of the base engine. The cost-effective alternative of pure CNG port fuel injection achieves CO_2 savings of around 25 % and with the downsizing alternative of gasoline DI up to 40 %, ❹. The benefits of CNG-fuel due to knock resistance and gaseous state can be utilised completely in CNG-PFI systems.

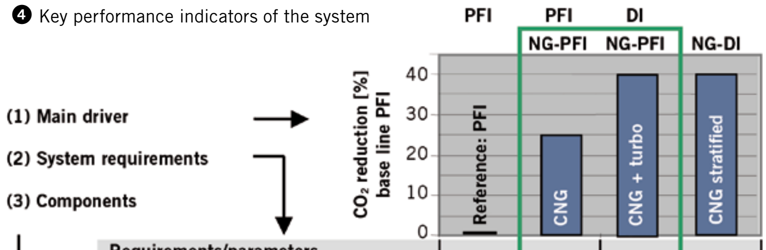
BIFUEL ECU

By integrating the functionality of CNG into a bifuel engine control unit (ECU), the related control, adaption and diagnostic functions of the base engine can be adapted easily. Thereby the development of an interface for communication with a separate CNG control unit is not necessary. The functionalities and diagnoses of the gasoline engine control unit



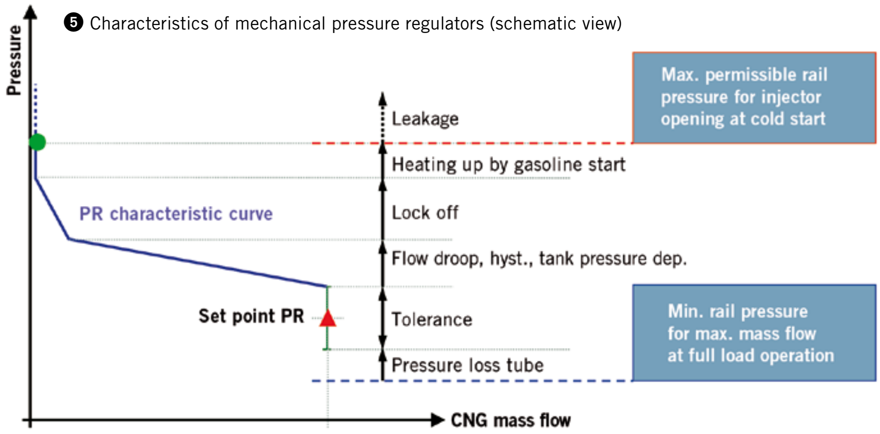
❸ Components of the CNG-PFI injection system from Bosch

❹ Key performance indicators of the system



Requirements/parameters	PFI	PFI NG-PFI	DI NG-PFI	NG-DI
Power	+	–	++	+
CNG start		+	+	+
System costs	++	++	+	–
Automotive robustness and diagnosis	+	+	+	Dev.
Series components availability	+	+	+	–
CO_2 reduction		+	++	++
Range	++	+	+	–
Emissionen Euro 5/6	+	+	+	Dev.
ECU bifuel				
CNG injector				
CNG tank pressure sensor				
CNG rail pressure sensor				
Gasoline high-pressure injector				
Gasoline high-pressure pump				

❺ Characteristics of mechanical pressure regulators (schematic view)



are especially designed for gasoline operation. For example the gasoline ECU needs to take notice of the modified air fuel mixture by the second CNG ECU to ensure that the feedback of the exhaust sensing is correctly evaluated for catalyst control and diagnosis. Missing adjustments in control functions of the gasoline engine can lead to a negative impact on function, emissions and diagnosis.

Future engine control units will include options for CNG operations to achieve emission limits during CNG operation. Bosch therefore has developed a bifuel engine control module to reach a maximum of functionality and reliability.

PRESSURE REGULATOR MODULE

The pressure regulator has to reduce the pressure from tank pressure to the nominal operating rail pressure of the CNG injectors. Basically the rail pressure at full power of the engine has to be high enough, that the necessary gas-flow can be injected during the available injection time.

Electrical pressure regulators are considered to be the best solution especially for engines with a wide power range. Hereby it is possible to set low pressure for idling and maximum pressure for full power operation. However, mechanical pressure regulators with characteristics like in ❺ are used mainly at the time. The adjusting point of the pressure regulator should be the maximum massflow of the engine which is required in worst case conditions of tank pressure, quality of CNG and temperature.

A pressure increase of 0.15 MPa from design point to stoppage pressure is state of the art. This is caused by pressure drop in the lines, the pressure regulating characteristic, tolerances and pressure increase in inactive situations (Lock off). Thereby internal leakage must not lead to a noticeable pressure increase during a long inactive periods. The characteristics of the pressure regulator has to be considered in the system application to ensure that the injection valves are working properly in starting operations even if low battery voltage and maximum pressure occurs.

CNG INJECTOR

Since 2006 the new generation of Bosch CNG injectors named NGI2 has been used both with monofuel and bifuel applications worldwide. In comparison to other CNG injectors, the NGI2 is extremely lightweight and compact. This means that integration into existing intake manifolds is possible. Furthermore current and future emission standards can be fulfilled.

The high-resistance magnetic solenoid of the NGI2 enables the injector control at present standards for fuel intake manifolds for injection valves. Additional costs for current power control levels (peak and hold) and the integration into the control unit respectively the use of a second control unit can be avoided. The valve was developed in consideration of the high flow stream mass flow that is reached in that compact design. The design was adjusted in that way that the pressure decreases in the valve were reduced to a minimum. The physical characteristic of the valve is approximately according like an ideal nozzle. If there is at least the double intake manifold pressure, an overcritical flow appears. Thus the fuel deliver control phase is independent of the manifold pressure and correspondingly more precise. At charged engines with an intake manifold pressure of up to 0.25 MPa, it results into a system pressure of a minimum of 0.5 MPa.

The NGI2 was developed for a technical lifetime of 240.000 km according to OEM standards. It was also verified by multiple internal and worldwide vehicle tests. It is characterised as a very robust component even at very high vibration acceleration conditions. Despite its elastomeric seat concept the NGI2 meets the demands of modern spark-ignition engines concerning accuracy of injected mass. This also applies for the minimum injection time of ≤2.0 ms at 0.7 MPa which is determined according to SAE and underlying static aspects.

COMBINED PRESSURE/ TEMPERATURE SENSOR, TANK PRESSURE SENSOR

To achieve a precise injected CNG mass the injection time has to be corrected by the CNG density based on pressure and temperature. Usually two separate sensors are used for this purpose. Bosch is offering a combined pressure and temperature sensor (DS-M1-TF-CNG) as a screw-in sensor which reduces the number of components and electrical connectors. A very high reliability concerning tightness can be reached because the stainless steel housing does not require any elastomer sealing for assembling and it provides a common interface to the silicon sensor chip. The temperature is measured via an NTC enclosed by a thin-walled stainless steel sleeve. Thereby the measurement of CNG temperature is decoupled successfully from the housing temperature even in case of small mass flow at idle condition.

The tank pressure sensor DS-HD KV4.2 is also designed as a stainless steel screw-in sensor. It is applied for detecting the tank level by mounting in the high pressure system like at the pressure regulator or at the tank valve.

CONCLUSIONS

The advantages of low CO_2 emissions, almost particle-free emissions and the possibility of adapting gasoline engines to CNG fuel with low effort, results in good chances for a stronger growth of CNG automotive market. To ensure that emission limits are achieved the ECU of the gasoline engine has to be adapted to CNG. Additional CNG ECUs require aligned interfaces and communication.

Including more than 160,000 technical terms for handling construction projects abroad

Klaus Lange

Elektronisches Wörterbuch Auslandsprojekte Deutsch-Englisch, Englisch-Deutsch; Electronic Dictionary of Projects Abroad English-German, German-English

Vertrag, Planung und Ausführung; Contracting, Planning, Design and Execution

2010. EUR 169,95

ISBN 978-3-8348-0883-7

The electronic technical dictionary „Projects Abroad“ is indispensable for all those communicating and negotiating with contractors, clients or engineers in English in the context of construction projects abroad.

With some 84,000 English-German and 76,000 German-English entries it is one of the most comprehensive reference works on the market, covering engineering, operations and legislation in the construction sector - a reliable companion to help you successfully handle construction projects abroad.

The UniLex Pro user interface includes many search features including a pop-up search option that automatically displays translations in a pop-up window - regardless of the program being used at the time.

System requirements:

- Windows 7, XP
- Available hard disk space: min. 200 MB
- Core memory: min. 512 MB
- CD-ROM drive

About the Author

He has worked together with international partners to offer numerous seminars preparing students for construction projects abroad.

Yes, please send me

Fax +49(0)6221 / 345 – 4229

___ Copies
Elektronisches Wörterbuch Auslandsprojekte Deutsch-Englisch, Englisch-Deutsch; Electronic Dictionary of Projects Abroad English-German, German-English
ISBN 978-3-8348-0883-7
EUR 169.95

Company | Surname, First Name

Department

Street (no P.O. boxes, please) | Postal Code | City

Date | Signature

Springer Vieweg

Ordering is easy at: SpringerDE-service@springer.com Phone +49 (0)6221 / 345 – 4301

VIRTUAL DEVELOPMENT OF CONTROL UNIT FUNCTIONS FOR FULLY VARIABLE VALVE TIMING

Model-based testing of real electronic control units on hardware-in-the-loop simulators has become an established standard method for function development of combustion engines. Using a control for a continuously variable valve lift as an example, this article from dSpace describes a completely integrated development procedure covering everything from model-based controller design, including early validation on developers' own PCs, to electronic control unit tests on a hardware-in-the-loop simulator.

AUTHORS

DIPL.-ING. TINO SCHULZE
is Product Manager at
dSpace GmbH in Paderborn
(Germany).

DR. RER. NAT. KARSTEN KRÜGEL
is Product Manager at
dSpace GmbH in Paderborn
(Germany).

DIPL.-ING. (FH) SONJA LILLWITZ
is Project Manager in Marketing
Communications at dSpace GmbH in
Paderborn (Germany).

INTEGRATED DEVELOPMENT PROCEDURE

Tougher requirements on fuel consumption and the introduction of stricter emission regulations are necessitating new systems and controls for combustion engines. For example, new control concepts for spark-ignition engines promise similar high potential fuel savings to those provided by diesel engines. The new concepts include new combustion processes such as HCCI, variable valve control timing, and variable valve lift, in which continuously variable valve lift replaces classic charge control by a throttle valve. However, the new freedom to control valve opening and closing times and valve lift involves extra work when developing and calibrating engine control functions.

Today's function development projects for combustion engine electronic control units (ECUs) are complex software projects in which the functions are frequently put into operation in real engines or real vehicles. Model-based testing of real ECUs on hardware-in-the-loop (HiL) simulators has become an established standard method for this. With the help of suitable simulation models, real-time processor systems and I/O functions, the real ECUs are operated with a HiL simulator in such a way that the ECU concerned detects no difference between a real engine and a simulated one. Automated HiL tests greatly enhance the testing depth, thereby improving the quality of control functions.

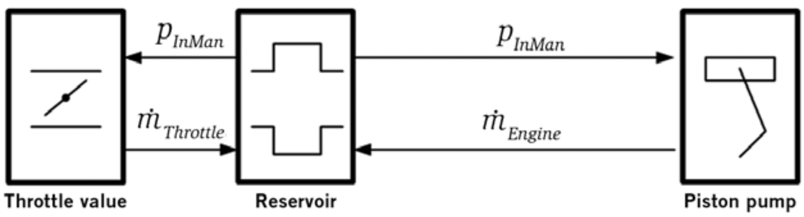
Using a control for a continuously variable valve lift as an example, this article describes a completely integrated development procedure covering everything from model-based controller design, including early validation on developers' own PCs, to ECU tests on a HiL simulator. Two basic aspects are dealt with. One is that complex simulation models are required for combustion engines. The models must provide the physical effects needed for controller design and be usable in both PC-based and HiL simulation. The other is that to access such a design environment, development teams require software tools that make the complexity of the models for the controlled system and the controller manageable. These software tools have existed for test bench operation, HiL simulators and ECU access for many years. To make the model-based development process truly seamless and efficient, it must be possible to use the same tools and simulation models in all phases of the development process, including PC-based simulation for function design.

COMPLEXITY OF THE SIMULATION MODEL

With variable valve trains, i.e., with variable opening times and/or variable valve lift, the gas mix quantity in an SI engine can be adjusted for the entire load/engine speed map without using a throttle. The charge cycle work, and therefore also fuel consumption, can be reduced because the mix can be drawn in across the entire operating range in unthrottled conditions. The classic mean-value engine models typically used on HiL test benches come up against their limits in simulations of continuously variable valve lift. This is because the pressure in the air intake system is represented by the interaction between a model of the throttle valve and a simple model of the cylinder as a piston pump, ❶.

The effect of variable intake and exhaust valves can therefore be represented only by additional efficiency functions. Because the effect of variable valve opening times and valve lifts in an engine simulation model would otherwise be missing, the existing models have to be extended by detailed

❶ Mean-value model



cylinder simulation with intake and exhaust valves [1].

IN-CYLINDER PRESSURE-BASED ENGINE SIMULATION

Representing an integrated, model-based development process requires dynamic models of the controlled system that can account for the relevant engine effects with sufficient precision. The dSpace Automotive Simulation Models (ASMs) provide an in-cylinder pressure-based engine model that uses the first law of thermodynamics to compute the temperature and the pressure inside the cylinder. The gas exchange can be computed by the valve models using the pressure difference between the cylinder and the intake or exhaust manifold.

This modelling approach covers all the effects needed to represent continuously variable valve lift. Two aspects of the engine must be modeled more accurately than with the previous mean-value models: First, the intake and exhaust valves must be modeled as a valve with isentropic flow and with a variable cross-sectional area in a way comparable to throttle valve modelling, ❷. The characteristic curve of the flow through the intake and exhaust valves is given by the cross-sectional area. It is calculated from a reference area in the valve channel and the discharge coefficient μ, resulting in the following model equation:

EQ. 1

$$\dot{m}_{Engine} = \sum_{i=1}^{Number\ of\ Cylinder} A_{InValve,i}\ \mu\,(l_{InValve,i})\ \frac{p_{InValve,i}}{\sqrt{R_{InValve,i}\ T_{Invalve,i+}}}\ \Psi\left(\frac{p_{Cylinder,i}}{p_{Inman}}\right)$$

The discharge coefficient depends on the valve lift and the direction of flow. Valve control times can easily be simulated by changing the camshaft position and valve lift. Second, the model of the combustion chamber must also be formulated in greater detail. The temperature in the combustion chamber is calculated according to the first law of thermodynamics. The pressure is then derived from the temperature via the ideal gas law:

EQ. 2

$$dT_{Cyl} = \frac{1}{m_{Cyl}\ c_{v,Cyl}}\,(dW_{Cyl} - dQ_{Wall,Cyl} + dQ_{Fuel} + dH_{IntakeValve} + dH_{Inj} - dH_{ExhaustValve} - \sum_i dm_{i,Cyl}\ u_{i,Cyl})$$

The energy flows that are taken into account are shown in [2]. The mass calculation is performed separately for each component (fuel, air, exhaust gas) and is based on continuous integration of the mass flow. This means, for example, that any internal exhaust gas recirculation is automatically included.

SIMULATION RESULTS

With the modelling approach described, continuously variable valve lift can be represented without much additional modelling work. The only requirement is a model that describes the mechanics of the valves and calculates the current opening cross-section of the intake and exhaust valves in each time step. The cylinder charge and therefore the air mass flow through the engine are then calculated in the physical equations.

The advantage of this kind of modelling is that all the degrees of freedom in controlling the air mass are included implicitly without having to change the structure of the model by introducing new look-up tables and so on.

In ❸, the charge cycle loops of an in-cylinder pressure model were calculated for three different valve positions. The same load/engine speed point was set each time, but different control strategies were used. The model's plausible simulation behaviour is clearly shown. With this type of modelling approach, the relevant effects in a combustion engine can be represented with a precision and simulation speed that allows seamlessly integrated model-based function design on a PC and in real time.

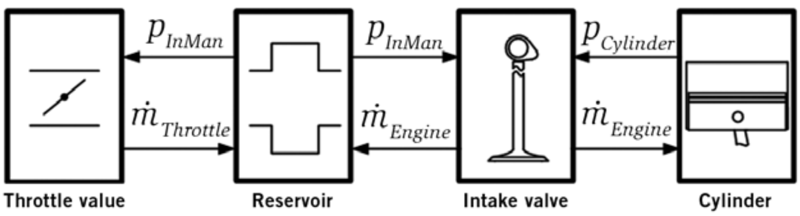
IMPROVED VISUALISATION

Because the models of functions and controlled systems used in developing engine controls are becoming ever more complex, there is an increasing need to improve the visualisation of simulation variables and parameters. The so-called Control Desk Next Generation was launched by dSpace in 2011 as a new experiment tool that can be used throughout the entire ECU development and validation process, and that is just as useful for function models or virtual ECUs on a PC as it is for real ECUs on a HiL simulator or test bench. Control Desk Next Generation lets developers generate photorealistic layouts that they can experiment interactively with during an ongoing offline simulation on a PC or a real-time simulation on a HiL simulator. In both these scenarios, the variables and the calibration values of the controller and of the controlled system can be accessed during simulation, so they can be integrated effortlessly into an automation or optimisation process. ❹ shows such a layout for the coupled simulation of a function model and an in-cylinder pressure-based engine model.

The ability to take an experiment tool from the HiL field and also use it in early phases of the development process makes interdisciplinary cooperation between function developers and HiL test engineers much smoother. Another advantage is that when performing early validation of control functions, developers can call on the large collection of layouts and tests that previously underwent long and successful use on a HiL system.

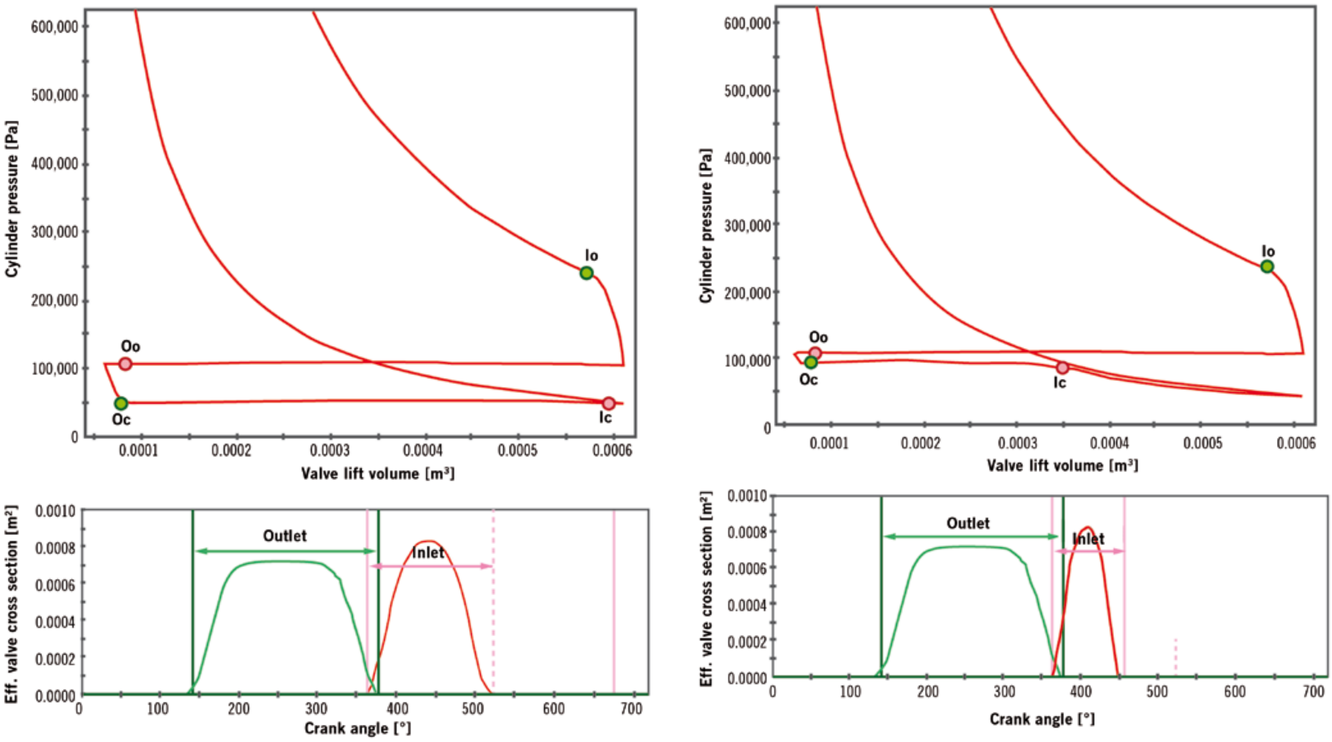
OFFLINE SIMULATION

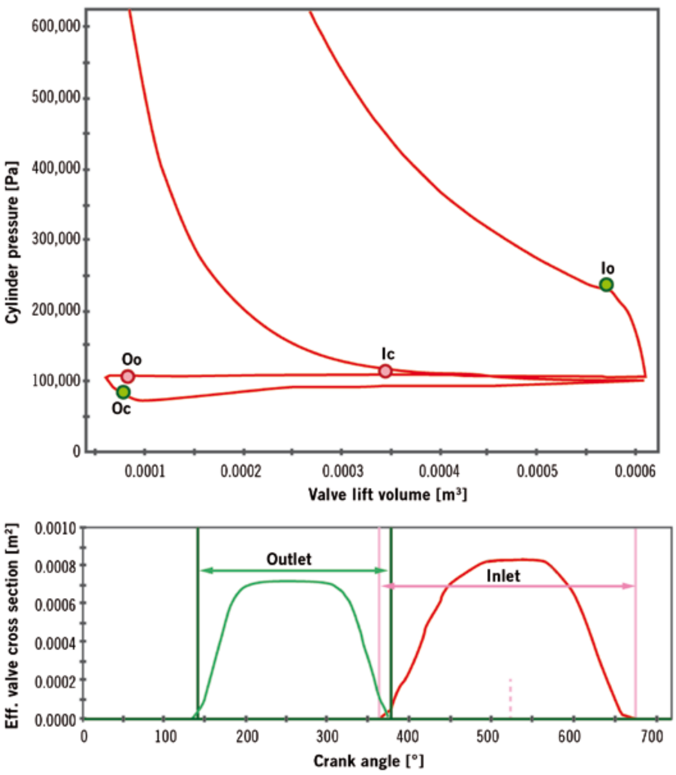
Ideally, PC computation uses simulation technology that can handle the same tools, models, transmission protocols



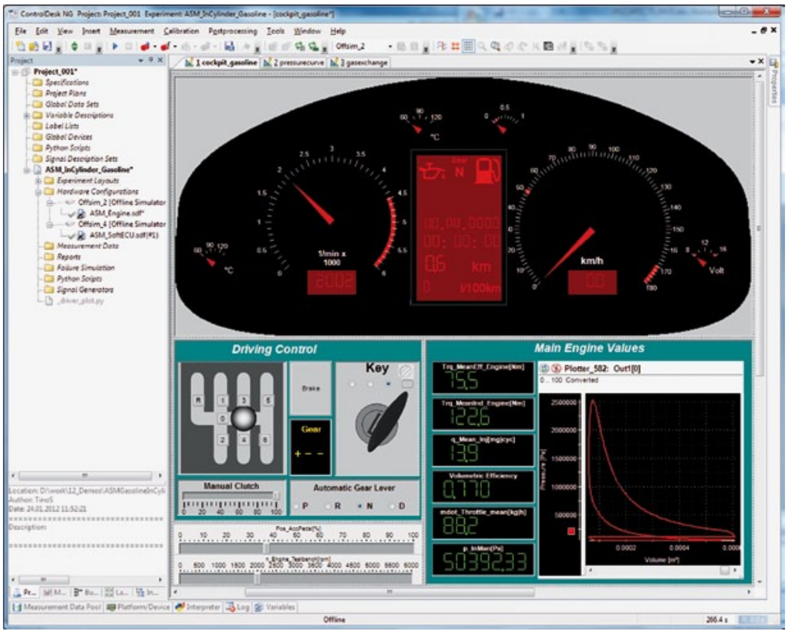
❷ In-cylinder pressure model

and variable descriptions that have long since become standard methods in the real-time world. Since the beginning of 2012, dSpace offers a simulation environment that provides precisely this seamless integration between PC offline simulations and real-time simulations on a HiL simulator, ❺. Even though function developers need complex engine models to design controllers, they are not necessarily experts in creating and parameterising such models. They therefore welcome the ability to use special models that test engineers already validated in numerous test runs on a HiL simulator. This is where function developers benefit from the dSpace system called Offline Simulator, because it saves them from

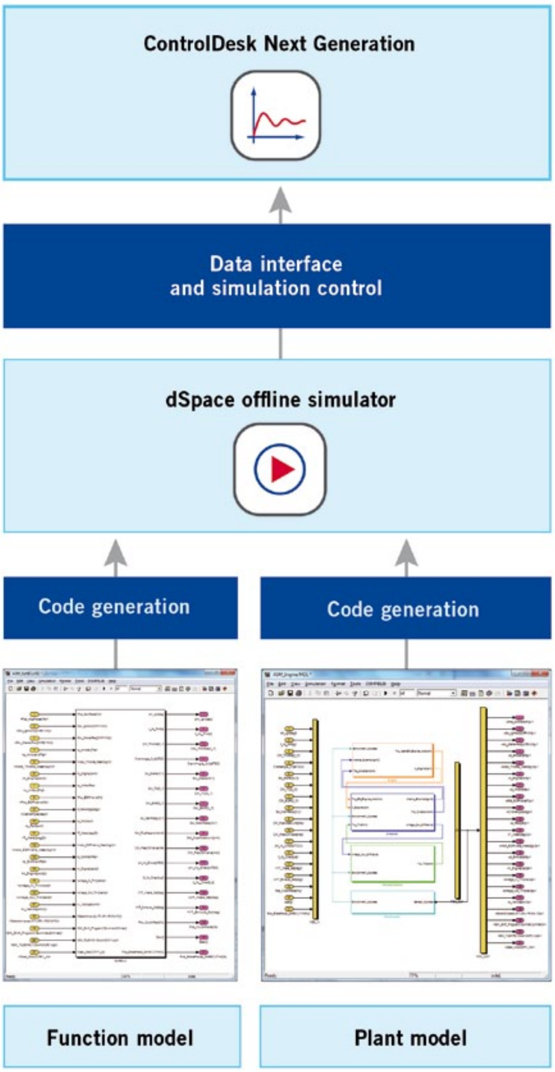




❸ Simulated pressure behaviour of an SI engine with continuously variable valve lift for different valve opening times and throttle valve controls (top left: air mass flow controlled by throttle valve; top right: throttle valve completely open, early intake valve closing; bottom left: throttle valve completely open, late intake valve closing)



❹ Layout for an offline engine simulation including a representation of a p-V diagram



❺ Workflow for an offline simulation

having to squeeze a system controlled by someone else into their function models. Instead, they can keep the controlled system model cleanly separated from the programme Simulink and link it to predefined interfaces.

CONCLUSION

Using the example of continuously variable valve lift, it was shown that all the means are available to represent a seamlessly integrated, model-based development process for complex control functions. In-cylinder pressure-based engine models provide the necessary complexity to represent the physical relations that controller development has to handle. Their computing speed is optimised for real-time execution. When they are combined with experiment tools and simulation platforms that can also be used in PC-based development, the same models, experiment user interfaces and test instructions can be used in all the steps from controller design to hardware-in-the-loop testing, and can therefore also be created and maintained at a central point. Now the first test drives with new functions can be performed purely virtually before being going onto the actual test bench or into the vehicle. By introducing physically based, real-time-capable engine models combined with proven experiment tools and an integrated simulation platform concept covering all phases from the offline to the HiL world, it is possible to achieve a more tightly integrated model-based development process and greater efficiency throughout development.

REFERENCES

[1] Schulze, T.; Wiedemeier, M.; Püschl, T.: Echtzeitfähige zylinderinnendruckbasierte Verbrennungsmotormodelle für die Entwicklung vollvariabler Ventiltriebe. Conference Autoreg, 2011
[2] Schulze, T.; Wiedemeier, M.; Schuette, H.: Crank-Angle-Based Diesel Engine Modeling for Hardware-in-the-Loop Applications with In-Cylinder Pressure Sensors. SAE Technical Paper No. 2007-01-1303, 2007

MTZ

WORLDWIDE

www.MTZonline.com

Founded 1939 by Prof. Dr.-Ing. E. h. Heinrich Buschmann and
Dr.-Ing. E. h. Prosper L'Orange

Organ of the Fachverband Motoren und Systeme im VDMA, Verband Deutscher Maschinen- und Anlagenbau e.V., Frankfurt/Main, for the areas combustion engines and gas turbines
Organ of the Forschungsvereinigung Verbrennungskraftmaschinen e.V. (FVV)
Organ of the Wissenschaftliche Gesellschaft für Kraftfahrzeug- und Motorentechnik e.V. (WKM)
Organ of the Österreichischer Verein für Kraftfahrzeugtechnik (ÖVK)
Cooperation with the STG, Schiffbautechnische Gesellschaft e.V., Hamburg, in the area of ship drives by combustion engine

06 I 2012 _ June 2012 _ Volume 73
Springer Vieweg I Springer Fachmedien Wiesbaden GmbH
P. O. Box 15 46 · 65173 Wiesbaden · Germany I Abraham-Lincoln-Straße 46 · 65189 Wiesbaden · Germany
Amtsgericht Wiesbaden, HRB 9754, USt-IdNr. DE811148419

Managing Directors Dr. Ralf Birkelbach (Chairman), Armin Gross, Albrecht Schirmacher I **Director Corporate Publishing, Corporate Content & Ad Sales** Armin Gross
Director Marketing & Direct Sales Rolf-Günther Hobbeling I **Director Production** Christian Staral

EDITORS IN CHARGE
Dr. Johannes Liebl, Wolfgang Siebenpfeiffer

EDITORIAL STAFF

EDITOR IN CHIEF
Wolfgang Siebenpfeiffer (*temporary*)
phone +49 611 7878-349 · fax +49 611 7878-462
wolfgang.siebenpfeiffer@springer.com

VICE-EDITOR IN CHIEF
Dipl.-Ing. (FH) Richard Backhaus (rb)
phone +49 611 5045-982 · fax +49 611 5045-983
richard.backhaus@rb-communications.de

MANAGING EDITOR
Kirsten Beckmann M. A. (kb)
phone +49 611 7878-343 · fax +49 611 7878-462
kirsten.beckmann@springer.com

SECTIONS
Electrics, Electronics
Markus Schöttle (scho)
phone +49 611 7878-257 · fax +49 611 7878-462
markus.schoettle@springer.com
Production, Materials
Stefan Schlott (hlo)
phone +49 8726 9675-972
redaktion_schlott@gmx.net
Research
Dipl.-Ing. (FH) Andreas Fuchs (fu)
phone +49 6146 837-056 · fax +49 6146 837-058
fuchs@fachjournalist-fuchs.de
Martina Schraad (mas)
phone +49 611 7878-276 · fax +49 611 7878-462
martina.schraad@springer.com
Transmission
Dipl.-Ing. Michael Reichenbach (rei)
phone +49 611 7878-341 · fax +49 611 7878-462
michael.reichenbach@springer.com

PERMANENT CONTRIBUTORS
Andreas Burkert (ab), Prof. Dr.-Ing. Stefan Breuer (sb), Dipl.-Ing. Jürgen Grandel (gl), Dipl.-Ing. Ulrich Knorra (kno), Prof. Dr.-Ing. Fred Schäfer (fs), Roland Schedel (rs)

ENGLISH LANGUAGE CONSULTANT
Paul Willin (pw)

ONLINE I ELECTRONIC MEDIA
Editorial Journalist / Portal Manager Automotive
Christiane Brünglinghaus (chb)
phone +49 611 7878-136 · fax +49 611 7878-462
christiane.bruenglinghaus@springer.com
Editorial Staff
Dipl.-Ing. (FH) Caterina Schröder (cs)
phone +49 611 7878-190 · fax +49 611 7878-462
caterina.schroeder@springer.com
Katrin Pudenz M. A. (pu)
phone +49 6172 301-288 · fax +49 6172 301-299
redaktion@kpz-publishing.com

SPECIAL PROJECTS
Managing Editorial Journalist
Markus Bereszewski (mb)
phone +49 611 7878-122 · fax +49 611 7878-462
markus.bereszewski@springer.com

ASSISTANCE
Christiane Imhof
phone +49 611 7878-154 · fax +49 611 7878-462
christiane.imhof@springer.com
Marlena Strugala
phone +49 611 7878-180 · fax +49 611 7878-462
marlena.strugala@springer.com

ADDRESS
Abraham-Lincoln-Straße 46 · 65189 Wiesbaden
P. O. Box 1546 · 65173 Wiesbaden, Germany
redaktion@ATZonline.de

MARKETING I OFFPRINTS

PRODUCT MANAGEMENT AUTOMOTIVE MEDIA
Sabrina Brokopp
phone +49 611 7878-192 · fax +49 611 7878-407
sabrina.brokopp@springer.com

OFFPRINTS
Martin Leopold
phone +49 2642 907-596 · fax +49 2642 907-597
leopold@medien-kontor.de

ADVERTISING

HEAD OF SALES MANAGEMENT
Britta Dolch
phone +49 611 7878-323 · fax +49 611 7878-140
britta.dolch@best-ad-media.de

KEY ACCOUNT MANAGEMENT
Rouwen Bastian
phone +49 611 7878-399 · fax +49 611 7878-140
rouwen.bastian@best-ad-media.de

SALES MANAGEMENT
Volker Hesedenz
phone +49 611 7878-269 · fax +49 611 7878-140
volker.hesedenz@best-ad-media.de

MEDIA SALES
Frank Nagel
phone +49 611 7878-395 · fax +49 611 7878-140
frank.nagel@best-ad-media.de

DISPLAY AD MANAGER
Petra Steffen-Munsberg
phone +49 611 7878-164 · fax +49 611 7878-443
petra.steffen-munsberg@best-ad-media.de

AD PRICES
Advertising ratecard from October 2011

PRODUCTION I LAYOUT
Heiko Köllner
phone +49 611 7878-177 · fax +49 611 7878-78177
heiko.koellner@springer.com

SUBSCRIPTIONS
Springer Customer Service Center GmbH
Haberstraße 7 · 69126 Heidelberg · Germany
phone +49 6221 3454-303 · fax +49 6221 3454-229
Monday to Friday, 8 a.m. to 6 p.m.
springervieweg-service@springer.com

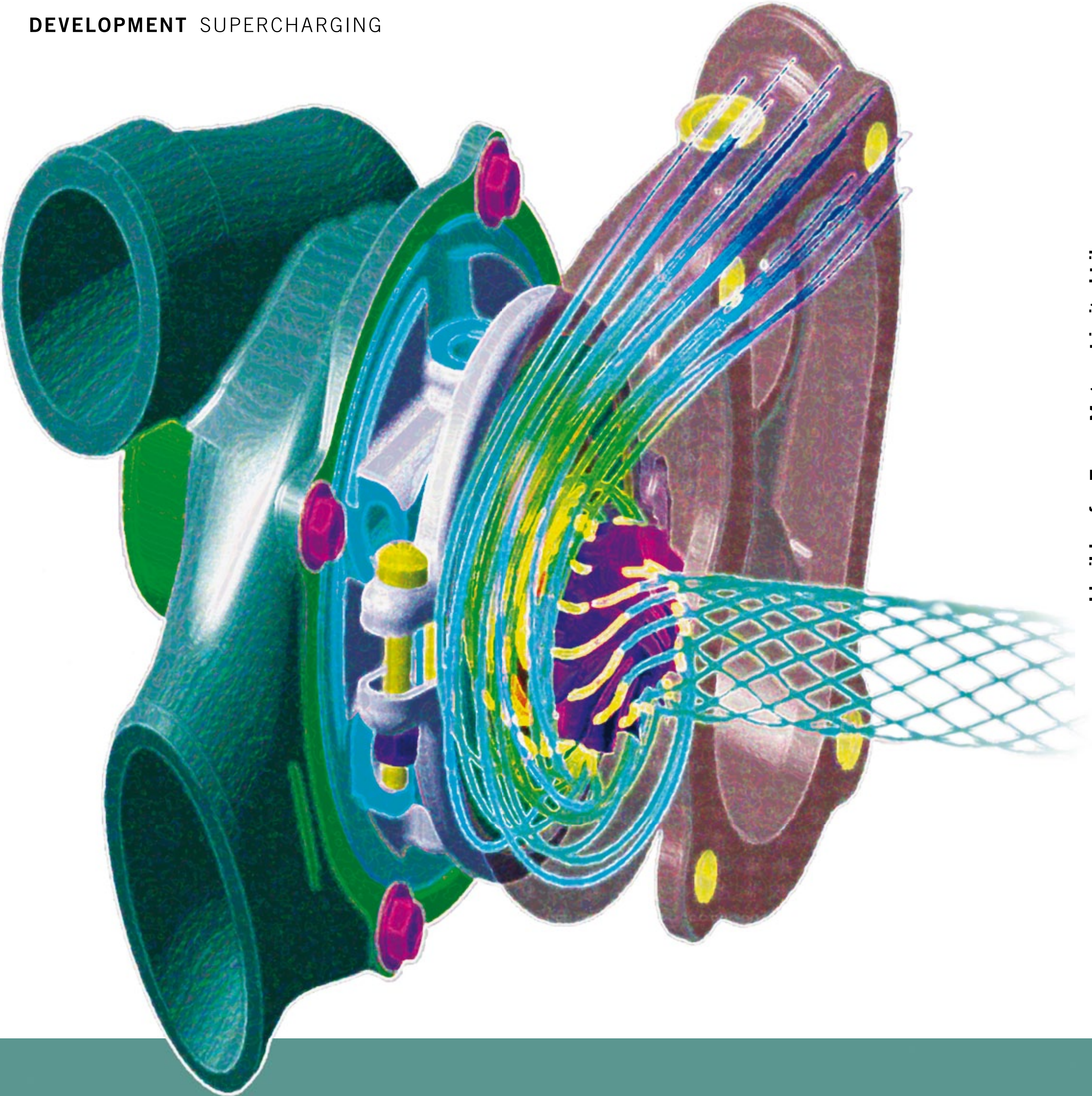
YOUR HOTLINE TO MTZ

Editorial Staff
☎ +49 611 5045982
Customer Service
☎ +49 6221 3454-303
Advertising
☎ +49 611 7878-395

SUBSCRIPTION CONDITIONS
The eMagazine appears 11 times a year at an annual subscription rate 199 € for private persons and 299 € for companies. Special rate for students on proof of status in the form of current registration certificate 98 €. Special rate for VDI/ÖVK members on proof of status in the form of current member certificate 172 €. Special rate for studying VDI members on proof of status in the form of current registration and member certificate 71 €. Annual subscription rate for combination MTZworldwide (eMagazine) and MTZ (print) 398 €. All prices include VAT at 7 %. Every subscription comes with access to the ATZonline archive. However, access is only available for the individual subscription holder. To obtain access for your entire company/library/organisation, please contact Rüdiger Schwenk (ruediger.schwenk@springer.com or phone +49 611 7878-357). The subscription can be cancelled in written form at any time with effect from the next available issue.

HINTS FOR AUTHORS
All manuscripts should be sent directly to the editors. By submitting photographs and drawings the sender releases the publishers from claims by third parties. Only works not yet published in Germany or abroad can generally be accepted for publication. The manuscripts must not be offered for publication to other journals simultaneously. In accepting the manuscript the publisher acquires the right to produce royalty-free offprints. The journal and all articles and figures are protected by copyright. Any utilisation beyond the strict limits of the copyright law without permission of the publisher is illegal. This applies particularly to duplications, translations, microfilming and storage and processing in electronic systems.

Springer Vieweg is a brand of Springer DE.
Springer DE is part of Springer Science+Business Media.



NEW TURBOCHARGER CONCEPT
FOR GASOLINE ENGINES

Honeywell has developed a new turbocharging concept for gasoline engines which uses an axial turbine. The new system increases the engine speed around 25% faster than conventional radial turbines, when accelerating from low revs. By using an existing turbine design and only conventional materials, it has been possible to keep costs low.

AUTHORS

JEFF LOTTERMAN
is Advanced Engineering Manager and responsible for the Development of Advanced Turbocharging Concepts at Honeywell Turbo Technologies in Torrance (USA).

VACLAV KARES
is Advanced Concepts Engineer and responsible for the Analytical Design of the Dual Boost System at Honeywell Turbo Technologies in Brno (Czech Republic).

DENIS JECKEL
is Light Vehicle Powertrain Director, responsible for Analysis and Assessment of Future LV Powertrains at Honeywell Turbo Technologies in Thaon-les-Vosges (France).

PAOLO DI MARTINO
is Gasoline Powertrain Manager, responsible for Analysis of LV Gasoline Powertrains and Target Setting and Assessment of Future Boosting Systems at Honeywell Turbo Technologies in Brno (Czech Republic).

MOTIVATION

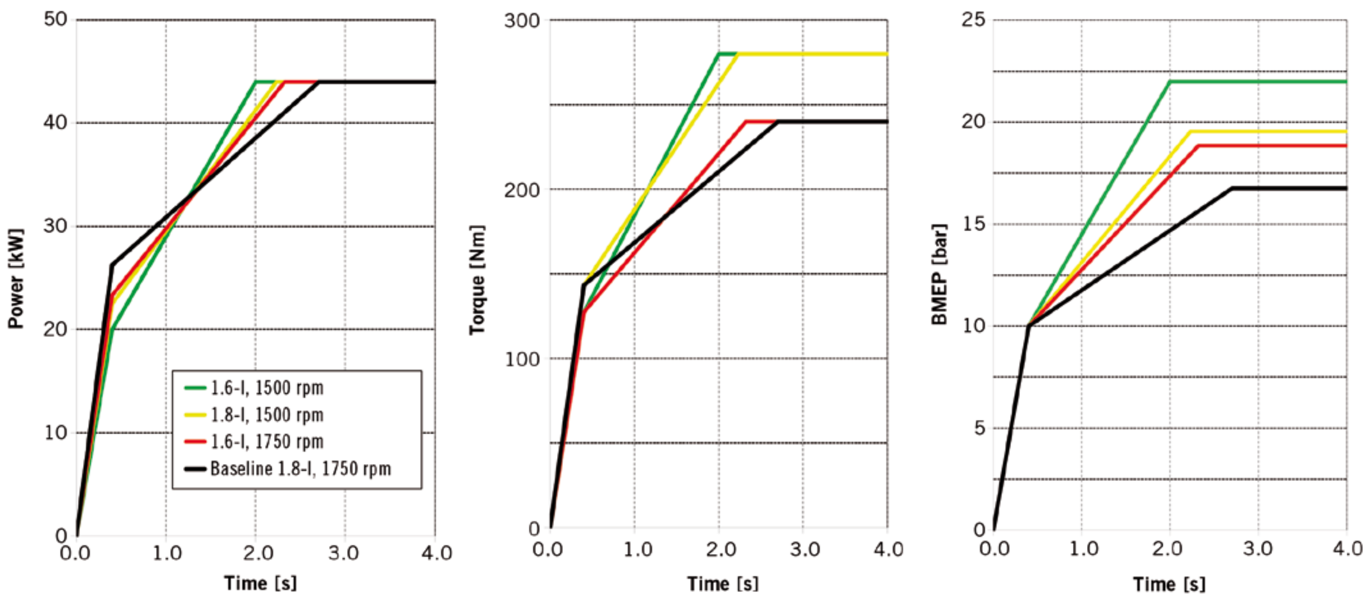
The turbocharging concept Dual Boost from Honeywell represents a paradigm shift in the field of supercharging for gasoline engines. Instead of the classic aerodynamic solution of a single sided centrifugal compressor and a radial inflow turbine that has been used by the industry for more than 35 years, it uses a double sided compressor wheel in combination with an axial turbine. It has equivalent efficiencies to its conventional competitors but boasts less than 50 % of the rotating inertia. This means it reaches regular steady-state targets but delivers exceptional transient performance. It can be used either to increase engine output and vehicle performance or to support the trends of engine downspeeding and downsizing which ultimately result in the most significant emission and fuel efficiency improvements.

POWERTRAIN NEED

In the ideal case the work done to accelerate a vehicle from one state to another can be approximated to the change in its kinetic energy. Also, the work done by the engine to do this can be considered as the area under the power versus the time curve. For two vehicles with different engines but identical performance, the work done must be equal if they are to perform in the same way, Eq. 1 and Eq. 2:

EQ. 1	$W = \Delta E = E_2 - E_1 = \frac{1}{2} m \left(V_2^2 - V_1^2\right)$
EQ. 2	$W = \int_0^t P(t)dt$

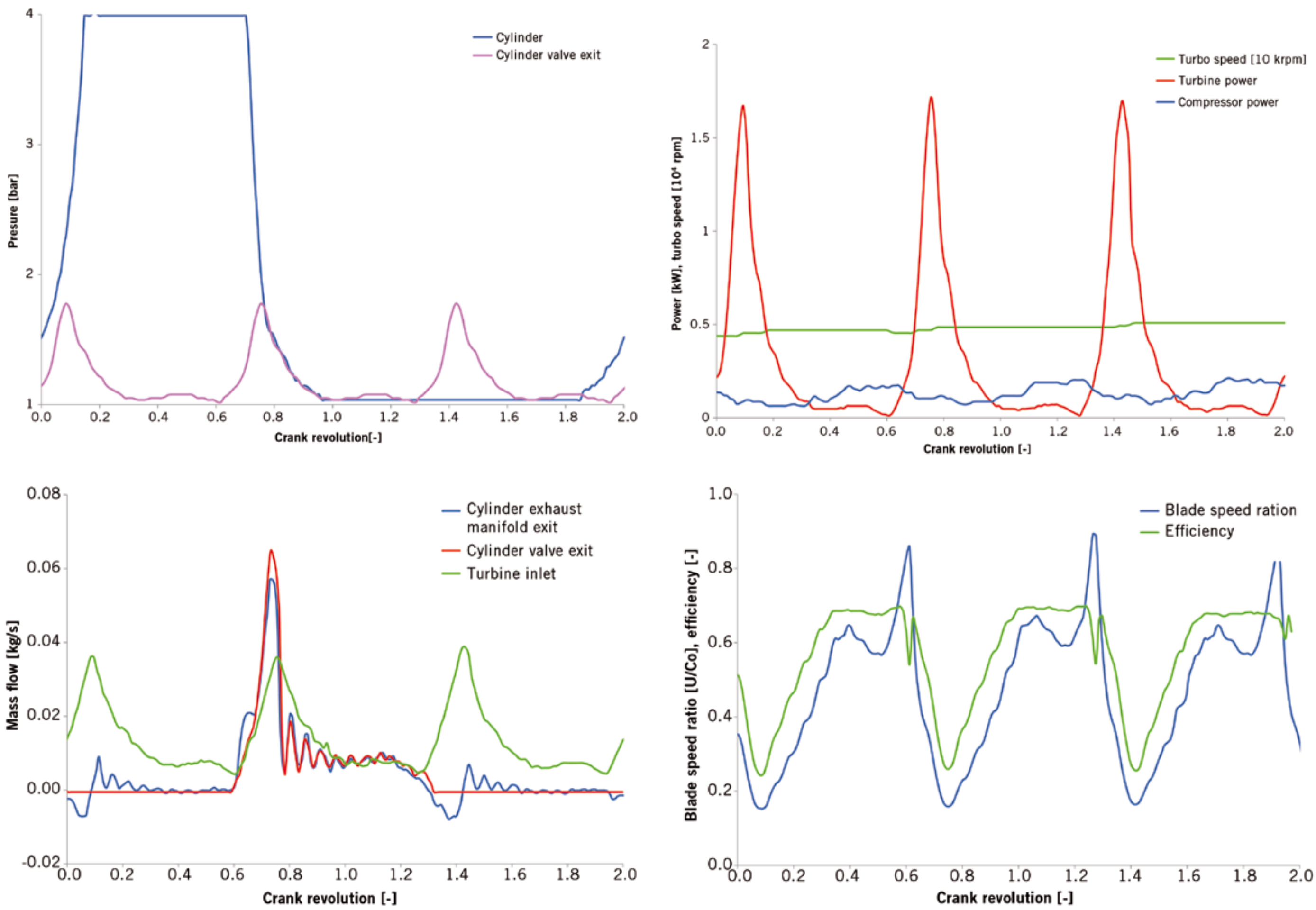
This simple concept allows it to calculate the target power, BMEP and time to torque curves for a typical downsizing and downspeeding problem statement. The baseline used is a modern 1.8-l DI gasoline engine with VVT developing 240 Nm (~17 bar BMEP) at 1750 rpm. ❶ highlights the results for three cases that were studied, a downspeeding of 14 % from 1750 to 1500 rpm, a downsizing of 11 % from 1.8 to 1.6 l and a com-



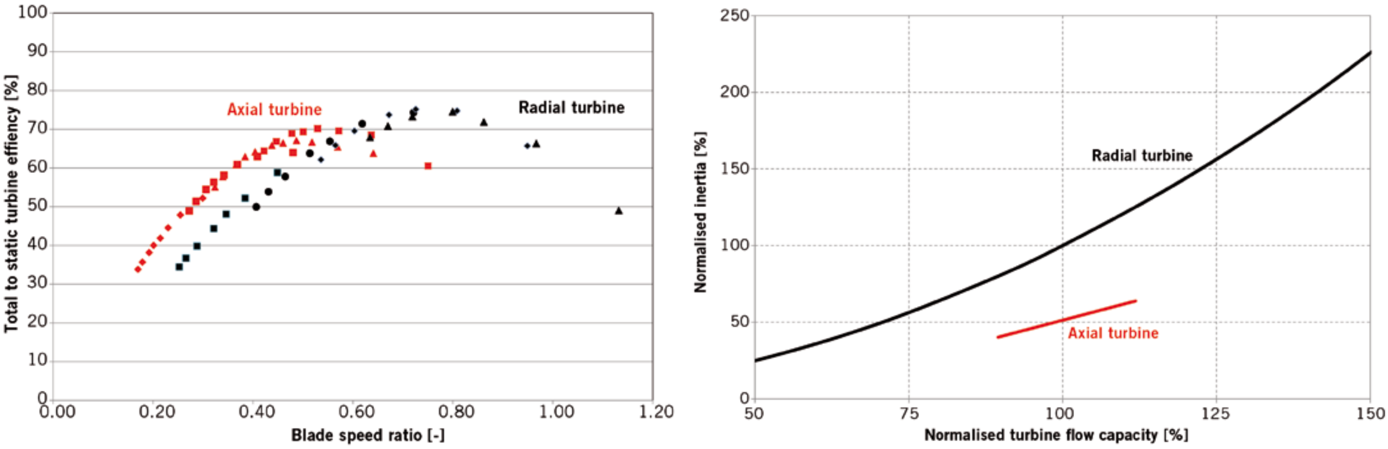
❶ Calculation results for the three cases downspeeding, downsizing and a combined case

	ENGINE SIZE [l]	SPEED [rpm]	BMEP [bar]	TORQUE [Nm]	TIME TO TORQUE [s]	TIME TO TORQUE 50 TO 90 % [s]	BOOSTED TORQUE SLOPE [Nm/s]	TORQUE AT 1 s [Nm]
BASELINE	1.8	1750	16.8	240	2.70	2.13	42	168
A	1.8	1500	19.5	280	2.23	1.86	75	188
B	1.6	1750	18.8	240	2.32	1.91	59	162
C	1.6	1500	22.0	280	2.00	1.71	95	185

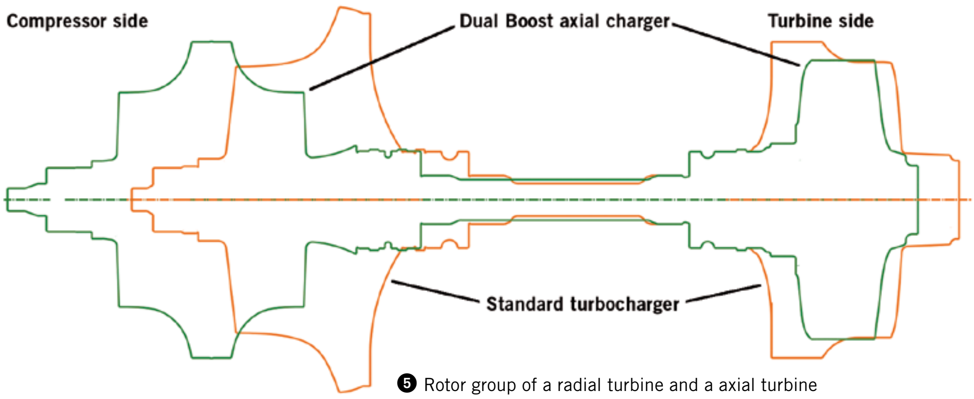
❷ Key engine data for the three cases downspeeding, downsizing and a combined case



❸ Key data of the turbocharger



❹ Comparison between radial turbine and axial turbine



❺ Rotor group of a radial turbine and a axial turbine

bined case. The important numerical results are shown in ❷. The combined case produces targets of 30 % increase in BMEP and 26 % reduction in time to torque and a doubling of the boost slope.

TURBOCHARGER TARGETS

A similar kinetic analysis can be applied to a turbocharger by replacing the mass-velocity (mv^2) term for the vehicle with a polar moment of inertia-rotational speed ($I\omega^2$) term for the rotor. Thus the equations become to Eq. 3, Eq. 4 and Eq. 5:

EQ. 3	$P_{accel} = \frac{\Delta E}{t} = \frac{E_2 - E_1}{t} = \frac{1}{2}\frac{I_p\,(\omega_2^2 - \omega_1^2)}{t}$
EQ. 4	$t = \frac{1}{2}\frac{I_p\,(\omega_2^2 - \omega_1^2)}{P_{accel}}$
EQ. 5	$t = \frac{1}{2}\frac{I_p\,(\omega_2^2 - \omega_1^2)}{(P_{turb} - P_{comp} - P_{brg})} = \frac{1}{2}\frac{I_p\,(\omega_2^2 - \omega_1^2)}{(P_{turb,isen}\,\eta_{turb} - \frac{P_{comp,isen}}{\eta_{comp}} - P_{brg})}$

TURBINE EFFICIENCY

Turbine efficiency is a function of blade speed ratio (U/Co), where U is the turbocharger turbine tip speed and Co is the isentropic spouting velocity speed of the inlet gas. It has been degraded over the years because of the trend of increasing compressor diameter and downsized low inertia turbines. This issue is exacerbated in a modern gasoline engine however by the need for better transient performance and the highly unsteady exhaust flow. The bulk of the energy in the exhaust is in the high pressure portion of each pulse. A U/Co ratio of 0.2 on the arrival of a pulse at the start of a transient is not unusual, ❸. Turbine efficiency at such conditions is normally poor making it difficult to extract energy and accelerate quickly. Improving the turbine efficiency at low U/Co conditions would clearly benefit both the transient and steady-state performance of the turbocharger and engine.

TRADE-OFF BETWEEN EFFICIENCY AND INERTIA

While highly simplified, Eq. 5 is very useful to get a feel for the relative influence and weighting of basic turbocharger parameters, like efficiency and inertia. Higher efficiency is always valuable but the only way to achieve a zero time to torque is actually to have zero inertia. The challenge to the modern turbine designer therefore is to simultaneously maximise turbine efficiency at low U/Co conditions and minimise rotating inertia using the correct weighting trade-off.

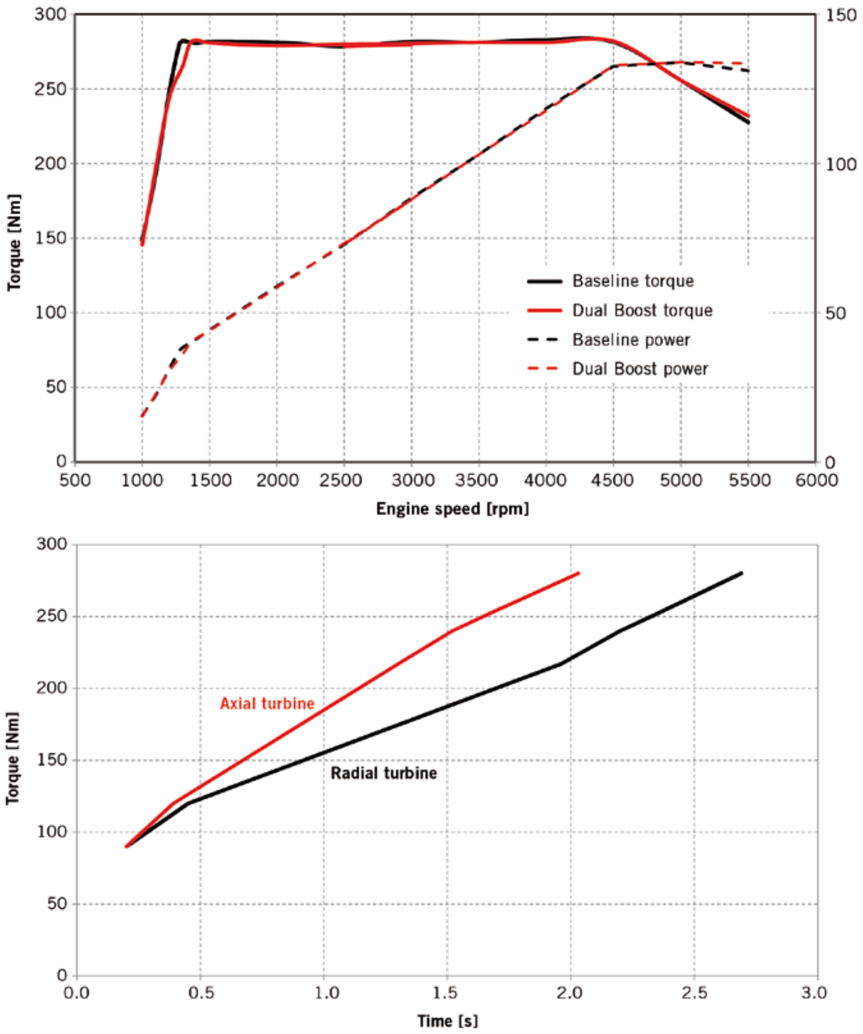
AXIAL TURBINE CONCEPT

Honeywell went back to basics and questioned the traditional aerodynamic concept of a centrifugal compressor paired with a radial turbine. Axial turbines have the advantage over radials of having better turbine efficiency at lower U/Co values, ❹ (left), especially when the designer takes advantage of their intrinsically lower mechanical stresses to utilise non-zero inlet angles for the blade. They are also intrinsically low in inertia. The development team at Honeywell has exploited all these phenomena and its new axial turbine has better turbine efficiency at low U/Co and 50 % less rotating inertia than an equivalent flowing radial turbine, ④ (right). Pairing it with a double-sided parallel flow compressor serves multiple purposes. Firstly, it accelerates the turbine further up the U/Co curve. Secondly it balances the aerodynamic thrust load in the machine to give a quasi zero load concept in steady-state and thirdly it has lower inertia again than an equivalent conventional compressor. The result is clear to see from the outline of the rotor groups in ❺. The Dual Boost while longer is clearly the “low inertia” concept and achieves this without using any exotic materials.

ENGINE TEST RESULTS

The first Dual Boost turbocharger has been tested on engine against a conventional radial device. The testing took place on a Ford 1.6-l inline four-cylinder gasoline engine with direct injection (λ=1) and variable valve timing VVT (case C in ②). The engine has a rated torque of 280 Nm (22 Bar BMEP) from 1500 to 4500 rpm and a peak power of 132 kW at 4750 to 5500 rpm.

Both turbochargers were sized and matched to have the same corrected mass flows at a 2:1 expansion ratio. ❻ (left) shows that both were capable of achieving the target full-load steady-state torque and power target. The full data showed that they had similar engine ΔP and BSFC as well. ⑥ (right) however, shows the real difference between the two devices. The transient torque curve for the Dual Boost rises much more steeply than for the standard turbocharger. 180 Nm was reached 400 ms earlier and 270 Nm was attained more than 600 ms before the baseline standard turbocharger.



❻ Comparison of key engine data with radial turbine and Dual Boost axial turbine

SUMMARY AND OUTLOOK

By re-examining the fundamental aerodynamic design of a gasoline turbocharger, Honeywell has been able to demonstrate a new turbocharger concept that

: has equivalent steady-state and fuel economy to a conventional turbo
: uses only conventional materials and simple fixed geometry
: provides more than 25 % reduction in time to torque at low engine speeds
: delivers more than 15 % more torque after the first second of a transient.

Thus the concept is a key enabler for gasoline engine downsizing and downspeeding which in turn will deliver improvements in fuel consumption and CO_2 reduction that are not achievable with conventional turbochargers with compromising driveability. The first iteration of the new turbocharger has already surpassed the transient performance of mature radial technology and shows still higher potential for future development.

REFERENCE

[1] Bauer, K-H.; Jeckel, D.; Lottermann, J.; Brinkmann, F.; Schorn, N.: New Turbocharger Concept for Boosted Gasoline Engines. 16. Aufladetechnische Konferenz, Dresden, 2011

THANKS

The following people also assisted in the production of this article:

: Karl-Heinz Bauer, Chief Technology Officer and responsible for engineering at Honeywell Transportation Systems in Rolle (Switzerland).
: Gavin Donkin, Vice President of Advanced Engineering and responsible for advanced engineering at Honeywell Turbo Technologies at Honeywell Turbo Technologies in Rolle (Switzerland).

Additional thanks are extended to Dr. Schorn, F. Brinkmann and colleagues at Ford in Aachen (Germany).

PEER REVIEW

PEER REVIEW PROCESS FOR RESEARCH ARTICLES IN ATZ, MTZ AND ATZ ELEKTRONIK

STEERING COMMITTEE

Prof. Dr.-Ing. Lutz Eckstein	RWTH Aachen University	Institut für Kraftfahrzeuge Aachen
Prof. Dipl.-Des. Wolfgang Kraus	HAW Hamburg	Department Fahrzeugtechnik und Flugzeugbau
Prof. Dr.-Ing. Ferit Küçükay	Technische Universität Braunschweig	Institut für Fahrzeugtechnik
Prof. Dr.-Ing. Stefan Pischinger	RWTH Aachen University	Lehrstuhl für Verbrennungskraftmaschinen
Prof. Dr.-Ing. Hans-Christian Reuss	Universität Stuttgart	Institut für Verbrennungs-motoren und Kraftfahrwesen
Prof. Dr.-Ing. Ulrich Spicher	Karlsruher Institut für Technologie	Institut für Kolbenmaschinen
Prof. Dr.-Ing. Hans Zellbeck	Technische Universität Dresden	Lehrstuhl für Verbrennungsmotoren

ADVISORY BOARD

Prof. Dr.-Ing. Klaus Augsburg	Prof. Dr. rer. nat. Uli Lemmer
Prof. Dr.-Ing. Michael Bargende	Dr. Malte Lewerenz
Prof. Dipl.-Ing. Dr. techn. Christian Beidl	Prof. Dr.-Ing. Markus Lienkamp
Prof. Dr. sc. techn. Konstantinos Boulouchos	Prof. Dr. rer. nat. habil. Ulrich Maas
Prof. Dr. Dr. h.c. Manfred Broy	Prof. Dr.-Ing. Markus Maurer
Prof. Dr.-Ing. Ralph Bruder	Prof. Dr.-Ing. Martin Meywerk
Dr. Gerhard Bruner	Prof. Dr.-Ing. Klaus D. Müller-Glaser
Prof. Dr. rer. nat. Heiner Bubb	Dr. techn. Reinhard Mundl
Prof. Dr. rer. nat. habil. Olaf Deutschmann	Prof. Dr. rer. nat. Cornelius Neumann
Dr. techn. Arno Eichberger	Prof. Dr.-Ing. Nejila Parspour
Prof. Dr. techn. Helmut Eichlseder	Prof. Dr.-Ing. Peter Pelz
Prof. Dr. Wilfried Eichlseder	Prof. Dr. techn. Ernst Pucher
Dr.-Ing. Gerald Eifler	Dr. Jochen Rauh
Prof. Dr.-Ing. Wolfgang Eifler	Prof. Dr.-Ing. Konrad Reif
Prof. Dr. rer. nat. Frank Gauterin	Prof. Dr.-Ing. Stephan Rinderknecht
Prof. Dr. techn. Bernhard Geringer	Prof. Dr.-Ing. Jörg Roth-Stielow
Prof. Dr.-Ing. Uwe Dieter Grebe	Dr.-Ing. Swen Schaub
Dr. mont. Christoph Guster	Prof. Dr. sc. nat. Christoph Schierz
Prof. Dr.-Ing. Holger Hanselka	Prof. Dr. rer. nat. Christof Schulz
Prof. Dr.-Ing. Horst Harndorf	Prof. Dr. rer. nat. Andy Schürr
Prof. Dr. techn. Wolfgang Hirschberg	Prof. Dr.-Ing. Ulrich Seiffert
Univ.-Doz. Dr. techn. Peter Hofmann	Prof. Dr.-Ing. Hermann J. Stadtfeld
Prof. Dr.-Ing. Bernd-Robert Höhn	Prof. Dr. techn. Hermann Steffan
Prof. Dr. rer. nat. Peter Holstein	Prof. Dr.-Ing. Wolfgang Steiger
Dr. techn. Heidelinde Holzer	Prof. Dr.-Ing. Peter Steinberg
Prof. Dr.-Ing. habil. Werner Hufenbach	Dr.-Ing. Peter Stommel
Prof. Dr.-Ing. Armin Huß	Dr.-Ing. Ralph Sundermeier
Prof. Dr.-Ing. Roland Kasper	Prof. Dr.-Ing. Wolfgang Thiemann
Prof. Dr.-Ing. Tran Quoc Khanh	Prof. Dr.-Ing. Dr. h.c. Helmut Tschöke
Dr. Philip Köhn	Prof. Dr.-Ing. Georg Wachtmeister
Prof. Dr.-Ing. Ulrich Konigorski	Prof. Dr.-Ing. Jochen Wiedemann
Dr. Oliver Kröcher	Prof. Dr. techn. Andreas Wimmer
Prof. Dr.-Ing. Peter Krug	Prof. Dr. rer. nat. Hermann Winner
Dr. Christian Krüger	Prof. Dr. med. habil. Hartmut Witte
Univ.-Ass. Dr. techn. Thomas Lauer	Dr.-Ing. Michael Wittler

Scientific articles of universities in ATZ Automobiltechnische Zeitschrift, MTZ Motortechnische Zeitschrift and ATZelektronik are subject to a proofing method, the so-called peer review process. Articles accepted by the editors are reviewed by experts from research and industry before publication. For the reader, the peer review process further enhances the quality of the magazines‘ content on a national and international level. For authors in the institutes, it provides a scientifically recognised publication platform.

In the Peer Review Process, once the editors has received an article, it is reviewed by two experts from the Advisory Board. If these experts do not reach a unanimous agreement, a member of the Steering Committee acts as an arbitrator. Following the experts' recommended corrections and subsequent editing by the author, the article is accepted.

In 2008, the peer review process utilised by ATZ and MTZ was presented by the WKM (Wissenschaftliche Gesellschaft für Kraftfahrzeug- und Motorentechnik e. V./German Professional Association for Automotive and Motor Engineering) to the DFG (Deutsche Forschungsgemeinschaft/German Research Foundation) for official recognition. ATZelektronik participates in the Peer Review since 2011.

THE SEAL OF APPROVAL FOR SCIENTIFIC ARTICLES IN MTZ.
MTZ PEER REVIEW
REVIEWED BY EXPERTS FROM RESEARCH AND INDUSTRY.

AUTHORS

DIPL.-ING. MARKUS EHRLY
is Research Assistant at the Institute for Combustion Engines (VKA) of the RWTH Aachen University (Germany).

DIPL.-ING. MARKUS JAKOB
is Research Assistant at the Institute for Combustion Engines (VKA) of the RWTH Aachen University (Germany).

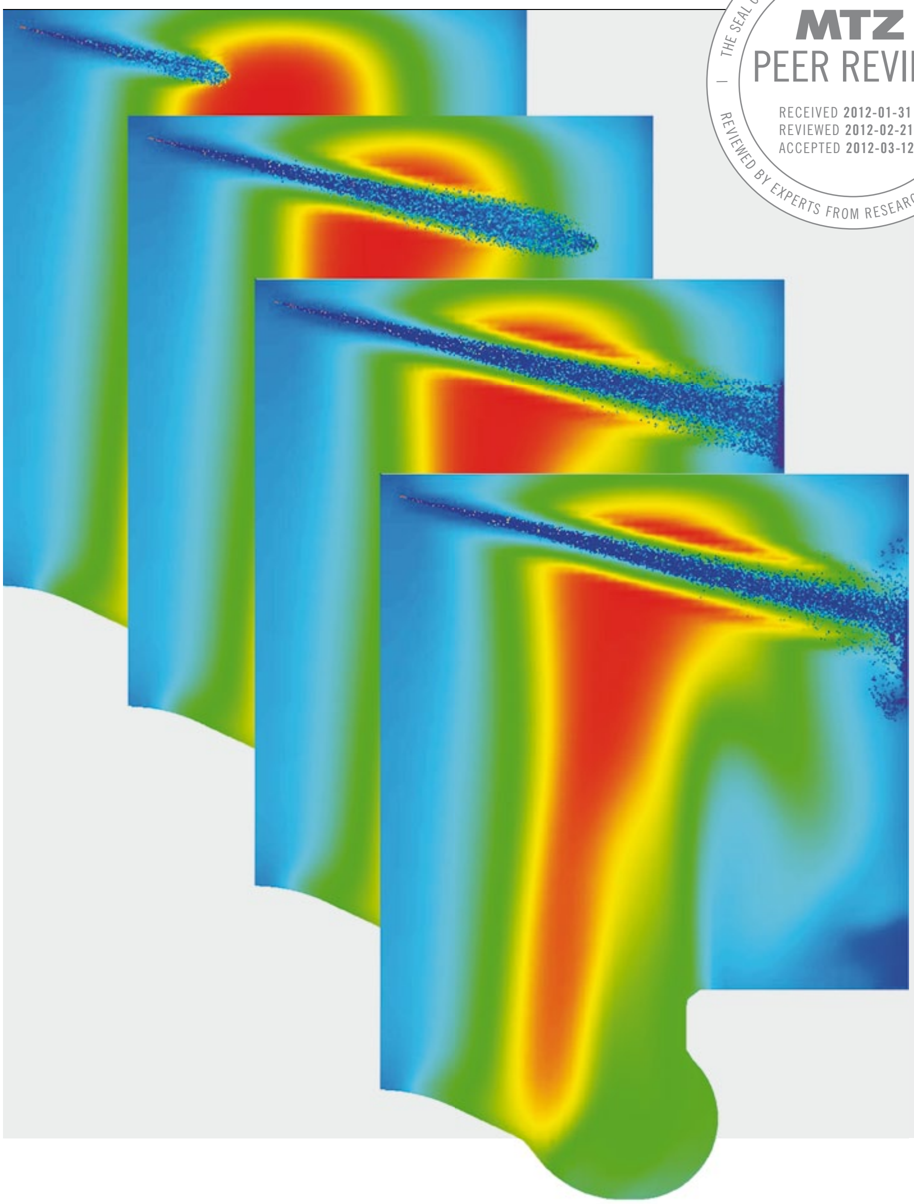
DIPL.-ING. MATTHIAS BUDDE
was Research Assistant at the Institute for Combustion Engines (VKA) of the RWTH Aachen University (Germany) and is now Technical Specialist Gasoline Engines at the FEV GmbH in Aachen (Germany).

PROF. DR.-ING. STEFAN PISCHINGER
is Head of the Institute for Combustion Engines (VKA) of the RWTH Aachen University (Germany).

SIMULATION METHOD FOR DIESEL FUEL ENTRY INTO LUBRICATION OIL

The exhaust aftertreatment systems in today's passenger car diesel engines require a high temperature level in the exhaust or must be operated with a rich mixture for regeneration purposes. Both can be implemented using late post injections, but these lead to the well-known problem of oil dilution. As part of a FVV research project, a simulation method was developed at the Institute for Combustion Engines at RWTH Aachen University in cooperation with the Institute for Measurement Technology at the Technical University Hamburg-Harburg and the Institute for Aerospace Thermodynamics at the University Stuttgart. This simulation method allows calculating the fuel entry into engine oil.

THE SEAL OF APPROVAL FOR SCIENTIFIC ARTICLES IN MTZ.
MTZ PEER REVIEW
RECEIVED 2012-01-31
REVIEWED 2012-02-21
ACCEPTED 2012-03-12
REVIEWED BY EXPERTS FROM RESEARCH AND INDUSTRY.

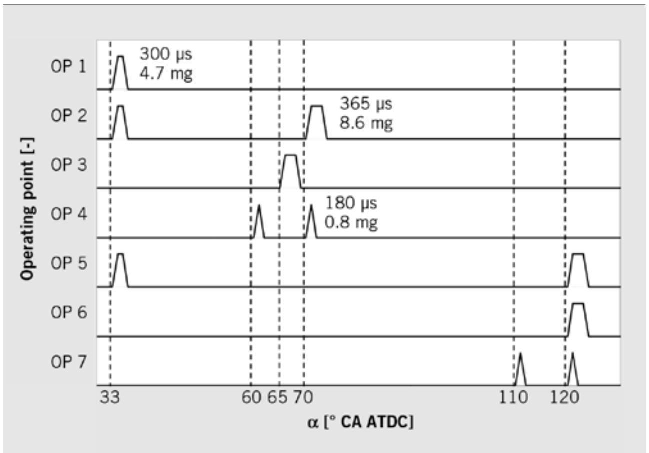


1 MOTIVATION

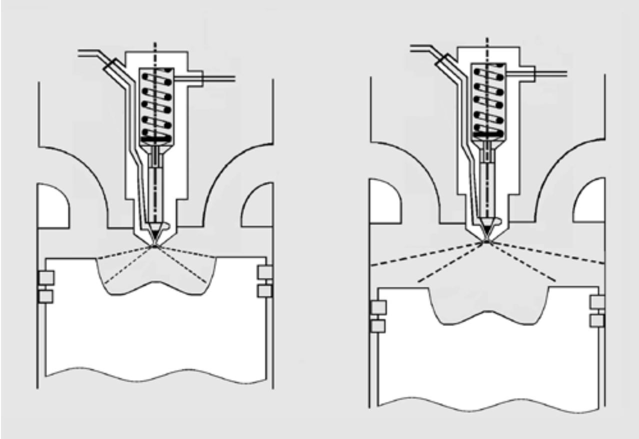
Today's emission limits require the use of particulate filters in diesel engines and the use of NO_x storage catalysts, for example to reduce NO_x levels. Both systems necessitate intermittent regeneration. The high exhaust temperatures that are needed for exhaust aftertreatment can be achieved by means of one or several post injections [1-3]. At low load points, relatively late post injections with large injection quantities are necessary to reach the required exhaust temperature. However, depending on the different parameters for combustion and injection as well as the injection nozzle and piston geometry, these late injections lead to fuel entry into the lubricating film at the cylinder wall and therefore, to oil dilution [4,5]. During NO_x adsorber catalyst regeneration, the in-cylinder mixture is enriched through the application of post injection for NO_x reduction purposes [6]. Particularly critical in terms of oil dilution are very late post injections, which do not react in the cylinder. This post injected fuel either reacts in the diesel oxidation catalyst and raises the exhaust gas temperature to regenerate the diesel particulate filter or supplies the exhaust gas components CO, H_2, CxHy to regenerate the NO_x storage catalyst. Oil dilution due to late injection timing is caused by a lack of geometric shielding of the piston bowl; the injection spray is no longer directed towards the piston bowl but pointed towards the oil-wetted cylinder wall. This can lead to fuel entry into the oil film. This situation is shown schematically in ❶.

DISPLACEMENT	390 cm³
STROKE	88.3 mm
BORE	75 mm
INJECTION NOZZLE	Eight hole
HYDRAULIC FLOW RATE OF THE NOZZLE	620 cm³/min
INJECTION SYSTEM	Bosch Crip 3 Piezo

❷ Engine data of the single-cylinder engine



❸ Start of injection, energising time and injection quantity for the analysed operating points



❶ Schematic representation of the injection sprays for an injection timing near Top Dead Centre (TDC) (left) and a late injection timing (right)

Fuel entry into the lubricating film caused by post injection is determined relatively late in today's engine development process with the help of complex engine and vehicle tests. The goal of this research project is to develop a simulation method that allows evaluation of different injection strategies in terms of fuel entry into the oil film. Furthermore, the aim is to better understand the mechanisms of this type of fuel entry.

To calculate the fuel entry, 3D CFD simulations of gas exchange, injection, combustion, droplet/film interaction and evaporation of fuel from the lubricating film are used. In order to develop and validate these models, fundamental investigations dealing with the impact of a fuel droplet on a lubricating film, investigations on a transparent engine, and tests on a single-cylinder research engine equipped with a measurement system capable of determining the fuel concentration in the lubricating film were performed.

2 TEST SET-UP AND TEST IMPLEMENTATION

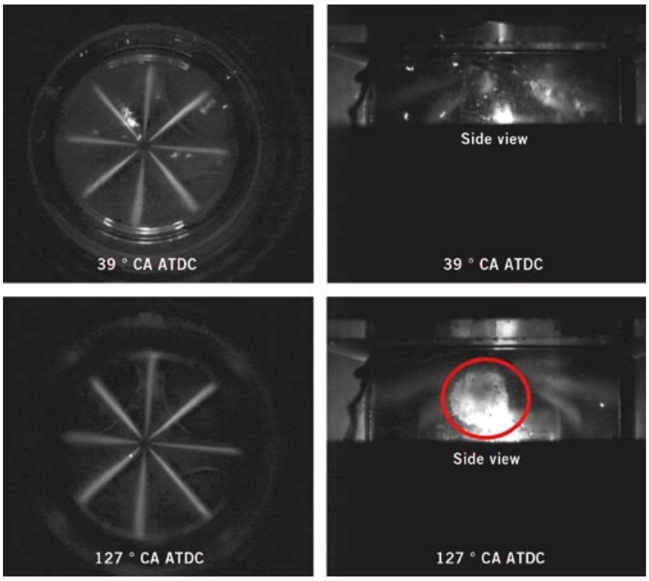
To analyse the fuel entry into the lubricating film and to develop the simulation method, measurements on a single-cylinder research engine and a transparent engine were performed with the same geometric design. The engine data is shown in ❷. The injection strategies shown in ❸ were used on both the research engine as well as the transparent engine at an operating point (OP) of 1500 rpm and 4.3 bar IMEP. The start of injection (SOI) of pilot injection and main injection, as well as the fuel quantity for the pilot injection were kept constant for all operating points. The injected quantity in the main injection was varied slightly to obtain the desired the load. The injection pressure for all operating points was set to 750 bar.

2.1 INVESTIGATIONS ON THE TRANSPARENT ENGINE

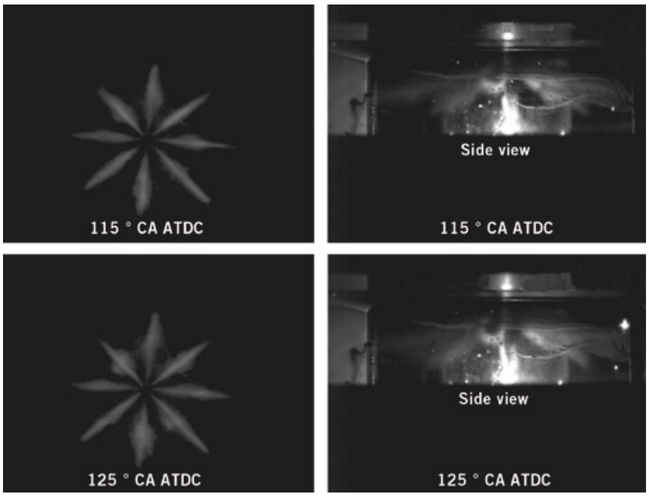
In order to visualise the interaction of the liquid fuel sprays with the gas phase and the cylinder wall during different operating strategies with post injection, visual investigations were performed on a transparent diesel engine. In comparison to thermodynamic single-cylinder engines, this engine was additionally equipped with window segments in the cylinder wall, a transparent piston bowl, and an extended piston, which allowed to affix a permanently installed passive reflector. The bowl of the transparent piston was based on the conventional ω bowl in order to perform the investigations under realistic geometric conditions. Light was routed into the combustion chamber through the window segment installed at the intake and exhaust side. The light scattered by the liquid fuel and the light emitted during the combustion process was routed out of the engine via the transparent piston bowl and the passive reflector and recorded by a high-speed camera.

The results for operating points 5 and 7 are shown as part of this article. Please refer to the research report [7] concerning results for the remaining operating points. ❹ shows the recordings for operating point 5 with a post injection at 33° CA ATDC and a very late post injection at 120° CA ATDC. On the left side, the recordings through the transparent piston and on the right side the recordings through the side window in the cylinder wall are shown. The recordings at 39° CA ATDC show that the injector is completely open during early post injection with an SOI of 33° CA ATDC and that the liquid fluid spray does not make contact with the cylinder wall at an internal cylinder pressure of approximate 17.5 bar. Based on the cylinder pressure trace, ignition and combustion of the early post injection can be identified. The recordings of the second post injection at 120° CA ATDC show a clear contact of the injection spray with the cylinder wall. Based on the recording that was made through the side window it is shown that the majority of the injection mass reaches the liner wall at a low cylinder pressure of approximate 5 bar.

❺ shows the recordings for operating point 7. This operating point has two very late post injections with a short actuation time of 180 µs. The injector does not completely open during this short actuation time. The recordings show that the penetration depth of the liquid fuel is considerably shorter than at operating point 5, which has the same start of actuation, but a higher actuation time of 360 µs. The liquid fuel does not reach the cylinder wall. It is also shown that the spray angle during injection with a short actuation time is significantly wider than during injection with a long actuation time. This effect can be attributed to the flow conditions in the injector and in the nozzle during the phase where the needle opens and closes [8]. However, at an actuation time of 180 µs, the fuel mass injected during this post injection is only 1/8 of the fuel mass that is injected during an actuation time of 360 µs.



❹ Recordings of the transparent engine at operating point 5
(post injection at 33° CA ATDC and 120° CA ATDC)



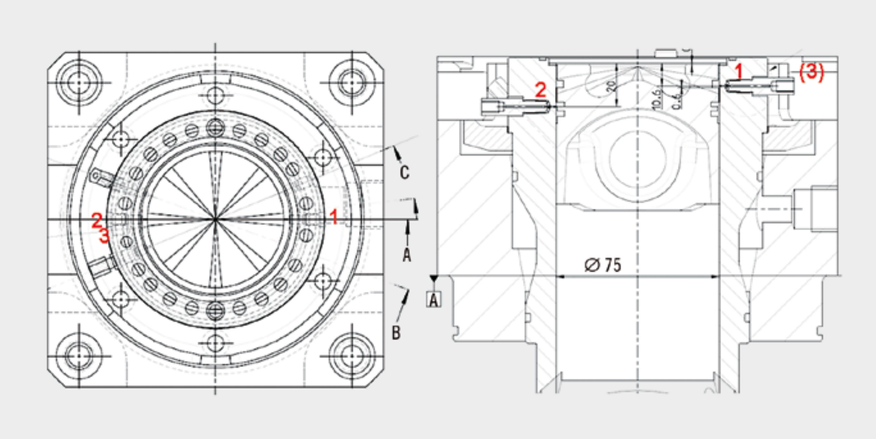
❺ Recordings of the transparent engine at operating point 7
(post injection at 110° CA ATDC and 120° CA ATDC; the actuation time is 180 µs)

2.2 SPECIAL MEASUREMENT

To determine the fuel concentration in the lubricating film after post injection, the Institute for Measurement Technology at TU Hamburg-Harburg developed a special measurement system [9]. Here, fluid was drawn from the lubricating film by means of a capillary tube in a cycle-resolved manner and stored in the capillary tube. After the measurement, the capillary tube was removed and the stored fluid was analysed with regard to fuel concentration with the help of a mass spectrometer. To be able to analyse the fuel concentration of the individual cycles separately, an air cushion was routed into the capillary tubes every time fluid was removed. Thus, the fluid samples from the individual cycles could be separated. To make cycle-resolved sampling possible, a quick metering valve was used, which releases the capillary tubes at a certain crank angle position for a minimum metering time of 10 µs. The repeat frequency was 1000 Hz and was therefore suitable for sampling in the speed range of the test object.

In this research project, the sampling procedure described above was used on a single-cylinder research engine. In this case, three locations were defined for sampling of the wall-applied film in the cylinder based on investigations in the transparent diesel engine. They were distributed along the circumference at different positions relative to the injection spray target: Position 1 directly in the injection spray target, position 2 below the spray, and position 3 offset to the side of the spray target, ❻. A special cylinder sleeve was prepared for this purpose, which had three cut-outs through the coolant jacket for the sensor bore. For each injection strategy, the fuel concentration in the lubricating film was determined at each sensor position for 40 consecutive cycles. To do this, the capillary tubes were loaded with fluid at 130° CA ATDC for a duration of 10° CA.

The measured fuel concentrations of the individual sensor positions and injection strategies are shown in ❼. It can be seen that the fuel concentration for the sensor position is highest in the spray target for all operating points. The measurements show that the operating point with an early post injection at 33° CA ATDC and the operating point with a split post injection with very short actuation times at 60 and 70° CA ATDC have a very low oil dilution. The operating points with a very late post injection at 120° CA ATDC on the other hand have an increased oil dilution. The results of the fuel



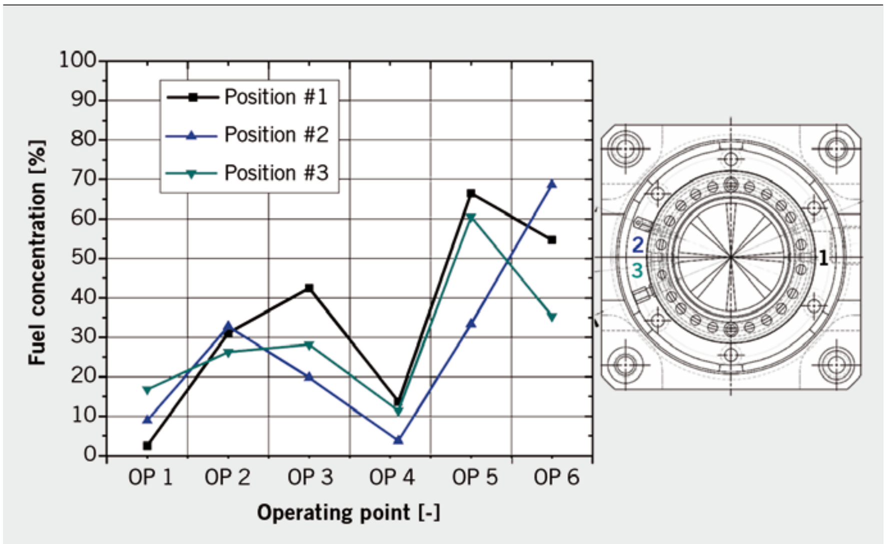
❻ Arrangement of sampling sensors in the single-cylinder engine

concentration measurement therefore confirm the results obtained by quantitative means in the transparent engine.

3 SIMULATION OF FUEL ENTRY INTO THE OIL FILM

Fuel entry into the wall-applied film was calculated using 3D CFD simulations. For this purpose, the simulation programme Kiva release 3,2 [10] was used. The droplet/film interaction was calculated with a method specifically developed for droplet impact on the lubricating film. This method was developed by the Institute for Aerospace Thermodynamics at Stuttgart University based on fundamental research experiments, DNS simulations of the droplet impact, and the principle of similarity [7]. Furthermore, routines were implemented in Kiva for modelling the lubricating film at the cylinder wall, calculating the heat exchange between in-cylinder-flow and the lubricating film, and calculating the fuel evaporation out of the lubricating film. To start the simulation of the post injection and to calculate the fuel entry into the lubricating film, it is necessary to know the conditions in the combustion chamber (temperature, flow pattern) at the time of post injection. These starting conditions were determined by means of a 3D combustion simulation of pilot and main injection. The injection of fuel and the mixture formation were calculated with ERC routines [11] for the internal nozzle flow and spray breakup. To model the ignition, the Shell model was used, which calculates the ignition of hydrocarbons based on an eight-step reaction mechanism. Combustion was simulated with a characteristic time scale model. The parameters for the injection and spray breakup model were calibrated based on the recordings from the transparent engine. The ignition and combustion model was specifically adjusted for post injection using a heat release analysis of the combustion process of the single-cylinder research engine.

To calculate the interaction of post injection with the lubricating film, the developed simulation method of droplet/film interaction was implemented as a routine in Kiva [7]. The routine used the local film thickness, the droplet size, and droplet speed to determine which portion of the droplet enters the film and which portion splashes back into the combustion chamber. For the splashed-back portion, the number of droplets, size, and speed were determined and these droplets were initialised in the mathematical grid. To be able to determine the local film parameters such as film temperature, fuel concentration, and film thickness, the lubricating film was discretised with a non-movable two-dimensional grid. To calculate



❼ Results of the fuel concentration measurement in the lubricating film made by means of sampling measurement system on the single-cylinder engine the heat flux into the lubricating film and to calculate the fuel mass evaporated from the film, the three-dimensional movable grid of the combustion chamber was linked to the non-movable two-dimensional grid of the lubricating film. The heat flux into the lubrication film and the evaporation of fuel out of this are calculated with the logarithmic law of the wall.

As boundary conditions for the lubricating film, a liner temperature of 130° C, a fuel concentration of 5 % in the engine oil, and a film thickness of 1 μm were used. ❽ shows an example of the simulation results for operating point 5 with post injections at 33° CA ATDC and 120° CA ATDC. It shows the injected fuel mass, the fuel mass that reaches the lubricating film, and the fuel mass in the film over crank angle. It also shows the film thickness, the fuel concentration in the film, and the film temperature in the simulated 45° sector of the lubricating film.

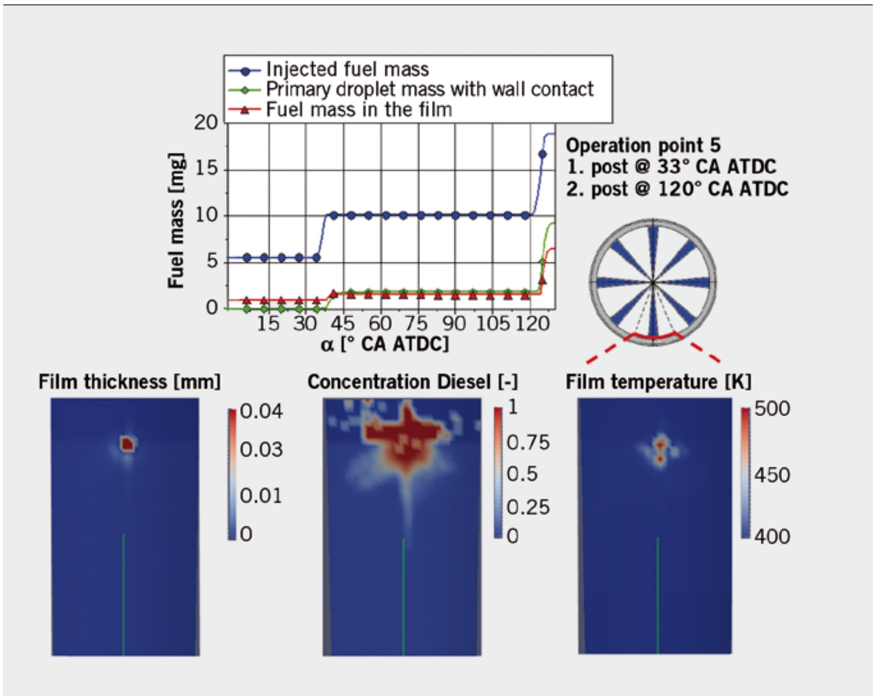
It is shown that only a small portion of the first post injection at 33° CA ATDC reached the lubricating film. During the second post injection at 120° CA ATDC on the other hand, the majority of the injected fuel mass reached the lubricating film due to the lower density in the combustion chamber. The fuel entry into the lubricating film during the first post injection was very low because the majority of the fuel that was being injected splashed back again. During the second post injection, the portion that was splashed back was lower than during the first one, which led to an increased fuel entry during the second post injection. In the illustration showing film thickness it is seen that the majority of the fuel entry took place on a small surface in the area of the spray target. In the illustration of the fuel concentration, it is shown that the fuel concentration was affected in a large area due to fuel entry. Because of the low lubricating film thickness, minor scale fuel entry was sufficient to significantly alter the concentration in the lubricating film.

❾ shows the fuel entry computations for all injection strategies that were analysed. It is shown that, during early post injection and split injection with short actuation times, no fuel entry is to be expected. The injection strategies with early combustion and late post injection lead to a proportionally lower amount of fuel entry than injection strategies that only involve late post injection.

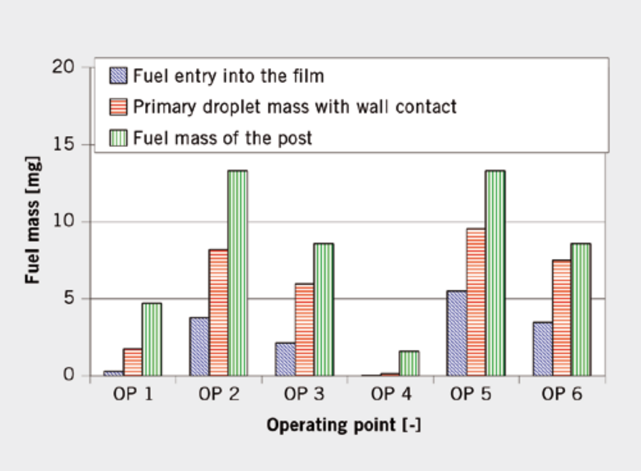
❿ shows the comparison between the fuel concentrations measured using the sampling system and the calculated fuel concentrations of the individual sensor positions and post injection strategies. It is shown that the calculated and measured concentrations for sensor positions two and three match pretty well. The calculated concentrations of the sampling position in the spray target (position one) are considerably higher than the measured concentrations. This can be explained by the fact that, due to the low lubricating film thickness, a small error in the fuel entry calculation will lead to a major error in the concentration. For the sensor position next to and below the spray target, a good match between measurement and simulation could be achieved.

4 SUMMARY

As part of this research project, a simulation system to calculate diesel fuel entry into the wall-applied lubricating oil film under regeneration mode conditions was developed. To do this, a new droplet/film interaction model was used that was specifically developed for the interaction of post injection with the lubricating film. In addition, the simulation results were validated by performing measurements on a single-cylinder diesel engine and a transparent optical engine of the same design. Further, the results from the optical tests on the transparent engine were used to calibrate the injection model for the post injections. They provided first qualitative information on the local fuel entry into the wall-applied film. To determine the fuel entry into the lubricating film, an online sampling system was used to determine the fuel concentration in the lubricating film. These sample measurements on the single-cylinder engine display the same trend as the optical investigations. The results of the simulation on the other hand also confirm the qualitative results from the



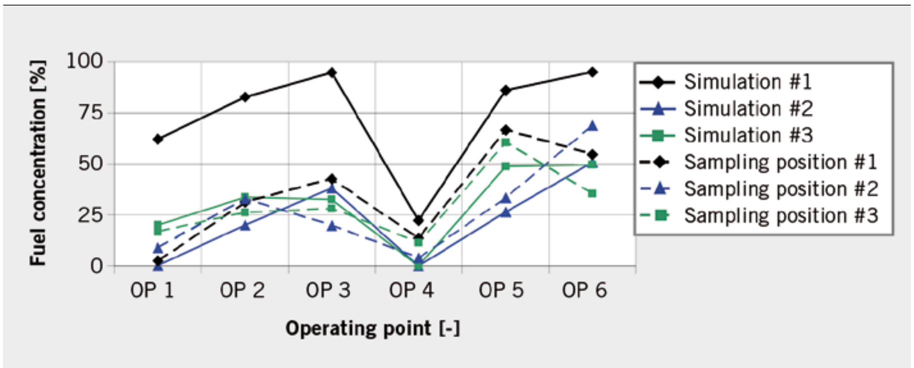
❽ Simulation results for operating point 5 with post injections at 33° CA ATDC and 120° CA ATDC; the plots of the film thickness, concentration diesel and film temperature are at 130° CA ATDC



❾ Results from the fuel entry simulation for different post injection strategies

THANKS

This article is the scientific result of the research project "Developing a Simulation System for Diesel Fuel Entry into Engine Oil Considering the Operating Conditions during Regeneration Mode", assigned by Forschungsvereinigung Verbrennungskraftmaschinen e. V. (FVV, Frankfurt). The project was supported by a working group of FVV under the supervision of Dr. Annette C. Jooss, Daimler AG. We would like to thank this working group for the great support. Furthermore, we thank Dipl.-Ing. Andreas Behn, Dipl.-Ing. Matthias Feindt, Dr.-Ing. Sven Krause, Dr.-Ing. Michael Wittler, Dr.-Ing. Grazia Lamanna and Dipl.-Ing. Hassan Gomaa for their active support in this research project.



❿ Comparison of sampling measurement system with the simulations

optical measurements and the results from the sampling measurements. The simulations provided additional information in terms of timing and location of fuel entry into the wall-applied film. The simulation also shows that there often is a fuel concentration > 75 % at the impact point of the fuel injection spray. Short actuation times of the injector reduce the penetration depth of the injection spray and thus prevent oil dilution. The transferability of the results to other load points and injection strategies will be determined in the FVV research cluster Fuel in Oil. In this research cluster, the transport of the lubrication film by the piston rings and the evaporation of fuel out of the oil pan also will be investigated.

REFERENCES

[1] Scholz, V.; Frisse, P.; Herrmann, H.-O.: Exhaust Emission Design to Improve Particulate Filter Regeneration. SAE-Toptec, September 2000, Göteborg
[2] Krüger, M.; Wiartalla, A.; Lichtenberg, T.; Körfer, T.: Emission Concepts for Future Passenger Car Diesel Engines. 24th International Vienna Motor Symposium, 2003
[3] Reggie, Z.; Yiqun, H.; Magdi, K.: Methodologies to Control DPF Uncontrolled Regenerations. SAE Technical Paper Series, 2006-01-1090
[4] Krüger, M.; Wiartalla, A.; Scholz, V.; Adomeit, P.; Rohs, H.: Regeneration Mode and Engine-Related Long-Term Effects in Diesel Engines. 13th Aachen Colloquium for Vehicle and Engine Engineering, 2004
[5] Stein, C.; Budde, M.; Krause, S.; Brandt, S.; Schlerege, F.: Beeinflussung der Schmierölemissionen durch die Gemischbildung im Brennraum, FVV Zwischenbericht zum Vorhaben Nr. 933, Heft R545, 2009, 2004
[6] Pischinger, S.; Schnitzler, J.; Wiartalla, A.; Scholz, V.: Investigation of a NO_x-Adsorber Catalyst used with a Passenger Car Diesel Engine. In: MTZ 64 (2003), No. 3
[7] Budde, M.; Jakob, M.; Ehrly, M.; Lamanna, G.: Developing a Simulation System for Diesel Fuel Entry into Engine Oil Considering the Operating Conditions during Regeneration Mode. Final report by FVV, project No. 990, 2011
[8] Baumgartner, C.: Modelling the Influence of Cavitation on the Primary Jet Breakup during High Pressure Diesel Injection. VDI Series 12, No. 543, VDI-Verlag, Düsseldorf, 2003
[9] Behn, A.; Feindt, M.; Krause, S.; Matz, G.: Entwicklung eines Gasentnahmesystems zur kurbelwellenwinkelaufgelösten Entnahme von Ölemissionen aus dem Brennraum von Dieselmotoren. Informationstagung Motoren, Herbsttagung 2011, Fulda, Heft R 556
[10] Amsden, A. A.; O'Rourke P. J.; Butler, T. D.: KIVA-II: A Computer Program for Chemically Reactive Flows with Sprays. Los Alamos National Laboratory Report, LA-11560-MS, 1989
[11] Kong, S.-C.; Han, Z.; Reitz, R. D.: The development and application of a diesel ignition and combustion model for multidimensional engine simulations. SAE 950278