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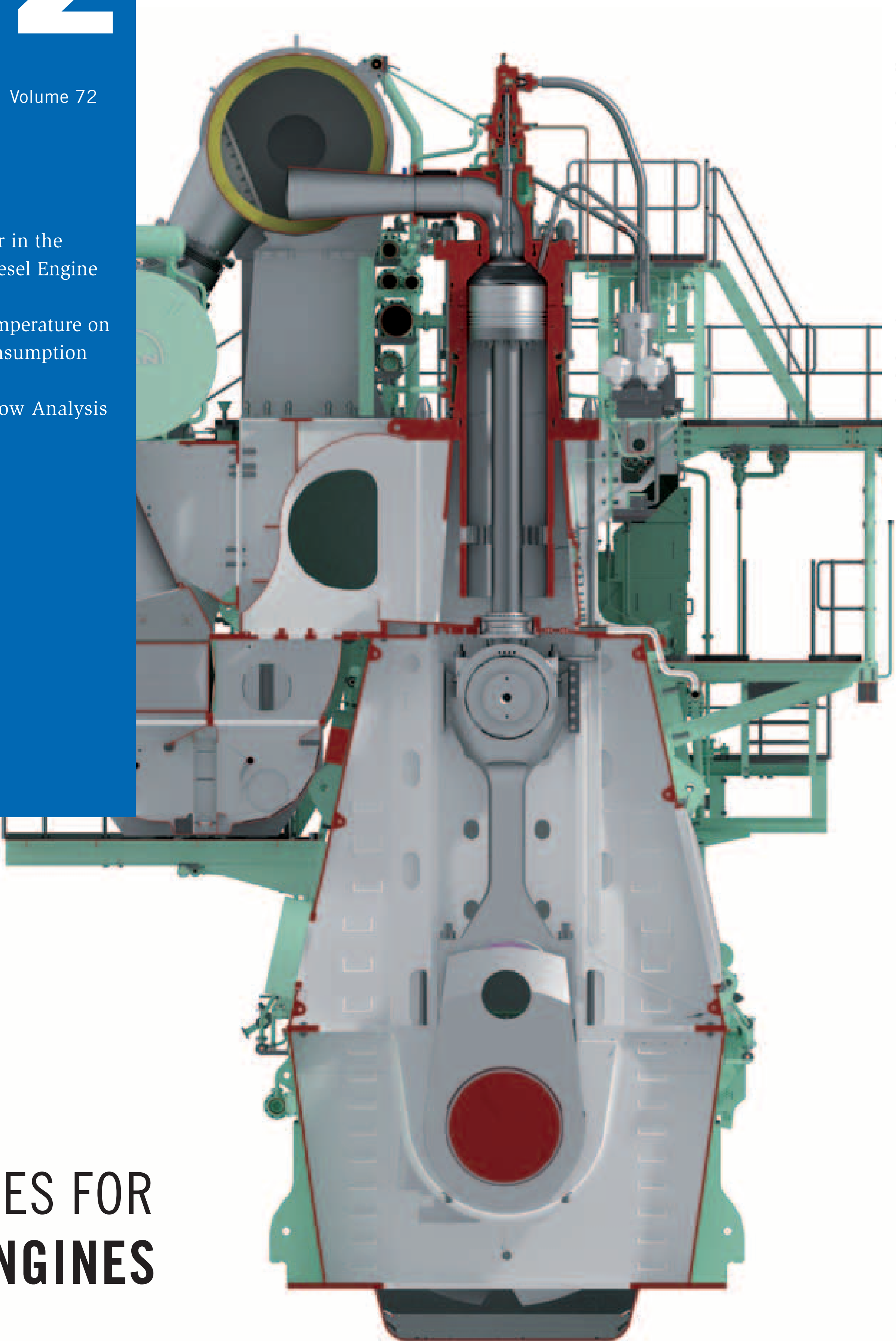
MTZ WORLDWIDE

11 November 2011 I Volume 72

VIRTUAL Oxygen Sensor in the Intake Manifold of a Diesel Engine

INFLUENCE of Glow Temperature on Emissions and Fuel Consumption

OPTICAL Method for Flow Analysis in Engine Combustion



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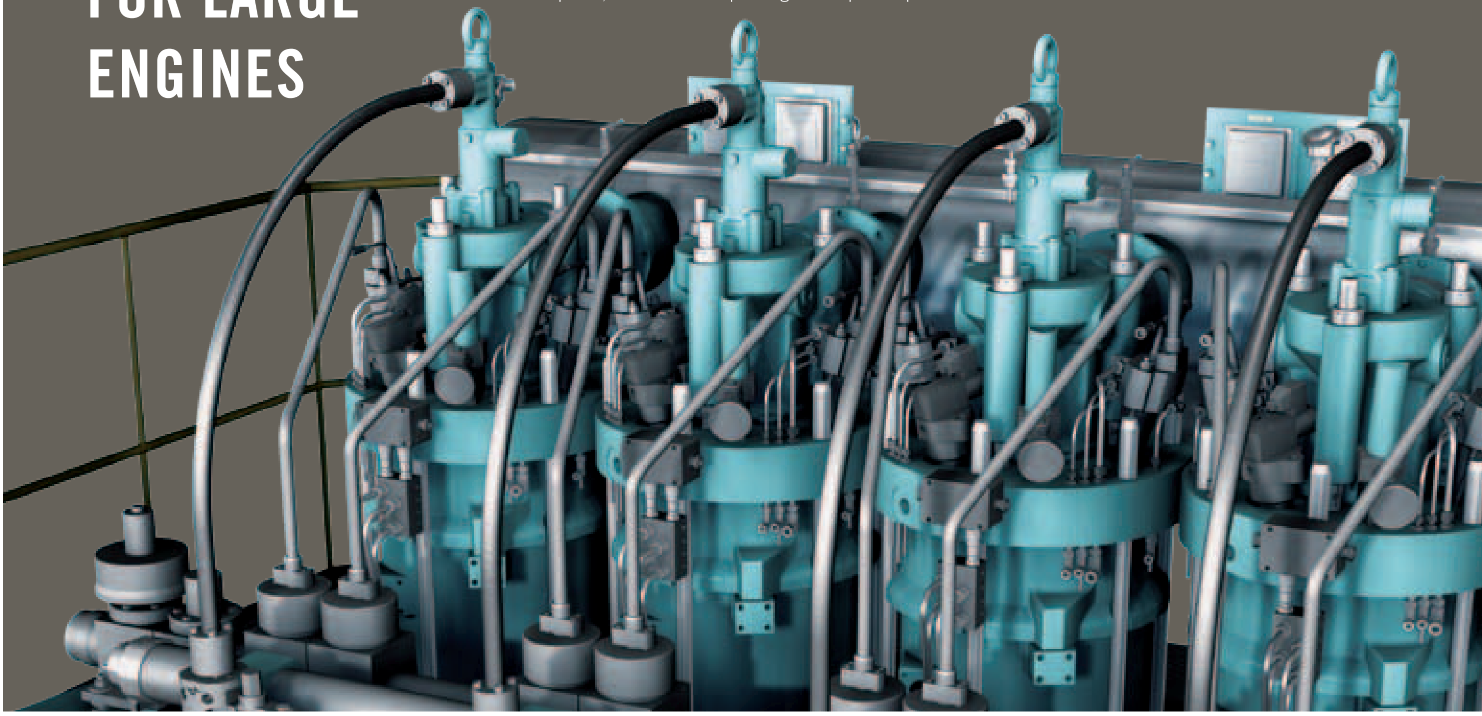
STRATEGIES FOR LARGE ENGINES

CONTENTS

COVER STORY

STRATEGIES FOR LARGE ENGINES

4, 10 I The extremes involved in the process of developing large engines relate not only to their physical dimensions. There are also conflicts in the specifications between, on the one hand, the requirement for reductions in emission levels and a long service life and, on the other, the need for cost-effectiveness, despite the low production volumes. As a result, the cover story focuses not only on the engineering aspects, but also on improving development processes.



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COVER FIGURE © MAN **FIGURE ABOVE** © Wärtsilä

PRESENTING THE FACTS

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Dear Reader,

The IAA, the world's most important car show, is an indicator of current developments and trends within the industry and there have rarely been so many innovations on show as was the case this year. The majority related to powertrains, but this was not at all obvious at first glance. The tangible technical progress was often well concealed behind carefully staged presentations of possible future projects. The exhibition is increasingly taking on the nature of a stage show, with the manufacturers' stands becoming ever more impressive. This is what attracts visitors and also clearly demonstrates the need for communication. The message is that cars can and will retain their emotional character in future, despite efficiency measures and despite electrification.

This year the spotlight was primarily on electric vehicles, generally in the form of prototypes. Electric cars have a strong public appeal, but the displays were also aimed at politicians, who will be providing research funding to support these projects. Existing drive systems were relegated to the second row of the grid, which is a pity, because they have achieved a number of genuine milestones in the process of reducing emissions, one example being the VW four-cylinder gasoline engine with cylinder deactivation, and also because these technologies will very soon be available on the market for end customers to buy. Unfortunately, manufacturers seem to believe that progress in this area is less beneficial to their public image than electric prototypes.

This "electric effect" is hardly surprising, given the ongoing public debate on the subject. However, what is often forgotten is that we first of all need to supply some basic information, for example, by clearly explaining the CO_2 strategy and accompanying this with objective, physical facts. This could help to increase public awareness of the significant progress that is currently being made.

We, as a representative of the media, and the numerous authors among you can play our own small part in this by continuing to make available an increasing amount of background information.

Yours,

RUBEN DANISCH, Vice Editor-in-Chief
Wiesbaden, 21 September 2011

DEVELOPMENT METHODOLOGY FOR **INDUSTRIAL DIESEL ENGINES**

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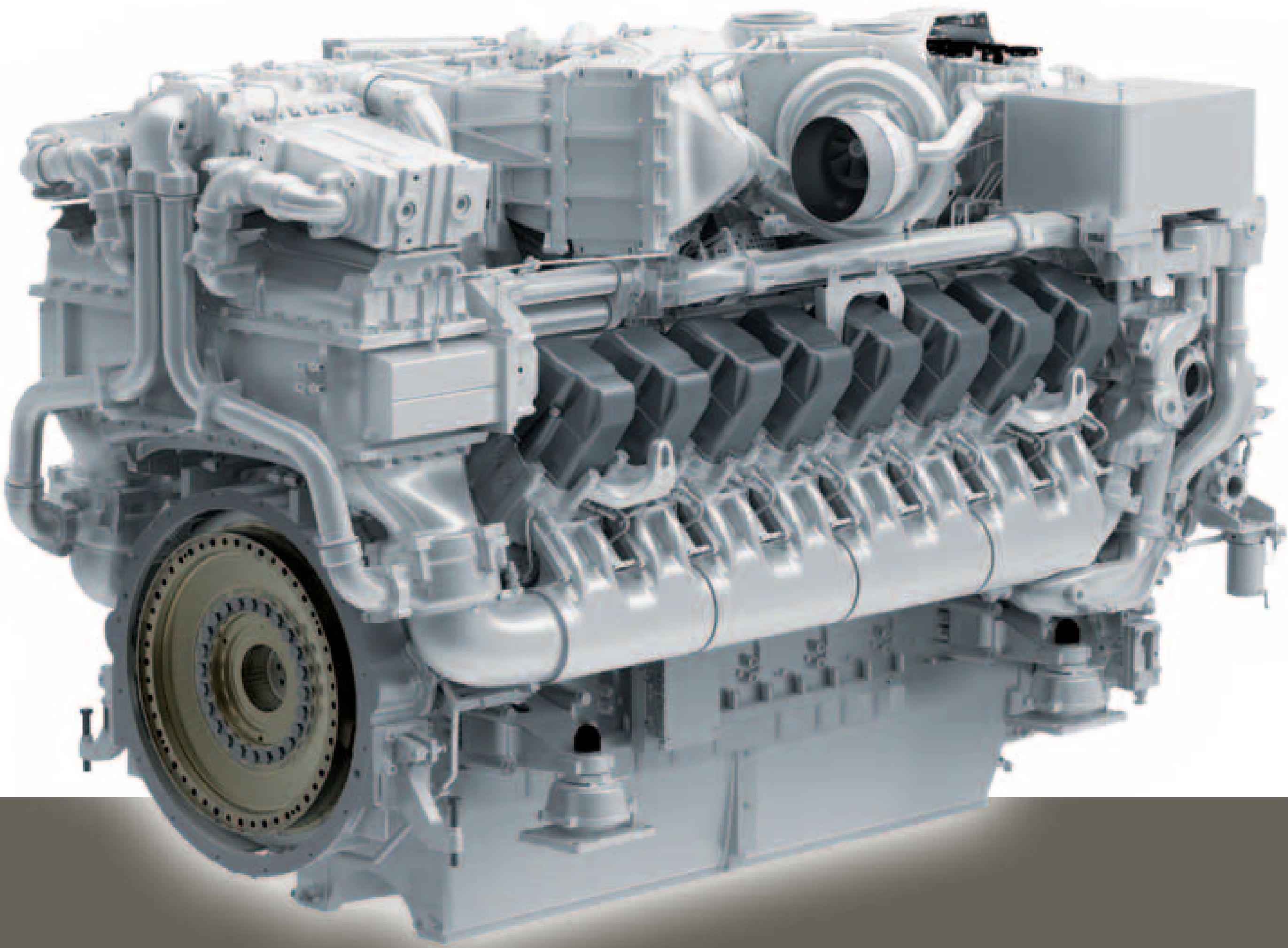

In order to remain cost-effective with relatively low production volumes in spite of the high requirements regarding emissions and durability, MTU uses a clearly structured development methodology with a close interlinking of technology and product development in the development of its large engines. For the new engine of the 4000 Series with cooled EGR, MTU applied this methodology in order to implement the emissions concept from the initial idea right through to the serial product.

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DIVERSE REQUIREMENTS

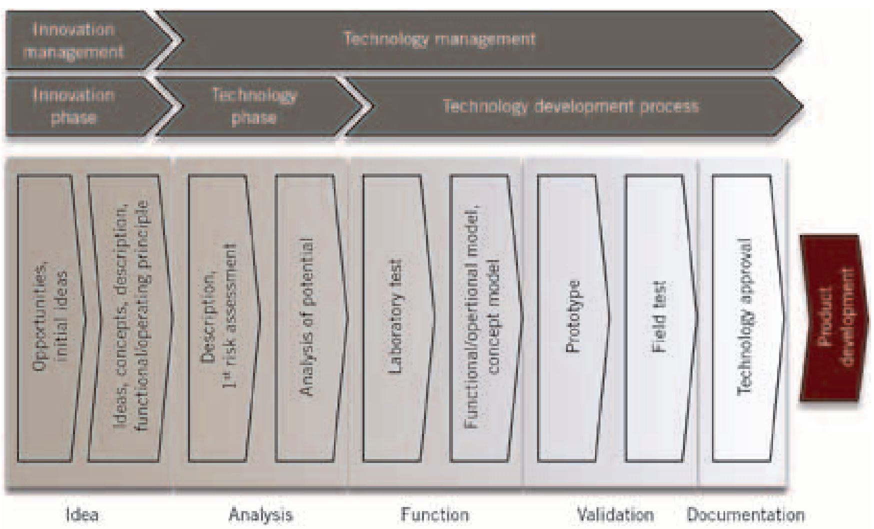
Diverse requirements must be taken into account when developing sophisticated, high-speed industrial engines: emissions standards are becoming increasingly strict and, to complicate matters further, they often vary from country to country; there is therefore a need for new system solutions in order to further reduce pollutant emissions from drive systems. Furthermore, customers now demand drive systems that offer low fuel consumption and low costs over the product lifetime, good reliability, and a space- and weight-optimized design. Due to the strict requirements involved, industrial engines are often trendsetters when it comes to new technologies. By way of example, MTU introduced the first high-speed, high-performance diesel engine with an exhaust gas turbocharger way back in 1934. MTU was also a pioneer with its electronic engine control system in the early 1980s and its common-rail injection system for large engines in 1996 [1]. In 2011, MTU unveiled the world's first large diesel engine developing over 560 kW in the shape of the modified Series 4000 unit, which uses exhaust gas recirculation (EGR) to reduce emissions [2]. Featuring the same basic technical concept with just minor application-specific modifications, the rail engines meet the requirements of the EU Stage IIIB emissions standard in Europe, while the units for the oil and gas industry are compliant with EPA Tier 4i in the USA.

INTERLINKED DEVELOPMENT METHODOLOGY

In order to ensure short development times and a high level of functional reliability when the highly innovative engines with EGR are subsequently put into service by customers, MTU has applied an all-inclusive development methodology, including close interlinking of technology development and product developmentas well as the extensive use of calculations, simulations, and component and engine testing. The methodology combines and synchronizes the technology development and product development processes, thus enabling efficient and targeted technology and product development. This methodology has proven successful at MTU and can be applied flexibly to an extremely wide range of new or further developments. In terms of technology development, i.e. advance development, five steps are used to identify the potential of a technology and then develop this technology until it is ready for pre-production, ❶. These five steps are: idea, analysis, function, validation and documentation. Taking the development of the EGR system as an example, the following sections show how this methodology optimizes the development process.

FIRST STEP: IDEA

The first development step is brainstorming, which involves identifying a functional or operating principle which could



❶ Development methodology in five steps

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❷ Series 4000 and its applications

be used to implement the required technical product features. The use of in-engine EGR measures to reduce emissions from commercial-vehicle engines is well-established. The idea of using EGR to likewise reduce nitric oxide levels in high-speed industrial engines was therefore fairly obvious. MTU conducted initial analyses and tests on an EGR system installed in previous Series 4000 engines as far back as 1993.

SECOND STEP: ANALYSIS

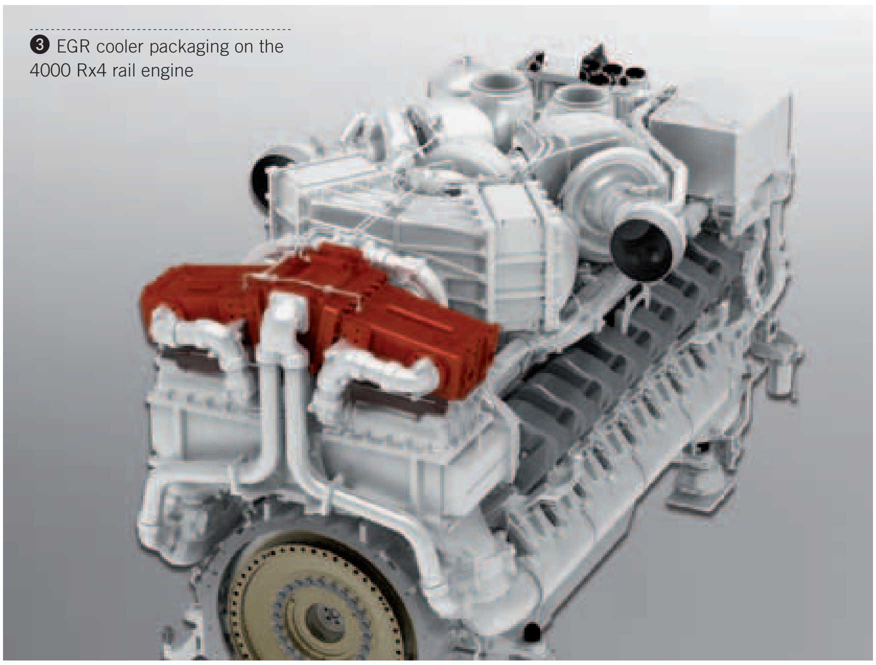
Although these initial analyses and tests confirmed the basic suitability of EGR for industrial engines, they did not lead to further development at first, since a more detailed analysis of the potential (cost/benefit, market potential, detailed time/milestone evaluation) revealed that the then applicable emissions requirements could be met at less expense by improving the combustion process. However, it was foreseeable that the legislators would introduce stricter emissions standards. In the year 2000, MTU therefore again analyzed and compared the potential of a range of different emission-reduction technologies. One criterion was the flexible use of the Series 4000 engines in various applications (e.g. rail, construction machinery and industrial applications), ❷. On the strength of EGR's advantages (flexible, robust, no second service product required) and positive customer feedback, the technology was then turned into hardware.

THIRD STEP: FUNCTIONAL DEVELOPMENT

Functional development involved developing the component and testing the concept platform. Drawing from its experience and knowledge gained in the commercial-vehicle sector, MTU focused on two main aspects when developing the EGR system:

: A low-particulate combustion process with EGR: although exhaust gas recirculation reduces nitric oxide emissions, it also leads to an undesirable increase in both particulate emissions and fuel consumption if counter-measures are not implemented.
: Dimensioning and configuration of the EGR heat exchanger(s): in the case of industrial engines with large mass air and exhaust gas flow rates, cooled EGR requires high cooling outputs, meaning that powerful heat exchangers are necessary, ❸.

Analytical calculations of the combustion process produced initial estimates of the charge pressures and air characteristics required in order to ensure an EGR-compatible combustion process that offers consistently high efficiency yet produces much less nitric oxide. From this point onwards, MTU brought on board potential suppliers and made them an integral part of the development process. The combination of MTU's engine and combustion know-how with the suppliers' component-specific know-how resulted in a development process that focused on a complete, marketable product. The injection parameters and the optimum piston recess geometry were determined on a Series



❸ EGR cooler packaging on the 4000 Rx4 rail engine

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❹ Shunting locomotive with Series 4000 prototype engine with EGR

4000 single-cylinder unit. As was shown, it is possible to achieve a 50 % reduction in nitric oxide emissions at an EGR rate of 12.5 % – without affecting fuel consumption or efficiency. This means that it is possible to reliably undercut all of the emission limits relevant to Series 4000.

Before a new technology can be considered for a product development concept, it must successfully complete the function-testing stage. On this basis, the first steps (concept selection, specification formulation, supplier screening) within a product development project and, at the same time, the further work stages in the technology development process can be tackled. Advantages of this synchronous approach include a far shorter overall development process and a continuous transfer of knowledge between technology development and product development staff, as the new technology is simultaneously further developed on different levels in both departments.

FOURTH STEP: VALIDATION

In the validation step, a real prototype engine is set up and tested, initially on a test stand and subsequently in the field. To this end, in 2002, a Series 4000 eight-cylinder engine was converted and equipped with prototype EGR heat exchangers. These heat exchangers were configured beforehand using simulations and in consultation with the supplier. As the test stand tests showed, the sooting of the EGR heat exchangers posed a major obstacle. It resulted in a worsening of the engine operating values. At the beginning of the tests, this problem prevented the engine from being operated for longer periods. By simultaneously further developing the combustion process, the injection system and the charging system, and by further improving the EGR heat exchangers (size/space), it was possible to increase the running time of the engine with EGR under all the expected operating load conditions to over 1000 hours. Finally, between 2005 and 2007, a converted production engine was operated in a shunting locomotive for 4600 hours in a joint research project with Deutsche Bahn AG, ❹. This load test is very meaningful, as shunting locomotives often operate in idle mode, and any corrosion and sooting problems clearly manifest themselves in the EGR system. The research project enabled the team to gain valuable experience, particularly in terms of material selection and the flow technology used when configuring EGR-specific components.

FIFTH STEP: DOCUMENTATION

Documentation in mid-2008 signaled the conclusion of the advance development stage for the EGR technology. Product development engineers were involved as early as the validation stage of the EGR concept. Here the aim was to enable a smooth handover of the technology to product development. The conclusion of the fifth step of the process represents a further synchronization point between technology development and product development. New technologies can only be incorporated into product development once the project has been fully documented and handed over.

THE ROUTE TO THE SERIAL PRODUCT

One of the aims of product development is to further develop the technologies from advance development into a production solution, as part of a complete product. In this case, key criteria include:
: service life
: costs
: packaging.

The challenge faced by the product development team is to ensure the perfect interaction of all technologies in the subsequent production engine under all conceivable operating and application conditions. When a new technology is handed over, technology development and product development staff work together to gauge its influence on the remaining engine functions and components. If necessary, further tests and analyses are then initiated with the subsequent product firmly in mind.

Since development of the EGR system needed to be implemented within a very short time, the technology development and product development staff worked hand in hand. By way of example, the technology development department evaluated the design practicability and tested the materials, while the product development department finalized the EGR cooler concept for the new engine model, ❺. In order to boost the operational reliability of the EGR system using validated components and reduce costs, MTU took the basic EGR heat exchanger modules from the commercial-vehicle domain and integrated them into an in-house-developed housing. The product development process involved defining the material concept and optimizing the heat exchanger housing construction while taking into account

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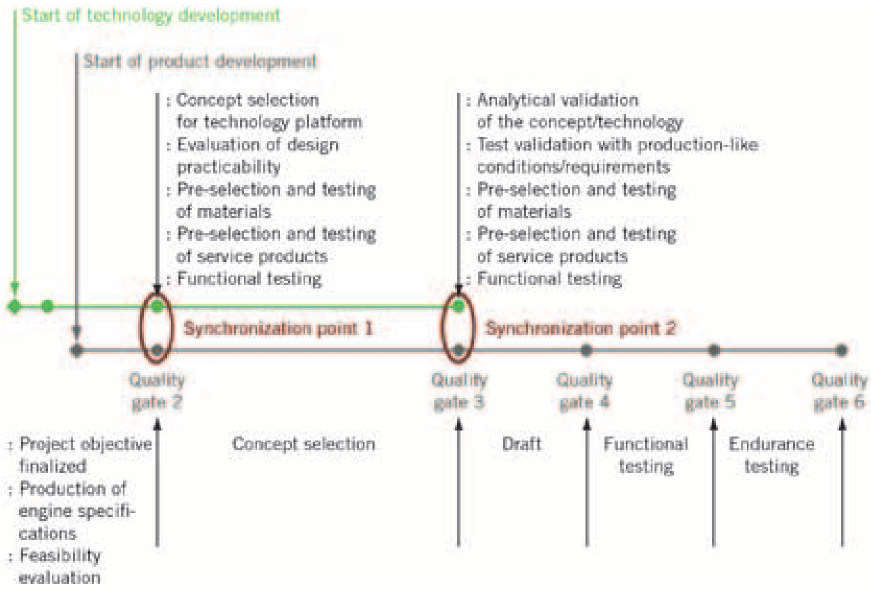

❺ Collaboration between technology development and product development departments

the available installation space, for example. Extensive tests were performed on the component test stand to test robustness in the event of thermal shock and sooting. The load profile used in this instance was derived directly from the experience previously gained in technology development.

During subsequent functional testing on the engine, the EGR cooling output and the overall engine concept were harmonized so as to minimize emissions and maximize the efficiency of the drive system. Series production of the new 4000 Series engine began in 2011 following successful completion of the endurance tests.

SUMMARY AND OUTLOOK

Due to the stringent requirements in terms of service life, economy and emissions, high-speed industrial engines are often technological pioneers in the field of engine construction. In order to implement the high degree of innovation quickly and economically with relatively low engine volumes, the use of a clearly structured development methodology, with close interlinking between technology development and product development, has proven successful at MTU. In this process, analytical tests in the form of calculations and simulations as well as component tests are of key importance. In the case of the new Series 4000 engine with cooled EGR, MTU has used the methodology to successfully implement the emission concept, from the initial idea to the pre-production product. The engine is the world's first large diesel engine with an output exceeding 560 kW to feature an EGR system. The technologies used are extensively tested until they are ready for production, forming the essential basis for high reliability and availability. Thanks to the ever-increasing capability of the software and hardware tools on the market, MTU will be able to further improve the already high level of its analytical methodology in the development process so as to enable a reduction in test stand tests.

REFERENCES
[1] Veser, N.; Braun, H.; Depfenhart, R.; Gebhardt, M.; Aupor, H.; Rehm, C.: Series 4000 – First large diesel engine with common-rail injection. In: MTZextra 100 years of MTU, 2009
[2] Wintruff, I.; Bücheler, O.; Rall, H.; Zitzler, G.: The new MTU Series 4000 rail engines for emissions standard EU IIIB. In: MTZ 72 (2011), No. 5

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NEW TWO-STROKE MARINE DIESEL ENGINES FROM WÄRTSILÄ

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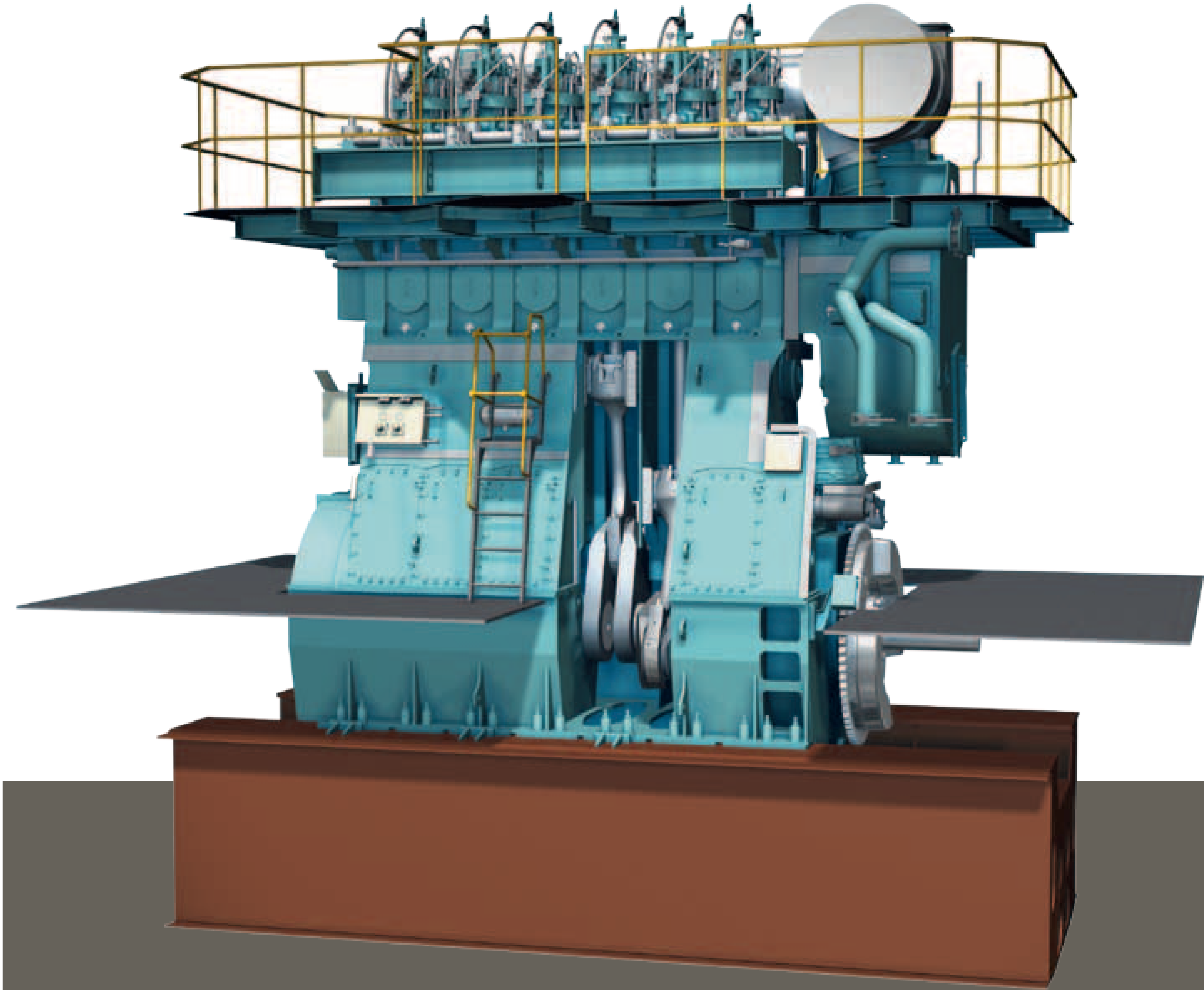

Wärtsilä has developed a new generation of small marine diesel engines with the designations RT-flex35 and RT-flex40 with cylinder bores of 35 cm and 40 cm. The engines are equipped exclusively with an integrated electronic control system, and for the first time in a low-speed two-stroke engine, a common rail fuel injection system has been adopted from the medium-speed four-stroke engine. The bore designs are based on a joint concept with Mitsubishi Heavy Industries and were developed in close cooperation. The acceptance test of the first engine, in accordance with the order of a six-cylinder engine, is planned for November 2011.

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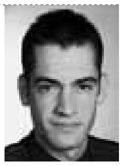

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MOTIVATION

In 2008, Wärtsilä decided to reinvigorate the small two-stroke marine diesel segment by bringing out two newly developed engines. The last new addition to the segment within the own company was the Sulzer RTA38 engine in the mid-eighties. In Asia in particular, there is a strong market for direct propeller-driven low-speed crosshead engines. The benefits are that they are cheap to produce, highly available thanks to local licensed production, simple to maintain and have low running costs [1]. Up to a bore size of around 40 cm, these engines are used in small and medium-sized commercial vessels, such as handysize bulk carriers and product tankers, general cargo vessels, container feeder ships, and small LPG carriers.

With Mitsubishi Heavy Industries Ltd. (MHI) in Kobe, Japan as a development partner, it was possible to build on the good working relationship from a previous development project, and this proved worthwhile with respect to Mitsubishi's extensive experience with the small UE range. MHI are deriving their own 35LSE and 40LSE UEC engines with mechanical injection from the RT-flex35 and RT-flex40 [2].

DEVELOPMENT OBJECTIVES

The development objectives were hence defined:

- low product life-cycle costs
- low emission level
- use of established technologies.

Reliability is always the top priority for all low-speed two-stroke engines used for marine power. For licensees, the fact that the engine is simple and economical to produce is also a key factor. From the point of view of the ship owner, operators and licensees, there is a need to minimize costs incurred throughout the life cycle of the engine, although the priority of this requirement can vary.

The RT-flex35 is the first new two-stroke engine from Wärtsilä which complies with the IMO Tier II emissions level as of its market launch. New technologies include a new design principle for the engine structure, a new injection and cylinder lubrication system, a turbocharger at the aft end of the engine and a simplified piston cooling arrangement. This means that simulation and test validation play a particularly important role, as even the first two-stroke engines in the new series will be serving a time of 25 years and longer. In order to achieve the global objectives of lower costs and emissions at the same time as high levels of reliability, a new process was used in the development of the engines which is briefly described later on.

MAIN DESIGN FEATURES

❶ shows the speed and engine performance figures for new engines in the two-stroke engine portfolio from Wärtsilä. In ❷ the main data for the new engines is listed in direct comparison to other engines. The specific figures show that the current two-stroke marine diesel engines are high-tech products. The basic features of the new engines are similar to those of typical large modern low-speed crosshead diesel engines, ❸.

ENGINE STRUCTURE

The engine structure is a welded construction with bedplate and column. The bedplate supports the crankshaft contained in it by means of a welded cast steel girder. The column, which is bolted to the bedplate and cylinder block through tie rods, incorporates the guide rails for the crosshead, through which the lateral forces from the powertrain are fed into the structure.

POWERTRAIN

The crankshaft consists of a single cylindrical shaft and webs, connected by means of a shrink fit. At the end of the crankshaft is the thrust bearing flange which feeds the propeller thrust into the ship structure through thrust pads fitted to the engine casing. A characteristic of all low-speed two-stroke large diesel engines is the rigid coupling of the engine crankshaft to the ship's propeller via the propeller shaft [3].

Because of the high levels of stress anticipated, the main bearings are aluminium shell bearings instead of the white metal bearings used in other Wärtsilä two-stroke engines. Lubrication involves a pipe connection through the bearing cover, while the upper and lower connecting rod bearings are lubricated through the crosshead. On these two-stroke engines, the oil is fed

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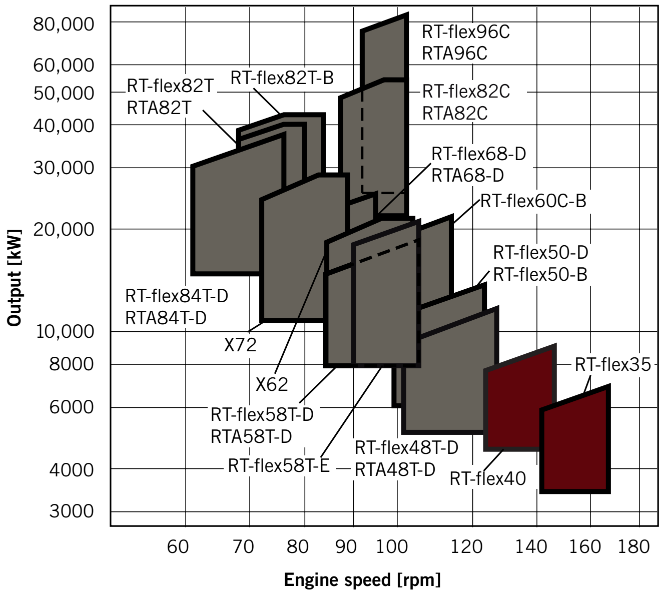
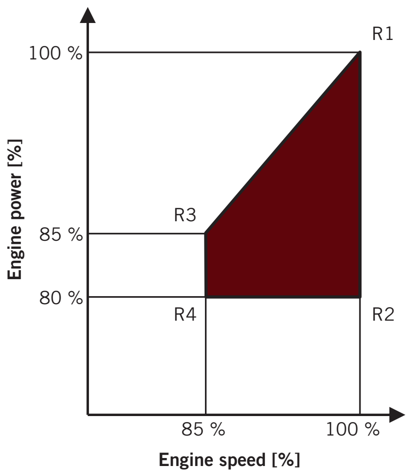
to the crosshead either using a telescopic pipe or using a knee lever, which is the solution favoured by Wärtsilä. The knee lever solution for the engines was selected following a design comparison in conjunction with development partner MHI, ❹. In order to optimize the tribological conditions on the crosshead, AVL List GmbH was enlisted to carry out elasto-hydrodynamic (EHD) simulations to help with the designs of the guide rails and guide shoes.





Engine type	RT-flex35	RT-flex40
Construction, cylinder number	Inline with welded structure, five to eight cylinders	
Bore/stroke [mm]	350/1550	400/1770
Stroke to bore ratio	4.43	
Power/cylinder [kW]	870	1135
Engine speed R1 [rpm]	167	146
Brake mean effective pressure [bar]	21	
Mean piston speed [m/s]	8.6	
Brake specific fuel consumption, standard tuning R1 [g/kWh]	176	175
Power range R1-R2 [kW]	3475 – 6960	4550 – 9080
Engine weight (six-cylinder version) [t]	80	125

❶ Wärtsilä low-speed engine portfolio

CAST CYLINDER BLOCK AND COMBUSTION CHAMBER COMPONENTS

The partition between the engine frame and the cylinder block is important for two reasons: On the one hand, it forms a safe partition between the components carrying scavenging air and exhaust gases and the crankshaft, so the power unit does not come into contact with the combustion products – one of the advantages of the crosshead design. On the other hand, it provides a transition between mainly welded and cast engine components. Depending on the engine size, around 40 % of the mass of a low-speed two-stroke large diesel engine is made up of welded structures. The engines utilize the longitudinal scavenging principle which is established for long-stroke two-stroke engines. There are scavenging ports at around bottom dead centre and by the central hydraulically actuated outlet valve, although the latter also has fully variable electronic controls.

The most striking innovation relative to the larger Wärtsilä two-stroke engines relates to the oil cooling for the pistons. Thanks to the thinner component wall thicknesses in absolute terms and the increased surface to volume ratio in the smaller combustion chamber, the system can move away from the more complex injection oil cooling using the jet shaker principle and achieve adequate component cooling by means of a simple through-flow system which is more economical to produce. The geometry of the oil-bearing parts has been designed using intense Computational Fluid Dynamics (CFD) analyzes such that the conventional production tolerances can be applied to guarantee sufficient heat transfer to the coolant medium. Here, too, the cooperation with MHI proved fruitful.

The second-largest cost factor in operating a two-stroke engine – after fuel – is the consumption of cylinder lubrication oil. A fully electronically controlled Pulse Lubrication System (PLS) has been utilized to achieve a low lubrication rate at the same time as a high level of reliability. This is in combination with the piston running concept adopted from the larger engines, which consists of plateau-honed cylinder friction surfaces with oil distribution grooves, chrome-ceramic coated, pre-profiled piston rings, gas-tight top ring and chrome-coated piston ring grooves. There is a new piston shirt with nitro-carburised friction surface to replace the otherwise standard version with set-in bronze bandages. Like the piston cooling system, the cylinder collar used around top dead centre for bore cooling in larger engines is not required, as the conventional coolant water sleeve is already capable of achieving the friction surface temperature profile specified.

Depending on the engine load, the running-in condition and sulphur content in the fuel, all these measures add up to a cylinder lubrication rate of just 0.7 g/kWh and the aim is to gradually reduce this further as of when the engine is launched on the market.

TURBOCHARGER AND SCAVENGING SYSTEM

One of the key features of the new turbocharger and scavenging system is the ompact design with integrated auxiliary blowers, ❺. Instead of the conventional

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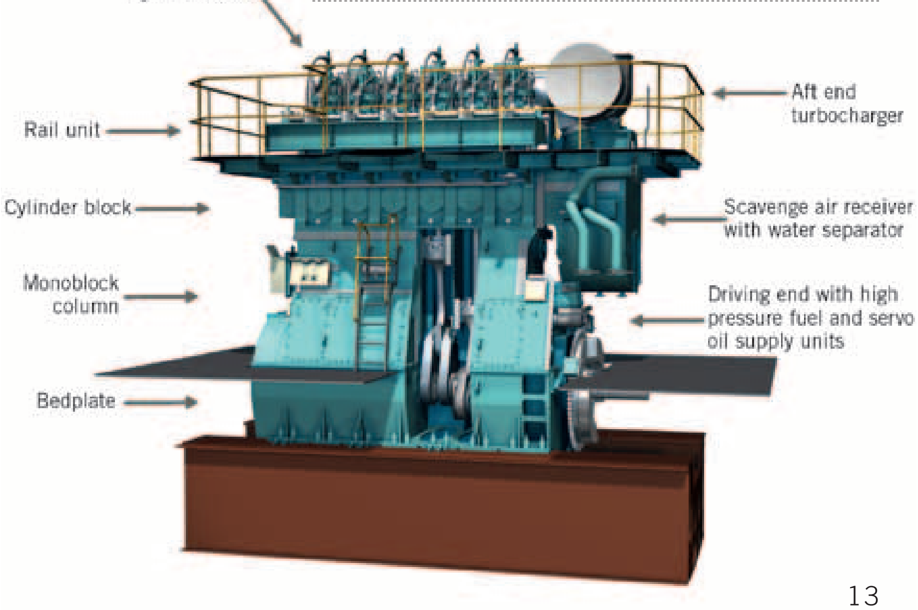
		WÄRTSILÄ 14RT-FLEX96C	WÄRTSILÄ 5RT-FLEX35	WÄRTSILÄ 8RT-FLEX40	WÄRTSILÄ 8L46F	DIESEL CV	DIESEL PC
WORKING PROCESS	–	Two-stroke	Two-stroke	Two-stroke	Four-stroke	Four-stroke	Four-stroke
BORE	mm	960	350	400	460	132	84
STROKE	mm	2500	1550	1770	580	145	90
CYLINDER DISPLACEMENT	dm^3	1810	149	222	96	1.98	0.50
TOTAL DISPLACEMENT	dm^3	25,334	746	1779	771	11.9	2.00
CYLINDER NUMBER	–	14	5	8	8	6	4
WEIGHT	kg	2,300,000	69,000	153,000	124,000	995	158
POWER OUTPUT	kW	80,080	4350	9080	9600	390	110
MAXIMUM TORQUE	kNm	7497	249	594	153	2.130	0.330
POWER/CYLINDER	kW	5720	870	1135	1200	65	27.5
NOMINAL SPEED	rpm	102	167	146	600	2100	4000
MAXIMUM BRAKE MEAN EFFECTIVE PRESSURE	bar	18.6	21	21	25	22.5	20.8
POWER DENSITY	kW/dm^3	3.2	5.8	5.1	12.4	32.8	55.1
MEAN PISTON SPEED	m/s	8.5	8.6	8.6	11.6	10.2	12
SPECIFIC TORQUE	Nm/dm^3	296	334	334	198	179	165
MEAN POWER / PISTON AREA	kW/m^2	7902	9043	9032	7221	4750	4962
BRAKE SPECIFIC FUEL CONSUMPTION	g/kWh	171	176	175	171	217	238
FUEL CONSUMPTION AT NOMINAL POWER	kg/h	13,694	766	1589	1642	85	26
FULL LOAD INJECTION QUANTITY	g/cycle	159.8	15.3	22.7	11.4	0.2	0.05
INJECTION VALVES PER CYLINDER	–	3 x 5-hole	2 x 5-hole	2 x 5-hole	1 x 10-hole	1 x 6 … 8-hole	1 x 5 … 8-hole
AVERAGE NOZZLE HOLE DIAMETER	mm	1.34	0.57	0.7	0.81	~ 0.22 (6)	~ 0.12 (8)
SPECIFIC WEIGHT	kg/kW	28.7	15.9	16.9	12.9	2.6	1.4

❷ Technical main data in comparison with other engines

lateral position of the turbocharger unit, the exhaust turbocharger is placed above the output at the end of the engine, in a similar position to medium-speed four-stroke engines. The benefit of this is the reduced overall width of the unit, which means the engine can be fitted much further back in the hull of the ship as the width begins to taper.

With constant pressure turbocharging, the size of the components carrying the scavenging air is very important. The CFD flow calculations were used to optimize receiver volumes and guarantee that all cylinders are impacted evenly. The engines also needed to be as modular in design as possible, and this requirement has also been met: the whole range from 5RT-flex35 to

❸ Basic design six-cylinder engine



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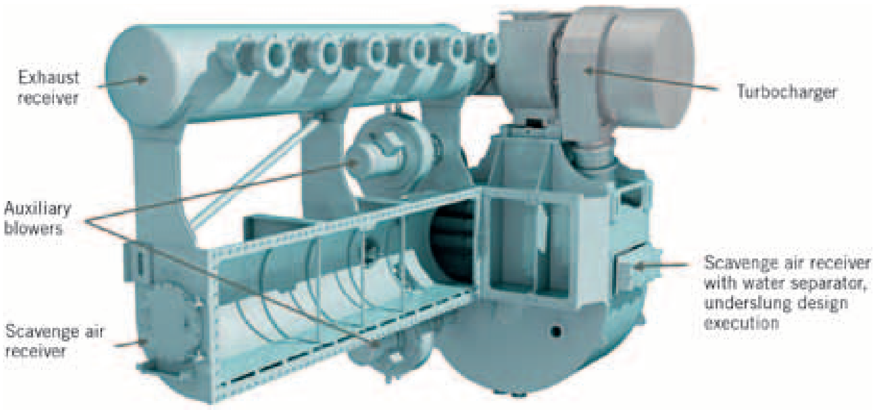
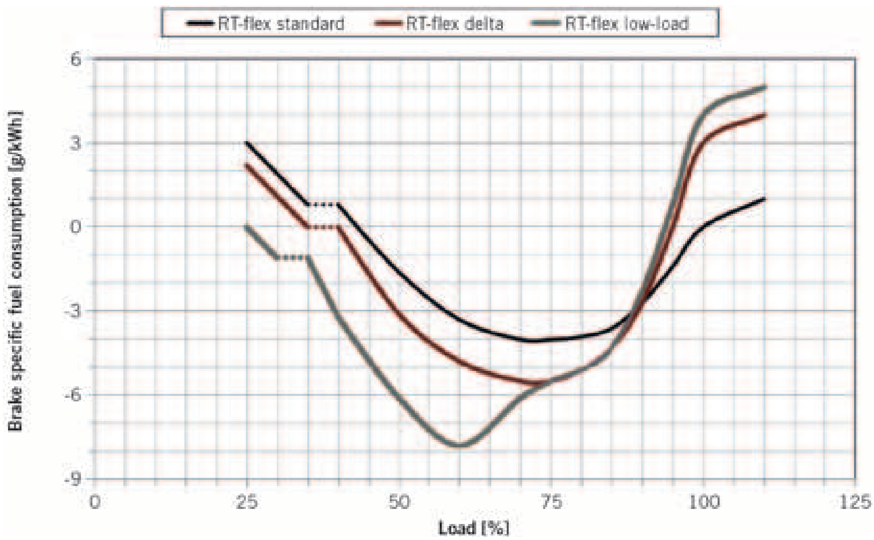
❹ Powertrain components



❺ Turbocharging and scavenging system



❻ Tier II tuning variants for constant NO_x cycle results

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8RT-flex40 is covered by two turbocharger sizes (with different performance levels) and two basic designs. There is a choice of exhaust turbochargers available from ABB (A series) and MHI-MET (MB series). The aft end turbocharger system Wärtsilä has used for the first time on the new engines has now been adapted for the RT-flex50 and is available as an option instead of the conventional, lateral turbocharger arrangement.

ELECTRONIC ENGINE CONTROL

At Wärtsilä, all electronically controlled two-stroke engines are called RT-flex. The system was developed entirely in-house and was introduced as a new concept in the low-speed two-stroke engines market in 2001 [4]. In line with the Wärtsilä development strategy, development work since 2008 has focussed exclusively on electronically controlled two-stroke engines. The fact that the improved flexibility, consumption and emissions are adapted to the performance figures represents real enhancement to customer benefits which translates into more economical fuel consumption in the medium and low-load range, ❻. Around 90 % of the engines in the current order book are electronically controlled.

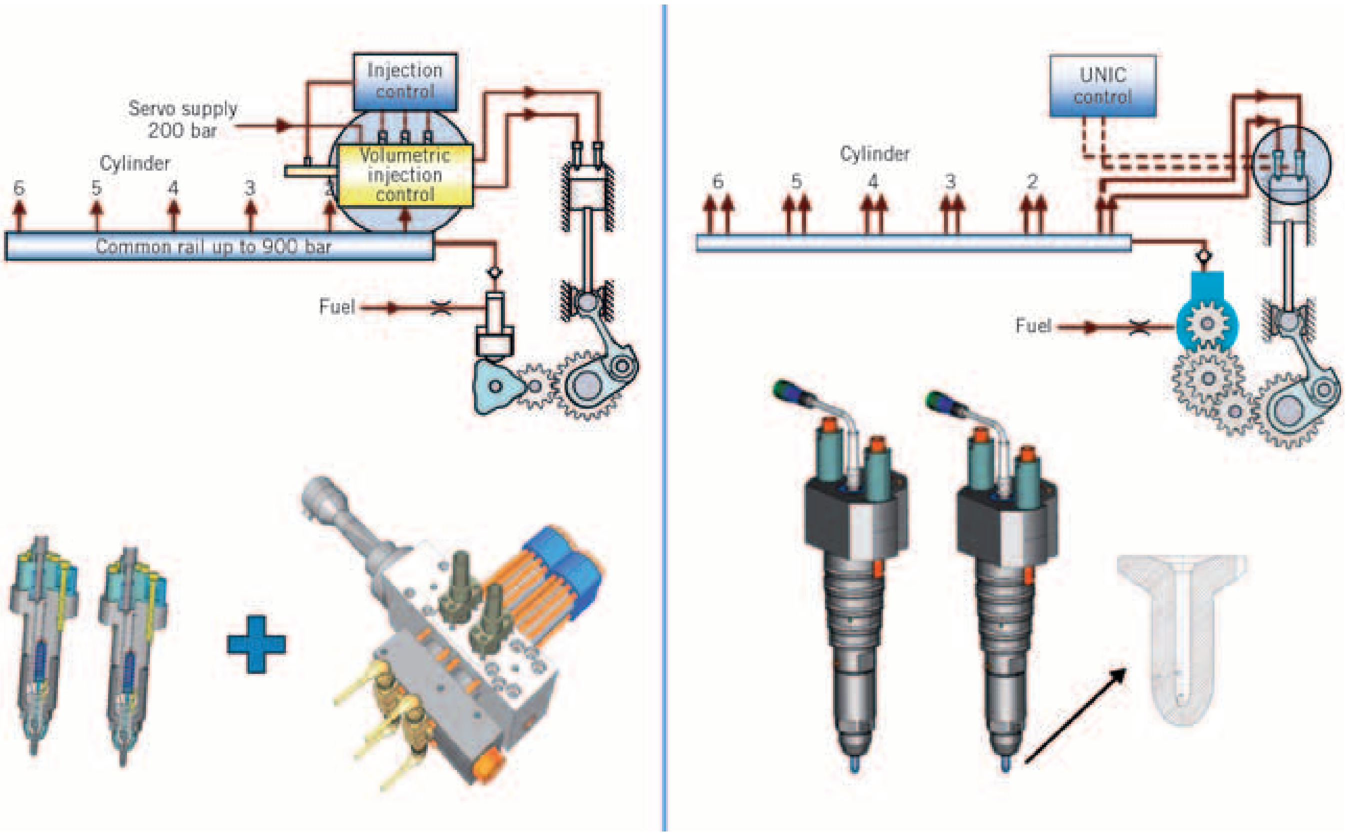
The electronic engine control incorporates the following component systems:

: common rail injection for operation with heavy fuel oil
: electro-hydraulically actuated exhaust valve control (i. e. without engine camshaft)
: pulse cylinder lubrication system (PLS)
: engine start system with starting air distribution.

These are all based on the Wärtsilä UNIC electronic engine controller, the sensors (e. g. crank angle detection) on which are utilized by the other component systems. The current C3 version of UNIC has been used in Wärtsilä's common rail four-stroke engines since 2008 and is now being used in the two-stroke sector for the first time. The system is modular in design and incorporates not only alarm, monitoring and safety functions but also selective cylinder control functions including cylinder pressure-based combustion control options.

COMMON RAIL INJECTION SYSTEM

Even before the design phase of the engine development process, Wärtsilä had considered using an established four-stroke common rail (CR) injection system on a two-stroke engine. The new smaller bore engines to be developed met the requirements:



❼ Common rail fuel injection systems with volumetric control for large bore engines (left) and with time control for small bore engines (right)

- similar sizes and compatible component dimensions
- cost-saving volume effects thanks to increased sales volumes anticipated in the small two-stroke engine sector
- benefits of time-controlled CR system compared to the previous volume-controlled CR for use on smaller, higher revving engines (dynamics)
- suitability of the smaller engines for test purposes for the basic development of an IMO Tier III-compliant system at a further stage.

A further benefit was the global research and development organisational structure within Wärtsilä with existing interdisciplinary project teams in place as of the beginning of the development phase. Wärtsilä therefore decided to develop the new injection system in conjunction with the project partners. All the project targets defined have been achieved thus far.

❼ shows a comparison of the CR injection systems for Wärtsilä two-stroke engines with large and small bore sizes. The system for large bore sizes shown on the left-hand side of the diagram uses a servo-hydraulically operated control unit, known as the Injection Control Unit (ICU) in conjunction with conventional injectors. An integrated volume piston provides accurate, crank angle resolved information for comparing the volume specifications to the actual amounts (volume control). On the right is the new system for small bore sizes, where the ICU functionality has been replaced with an electrical solenoid valve in the upper injector portion, allowing the fuel itself to replace the servo oil as a control medium. Injection is triggered when the built-in magnetic valve is actuated in the normal time-controlled way.

As a result of the changes to the system architecture, the costs incurred by the licensee for all the injection equipment can be reduced by half relative to the same engine performance. What is all the more remarkable is the fact that the system costs for the new CR injection system are below those for a conventional mechanical two-stroke diesel injection system for the first time.

❽ shows the supply unit on the driving end of the engine, with two high-pressure fuel pumps and two servo oil pumps. In order to reduce the power required, the high-pressure pumps are fitted with a throttle device on the inlet side. The Wärtsilä two-stroke diesel engines currently work with injection pressures of 900 bar and 1000 bar. On both of the above systems, the injection rate can be shaped by actuating either two or three of the injectors placed on the circumference of the injectors in sequence. This technology is used in Wärtsilä RT-flex engines to reduce smoke and NO_x emissions in the partial load range and to ensure the engine runs smoothly even in single digit rev numbers. The new "small" system also has the option of multiple injection for each injector. In principle, it is compatible with up to 1600 bar and thus offers additional potential for developing the combustion system further.

❾ shows the individual components of the high-pressure system, with rail, pressure control valve, flow limiter valves and high-pressure lines developed in Effretikon, Switzerland, in conjunction with Nova Werke. The high-pressure pump and in-

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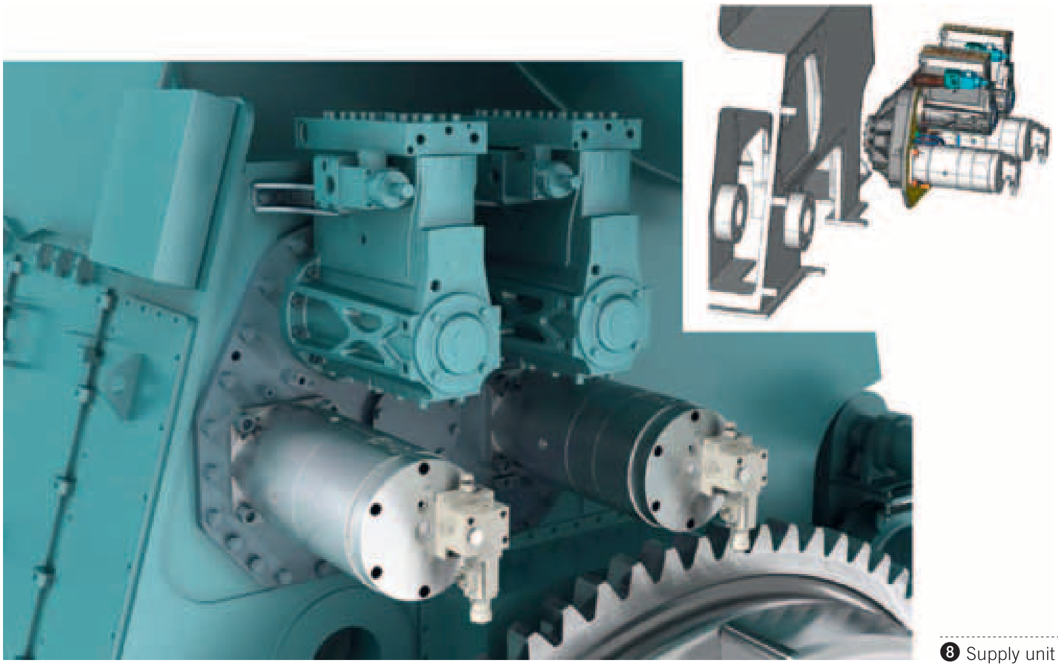


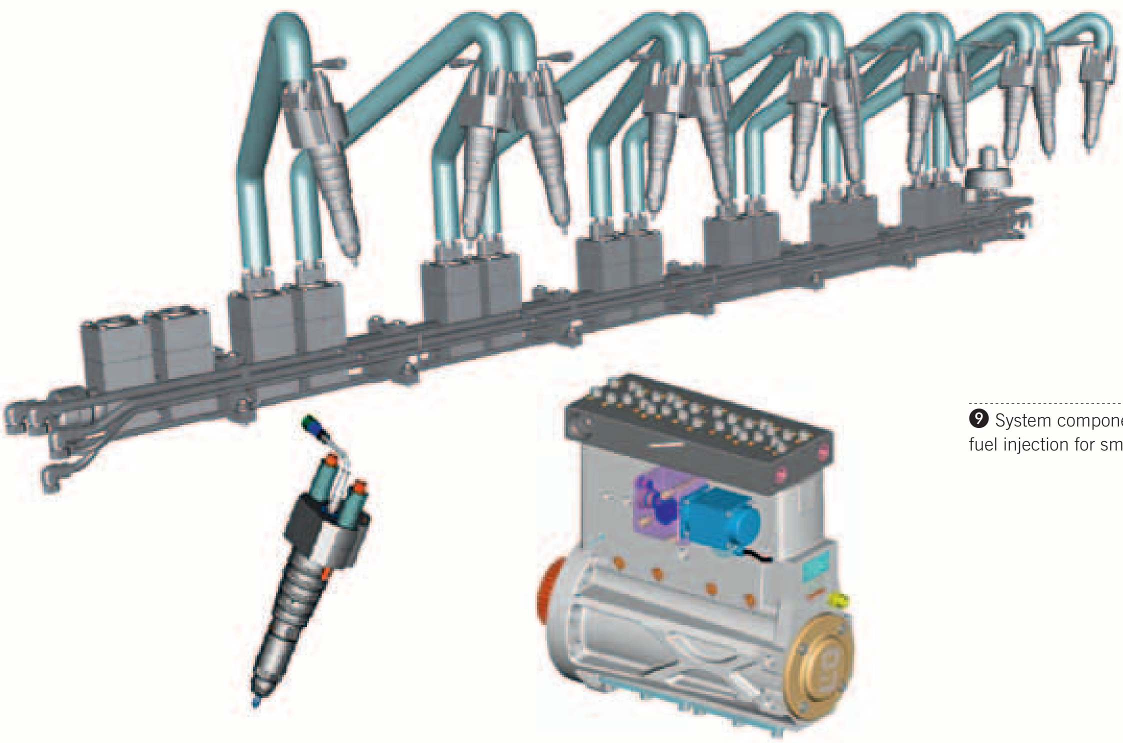
❽ Supply unit

jectors were developed by L'Orange GmbH, Stuttgart, Wärtsilä's main cooperation partner in the injection component project.

CYLINDER LUBRICATION SYSTEM

Separating the powertrain and gas exchange areas of the crosshead engine means that the lubrication system is different on two-stroke large diesel engines than on trunk piston engines. The cylinder lubrication oil is not connected to the system oil in the crankcase by means of an oil circuit. At the end of the day, this means a loss or continual top-up of the lubricant used up on the friction surface of the cylinder, and this needs optimization. An external pump delivers the lubricant oil quantities to each engine cylinder liner from the outside through dedicated bore holes.

The electronically controlled PLS pulse lubrication system was developed in cooperation with SKF Lubrication Systems Germany AG, Hockenheim (previously Vogel AG) and introduced for Wärtsilä two-stroke engines in 2006. The higher speed (167 rpm) of the 35 cm sets more exacting requirements of the dosing accuracy, frequency and minimal volumes needed. In order to comply with these,



❾ System components of the new common rail fuel injection for small cylinder bore sizes

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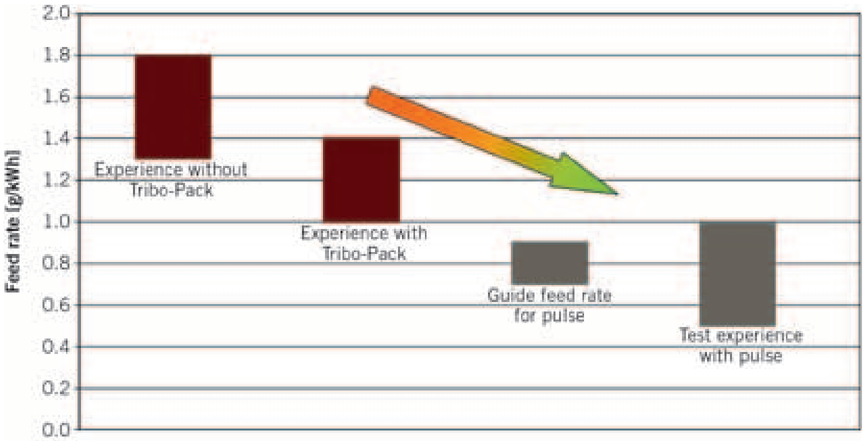

⓾ Lubrication oil feed rate development for Wärtsilä two-stroke engines

the new double-acting pump CLU5 was developed. As the double-action principle only requires one action of the 4/2-way valve per pumping stroke, the overall number of cycles is halved relative to single-action pumps. ⓾ shows the development of cylinder lubrication rates on Wärtsilä engines since the introduction of the Tribo-Pack standard described in [5].

DEVELOPMENT METHOD

The so called design-for-x target-criteria-based development method has been successfully introduced and refined for a previous Wärtsilä engine product. At the beginning of the development project, the design-to-cost discipline was firmly anchored into the organisation of project and line structures at a relevant level in order to ensure that the factor of engine costs was considered and to guarantee the competitiveness of the new two-stroke engine. In practice, this resulted in clear specifications for each engine design group which represented an important, accepted control instrument both at the design phase and throughout the entire term of the project. This meant that the original costs target for the entire engine was reached just half way through the project in August 2009, at which point the target was given a moderate increase.

SIMULATION AND VALIDATION SYSTEM

During the development phases for the new engines, major advances were also made in terms of simulation. Fatigue and vibration analyzes were more often based on complete engine models to allow projected statements on vibration behaviour of critical engine components. This was backed up by experience with earlier comparisons of calculations and measurements on partial models. The extensive simulation activities on the first six-cylinder version of the engine included:

: fatigue assessment based on dynamic stress calculations
: multi body simulation of the complete powertrain
: elasto-hydrodynamic simulation of plain bearings
: thermo-mechanical simulation of the combustion chamber
: computational fluid dynamics of combustion, lubrication and gas flows
: harmonic response simulation of the entire engine vibration regime
: explicit dynamic FE simulation of high velocity impacts on fuel injection components.

The expectation is that the accuracy of simulation results will increase significantly after the measurement campaigns planned for the first engine have been analyzed and that this will be beneficial to internal know-how and future engine development.

This is why there are plans to carry out a 500-h comprehensive engine testing programme in cooperation with licensee 3. Maj Engines & Cranes in Rijeka, Croatia, which will be a first of its kind when it comes to the testing of two-stroke engines. At the same time, the extended performance tests will help validate the newly developed component systems and how they interact in the engine. Essentially, the functionality of newly developed Wärtsilä components and systems is guaranteed by testing on specially built functional and continuous test beds for a period > 3000 h. At the Wärtsilä Diesel Technology Centre in Oberwinterthur, functional and durability test rigs were purpose-built for the fuel injection and PLS cylinder lubrication systems of the new engine.

SUMMARY AND OUTLOOK

The Wärtsilä RT-flex two-stroke 35 cm and 40 cm bore marine diesel engines are low-cost, high-tech products whose development has focused more than ever on excellent reliability and low life-cycle costs for the customer. Development work involving new, sophisticated methods has been successfully completed. The first RT-flex35 six-cylinder engines are currently under construction. Tests are due to finish in November 2011.

REFERENCES

[1] Heim, K.; Frigge, P.: The Wärtsilä low-speed engine programme for today's and future requirements. 26th CIMAC World Congress 2010, Bergen, Norway
[2] Sakabe, H.; Hosokawa, N.: Cutting edge technologies of UE engine for higher efficiency and environment. 26th CIMAC World Congress 2010, Bergen, Norway
[3] Mollenhauer, K.; Tschöke, H. (Pub.): Handbuch Dieselmotoren. 3rd Edition Berlin: Springer, 2007
[4] Demmerle, R.; Heim, K.: Evolution of the Sulzer RT-flex common rail system. 24th CIMAC World Congress 2004, Kyoto, Japan
[5] Amoser, M.: Verbesserter Kolbenlauf von langsam laufenden Dieselmotoren. In: MTZ 63 (2002), No. 4

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THE NEW FOUR-CYLINDER DIESEL ENGINE FOR THE MERCEDES-BENZ B-CLASS

Based on the 2.2 l diesel engine OM 651, Mercedes-Benz has developed a specially adapted variant with the same basic engine. It will first go into series production with the new B-Class. In future this new engine will be used in all passenger cars from Mercedes-Benz with front wheel drive. This is the first time that the full consumption, emissions and performance potential of this engine, which already drives a wide range of Mercedes-Benz cars including the S-Class, has been transferred to compact models.

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OBJECTIVES

The new B-Class differs from its predecessor in that its drive configuration positions the engine in front of the front axle as opposed to behind the front axle. The basic OM 651 diesel engine was originally designed so as to allow transverse installation in compact vehicles while requiring a minimum of adaptive work. In view of the mandatory CO_2 reductions, it was necessary not only to develop an engine which was a benchmark in its class with respect to fuel consumption but also to achieve significant progress in terms of performance and NVH characteristics [1]. The following development targets arose as a result of these specific conditions:

: significant reduction of fuel consumption/ CO_2 emissions by more than 20 g/km compared with the predecessor engine
: to increase the specific performance and torque values as well as agility
: to achieve Euro 5 emission level without active NO_x reduction and to create a concept for future global emissions legislation
: to achieve a high degree of commonality with the basic engine, requiring few new parts
: to create a standardized engine for left-hand and right-hand drive
: to achieve a high level of quality and maturity by keeping design close to that of the basic engine.

BASIC ENGINE

After the introduction of the OM 651 into passenger car series with longitudinal installation as well as the transporter applications, the modular structure of the OM 651 has now been fully transferred to transverse installation. The engine capacity of 1.8 l has been represented by an engine variant with a stroke of 83 mm while the main dimensions of bore and cylinder spacing remain the same as in the basic 2.2 l engine, ❶. As a result of this modular approach, it was possible to incorporate many of the original components.

CYLINDER CRANKCASE

Use of the engine in the B-Class led to the creation of a crankcase variant which has been designed especially for transverse installation and optimized in terms of assembly and weight. As the exhaust gas turbocharger arrangement has been modified in comparison with the longitudinal model series, a specific oil return flow has been determined. With this engine arrangement, the crankshaft and Lanchester shaft bearing are subject to a single bearing cover concept. It was also possible to reduce the crankcase weight by 5 % due to omission of bosses specific to longitudinal installation.

POWERTRAIN

As mentioned above, the adjusted engine capacity of 1.796 l was represented by a powertrain variant. This consists of the following components:

: crankshaft with stroke of 83 mm
: connecting rod adapted to the reduced stroke
: optimized piston with reduced hoop stress
: adapted Lanchester shaft
: dual-mass flywheel and belt pulley decoupler.

		B-Class (model series 245) OM 640		New B-Class (model series 246) OM 651	
Cylinder arrangement/number		I4		I4	
Number of valves		4		4	
Displacement	cm³	1991		1796	
Cylinder offset	mm	90		94	
Bore	mm	83		83	
Stroke	mm	92		83	
Stroke/bore ratio		1.108		1	
Connecting rod length	mm	147.85		154.40	
Nominal power at speed	kW rpm	80 4200	103 4200	80 3200-4400	100 3400-4400
Max. torque at speed	Nm rpm	250 1600-2600	300 1600-3000	250 1400-2800	300 1600-3000
Compression ratio		18.0		16.2	
Emissions standard		Euro 5		Euro 5	

❶ Dimensions and performance data for the diesel engine OM 651 in the B-Class

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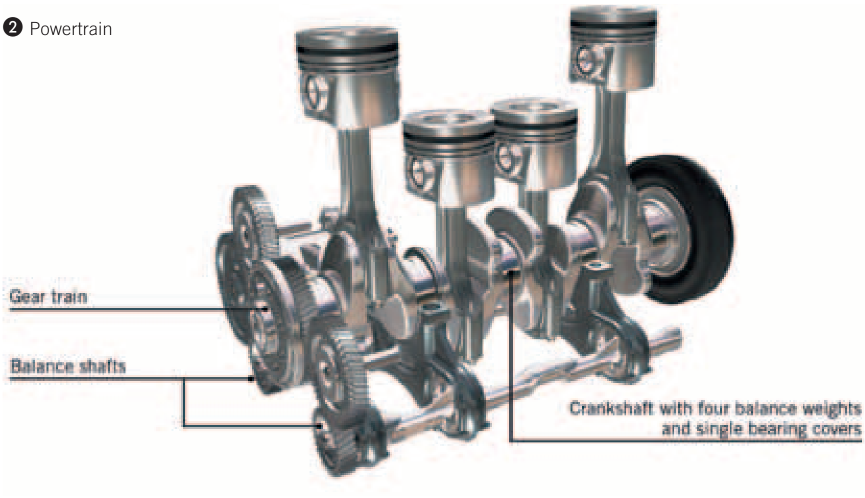
❷ Powertrain



The crankshaft is designed with four counterweights and enables a further weight reduction of 5.6 kg compared with the eight-counterweight crankshaft used in the 2.2 l basic engine. The hoop parcel used for the piston with reduced hoop stress at the third hoop leads to a CO_2 benefit of 2 g/km in NEDC while the blow-by remains the same. With identical drive via gear drive on the transmission side of the engine, the second order inertial forces are completely eliminated through the adapted Lanchester balancer, ❷.

With the introduction of a start-stop system, robust bearing shells and a decoupler are used in the belt drive. The decoupler in the belt drive also leads to a reduction of the tension forces with a CO_2 benefit. With possible performance of 80 kW to 100 kW, a weight-optimized design of the dual-mass flywheel is used.

This powertrain variant reduces the complete motor weight by 14 kg in accordance with DIN 70020-GZ. Further development towards Euro 6 was incorporated into the concept and can be continued on the bases of modular components.

CYLINDER HEAD

It is necessary to adapt the cylinder head in order to compensate for the reduced swirl ratio due to the decreased stroke of the 1.8 l engine. The combustion requirements are satisfied as a result of modifying the intake tangential channel and reducing the lift of the valve in the inlet spiral channel from 9 to 7 mm. This means that the lower swirl number can be raised again to the required value of 2.7.

OIL PUMP

In order to achieve the low CO_2 output, the oil pressure is adapted to the engine requirements in addition to the volume-flow regulated oil pump already used in the basic engine. Up to a medium engine load, only a low oil pressure is required for the cooling and lubricating requirements of the engine components. The maximum oil pressure, and therefore full cooling for the engine components, is only required with a high load. This is represented by a dual-pressure and volume-flow regulated vane cell oil pump, ❸.

The functions are achieved by a 3/2-way hydraulic shift valve which regulates the counterforce for the control piston:

: Low pressure stage 2.0 bar: The control piston counterforce consists only of the spring force.

: High pressure stage 5.0 bar: The control piston counterforce results from adding the spring force to the oil pressure force arising from the product of the control piston mating surface times the control pressure.

The fail-safe function is designed in such a way that the high oil pressure is always present in the event of a disruption to the oil pressure shift valve.

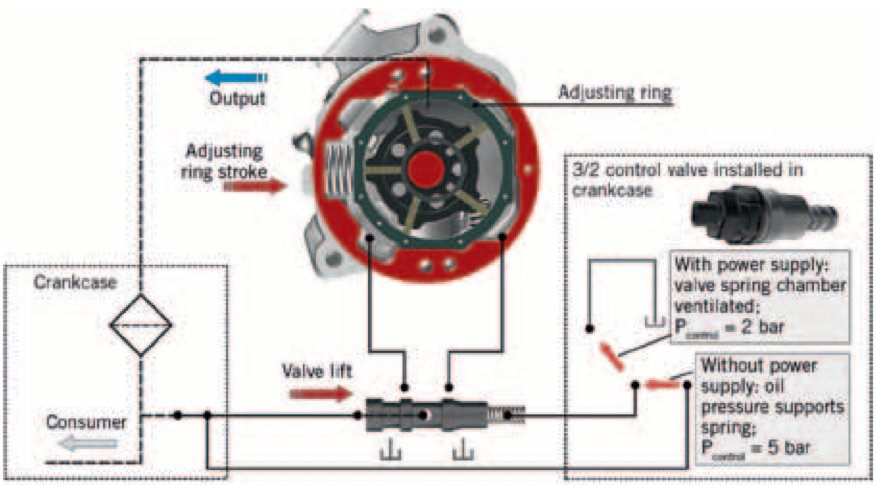
Another oil circuit measure for reducing fuel consumption is the adjustable piston cooling. A separate oil channel is also positioned in the crankcase to supply the oil injection nozzles. The oil supply is controlled by an electrical valve. This piston cooling is activated and deactivated depending on the performance map.

VACUUM PUMP

Another key accessory is the vacuum pump, which has also been enhanced for this engine in terms of minimizing CO_2. The target was to significantly reduce the required drive output without loss of air removal time. This is achieved through optimization of the gas cycle input in the pump and modifications to the vane material. As a result of these measures, the necessary driving power of the vacuum pump is reduced by 40 %.

AIR DUCTING

An on-board damper filter is used for the air intake system, ❹. This allows large air volumes and air duct-sections which enable low flow losses. Combined with spe-



❸ Principle diagram of the dual-pressure stage controlled oil pump

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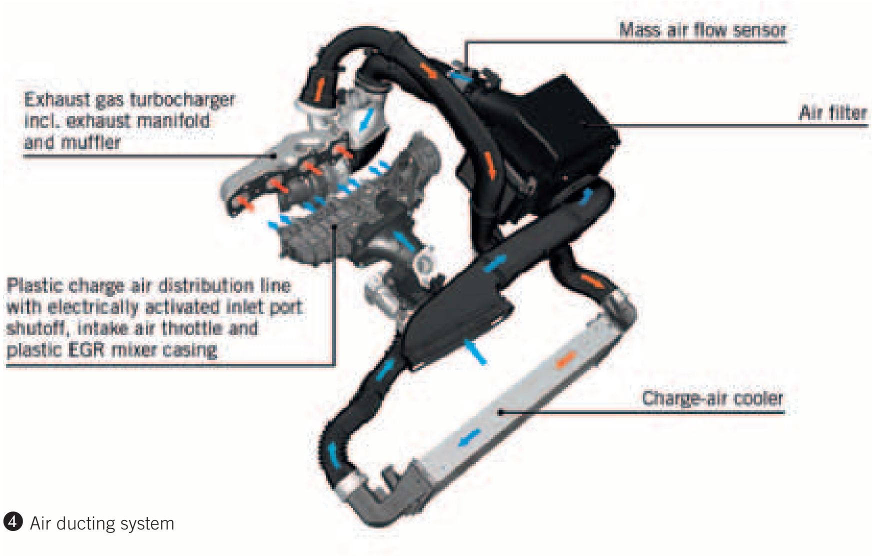
cial acoustic materials, this has led to good intake and flow noise damping. The design of the raw air duct, damper filter and clean air duct is matched such that uniform loading of the damper filter cartridge results in an even inflow to the air mass sensor and compressor. The rest of the air ducting, consisting of the charge air line, intake air throttle, charge air manifold with exhaust gas recirculation (EGR) introduction, charge air distribution line with inlet port shut-off, was taken over from the current series production engine. The EGR system with precooler, electrically driven exhaust gas recirculation valve, EGR cooler and EGR introduction into the charge air manifold, which was successful in the north-south installation engine, has been used.



❹ Air ducting system

CHARGING

The RHV34 exhaust gas turbocharger produced by IHI Charging Systems International is a new development arising as an optimized variant based on the RHV3 and RHV4 types. The exhaust gas turbocharger has a variable turbine which is activated with an electrical actuator. Special features include:

: small turbine design for good response characteristics
: reduced leakage loss in the turbine
: optimized flow around the turbine vanes.

The focus of the aerodynamic design was the left half of the engine map which is of great importance for the fuel consumption. As a result of this, the inertia moment of the rotor could be reduced by approximately 14 % compared with the exhaust gas turbocharger of the OM 640 predecessor engine. With this design, the exhaust gas turbocharger achieves excellent transient characteristics. As a result of the measures aimed at improving efficiency, the gas exchange work was reduced to a large extent within the engine map. ❺ shows the reduction of up to 1.0 bar of the gas exchange work compared with the OM 640 predecessor engine.

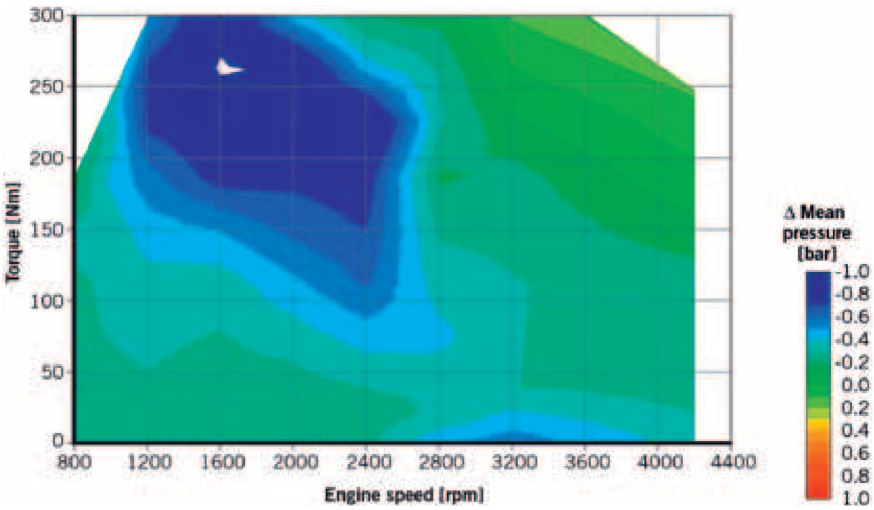
EXHAUST MANIFOLD

The exhaust manifold with air gap insulation (LSI) was chosen in order to meet the exhaust emission values. The external and internal components are presented as deep-drawn half-shells due to the compact design required in transverse engine direction and with a view to low costs, ❻. The durability requirements were further arguments in favour of the LSI principle. The separation of the exhaust gas turbocharger and the exhaust manifold results in a significant recess clearance saving of the external shells for access to the assembly in the direction of the cylinder head. A double flange is used in order to ensure thermomechanical rigidity in this area. As the mass of the exhaust gas turbocharger is mainly supported at the outlet flange, the outlet flange had to be robustly attached to the lower shell. Dynamic and thermomechanical stability were ensured at this point using a contoured, rigid forged flange and an external weld seam. This variant also avoids welding residues in the gas-distribution area.

EXHAUST SYSTEM

The OM 651 engine's exhaust system in the new B-Class meets the legal requirements of the target markets as well as the high standards expected of Mercedes-Benz vehicles. These expectations particularly relate to matters of acoustic comfort, environmental compatibility and, not least, longevity. To meet these requirements, the following issues were solved during development:

: introduction of the exhaust aftertreatment components to achieve Euro 5 emission level



❺ Reduction of gas exchange work

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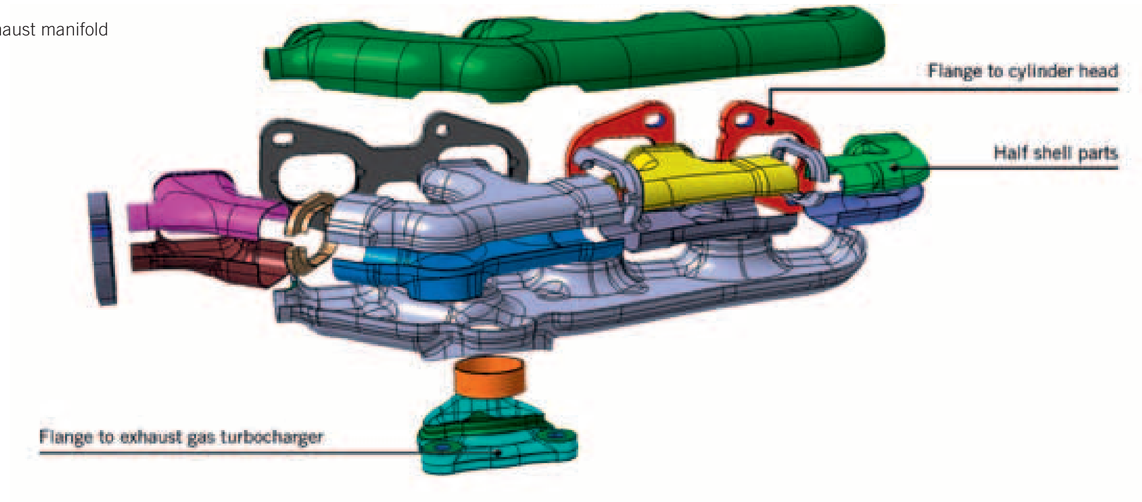
❻ Structure of LSI exhaust manifold



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- : weight optimization of all components with simultaneous optimization of lifetime
- : optimization of the exhaust system's exhaust back pressure to ensure engine efficiency
- : generation of a high level of exhaust noise comfort and minimization of vibrations entering the vehicle
- : achievement of the target values for external noise.

The exhaust system of the new B-Class is designed as one component and attached after the turbocharger with a decoupling element on-board by means of a mount on the integral support frame and with four rubber suspensions each on the vehicle shell. The entire exhaust system is made of stainless steel and contains a combination box 6.2" in diameter as well as a transverse, volume-optimized rear silencer.

The gases are discharged at the vehicle rear end via a tailpipe, with tailpipe finish depending on the vehicle equipment. A diameter of 65 mm is used for all system piping resulting in a lower back pressure value. The internal muffler structures were designed to optimally meet the acoustic requirements without exceeding the back pressure target values. FEM calculations were performed right from the start of the system design phase in order to minimize any component tensions that might occur by means of optimization loops. This method is necessary to present the components with the lowest possible weight. Operational vibration analyses were performed to determine the vibration characteristics of the exhaust system, which were then modified to ensure lifetime. The inflow of the catalytic converters was already determined and optimized at an early stage during development by way of CFD flow simulation.

The following steps were performed for the acoustic development of the exhaust system:

- : gas exchange calculation for the basic design of the intake and exhaust level
- : measurement of noise on the acoustic engine dynamometer
- : adjustment of measurement-computation and further optimization steps via calculation
- : measurement of optimized variants in the vehicle
- : on-board optimization loops.

The result is a moderate overall level and a harmonious 2nd engine order without disruptive amplification. The resulting sound provides the driver and all occupants with comfortable acoustics, thus underlining the vehicle sophistication typical of Mercedes-Benz. The described configuration ensures that the vehicle can be certified in accordance with the applicable legal emission categories.

PACKAGE / BELT DRIVE

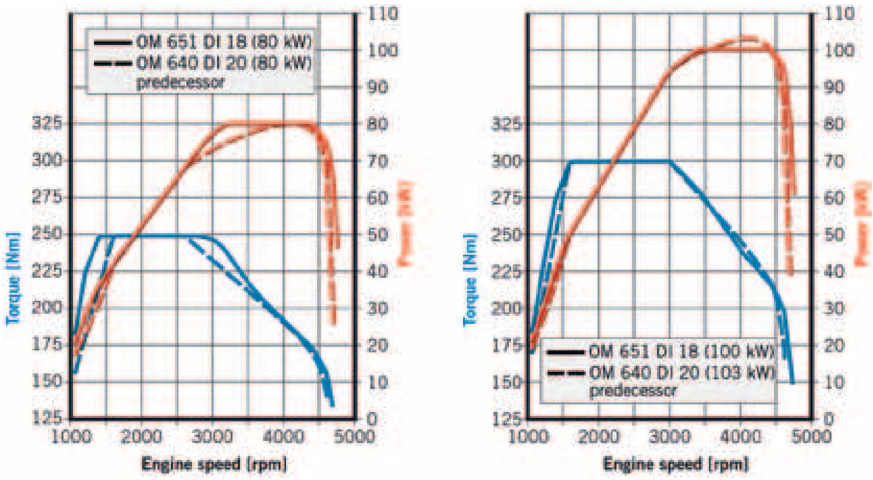
From the very beginning, the OM 651 was also designed in order to meet the various, in some cases inevitable, transverse installation-specific installation requirements by means of a skilful peripheral interface component design. The number one priority when packaging the OM 651 in the transverse installation position was to transfer as many emission-relevant modules from the longitudinal installation variant as possible. The engine installation position at an angle of 15° to the outlet side enabled the complete transfer of the so-called cold side of the exhaust gas recirculation including switchable EGR cooler and charge air distribution line with inlet port shut-off in the transverse installation of the OM 651.

Due to transverse installation, it was inevitable that the components were arranged in the friction loss-optimized five-groove belt drive. A special element of this is the map-controlled thermostat which is adapted axially in the specifications to the water pump located below. In this way, the thermostat directly represents the short circuit within the component. All additional components including mechanical belt tensioner are supported by the component carrier specific to transverse installation. This is a complex aluminium component produced using lost foam technology which also integrally directs the cooling water collection flow from outlet of the cylinder head to immediately in front of the thermostat.

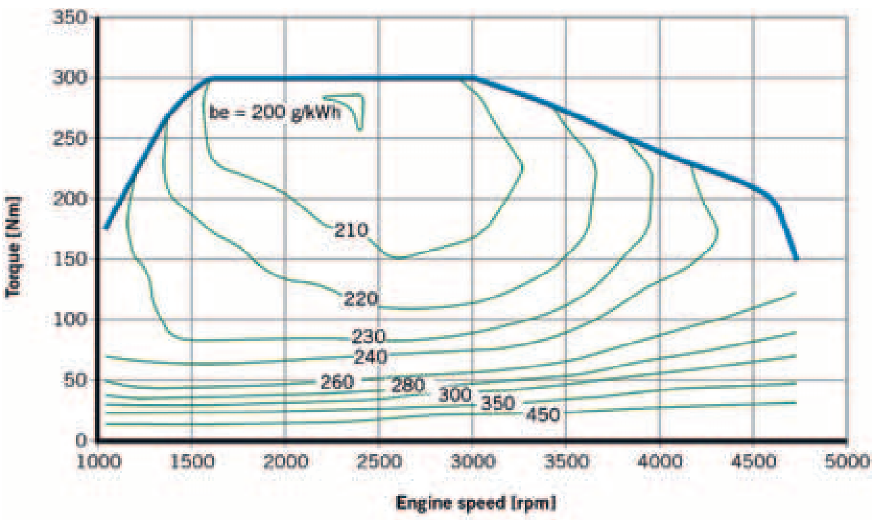
INJECTION HYDRAULICS

For the OM 651 in the B-Class a system with the following main characteristics is used:

- : maximum injection pressure of 1800 bar
- : solenoid servo injector
- : feasibility of up to five injection events per combustion cycle
- : double-stamped high pressure pump with volume control on the intake side
- : fuel-quantity drift compensation by means of structure-borne noise sensor control



❼ Full-load curves



❽ Specific fuel consumption

: activation of the fuel filter heater as needed
: regulation of the volume flow of the electric fuel pump.

The injector is a further development of the successful design for the OM 651 north-south installation variant. It uses a compact design with a balanced pressure servo valve in close proximity to the nozzle. The injector is characterized by an extremely low dead space in the hydraulic circuit and significantly reduced leakage volumes. Thanks to a volume optimization in the injector's high-pressure range, controllability in the pilot quantity range at high rail pressures and the shot/shot variations have been further improved.

In order to minimize the entry of heat into the fuel system, an inlet-metered high-pressure pump is used. Consequently, there is no need for a separate fuel cooling system. The electric fuel filter heater is controlled according to requirement depending on the fuel temperature. This means that the heating performance can be adjusted individually depending on the degree of gelling. The volume flow of the electric fuel pump is controlled according to requirement by means of pressure sensors. These two measures make it possible to reduce the electric power requirement, which also contributes to reducing fuel consumption.

POWER / TORQUE

In order to achieve the challenging consumption targets, the engine capacity was reduced by approximately 10 % in comparison with the predecessor engine to 1.8 l. The maximum power and torque values of 100 kW and 300 Nm were retained, ❼. In the lower engine speed range of the 80 kW variant, the torque was increased by up to 16 % compared with the predecessor. At the same time, there was a further noticeable improvement in the transient response. To achieve these targets, extensive changes to the exhaust gas turbocharging and mixture formation were necessary. The selected turbocharger is smaller than the charger used in the 2.2 l engine for north-south installation and is equipped with state-of-the-art aerodynamics.

Modifications to the cylinder head tangential channel and to the lift of the valve in the inlet spiral channel resulted in optimization of the mixture formation. This had been negatively influenced by stroke reduction compared with the basic engine. Despite reduced engine capacity compared with the north-south installation variant, this ultimately allowed the output and torque values to be maintained and had a positive effect on the transient response in the event of load surges from low engine speeds.

EMISSIONS

In addition to the mixture formation measures described above, the geometric parameters of the injection nozzles were also adapted for improved air utilization in order to remain below the Euro 5 emission threshold, (e. g. eight holes instead of seven). The increased degrees of turbocharging in the partial load make it possible to use higher rates of exhaust gas recirculation. The small-scale turbine design also increases the degree of turbocharging with partial load. The very high-performance EGR tract was taken over from the 2.2 l basic engine to lower the combustion chamber temperature and therefore to reduce NO_x. All these measures combined (mixture formation, charging and EGR tract) produce an optimum emission/consumption trade-off and make it possible to remain safely below the Euro 5 threshold values within the engine. This is an excellent basis for further development to an Euro 6 combustion system.

FUEL CONSUMPTION

As the engine map, ❽, shows, the new 1.8 l engine results to a large extent in low specific fuel consumption below 230 g/kWh. The consumption figures for the low-load

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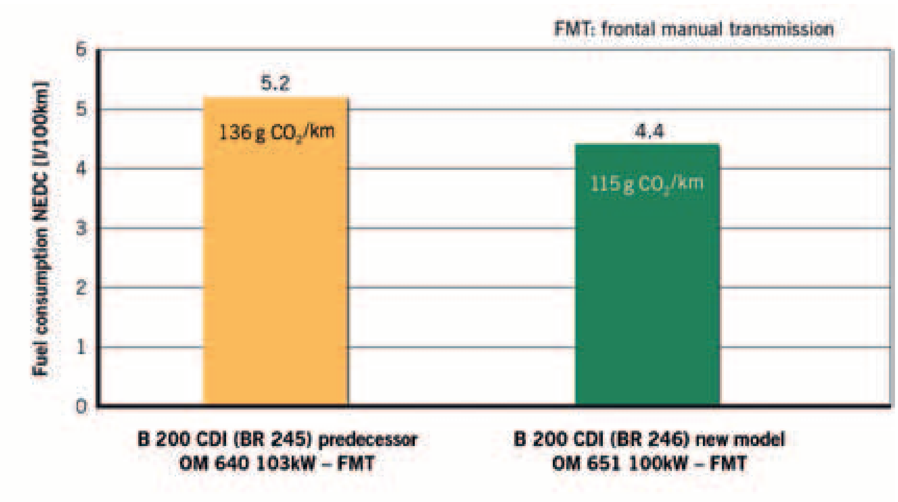


❾ CO_2 emission in NEDC
(80 kW version: 114 g CO_2/km)

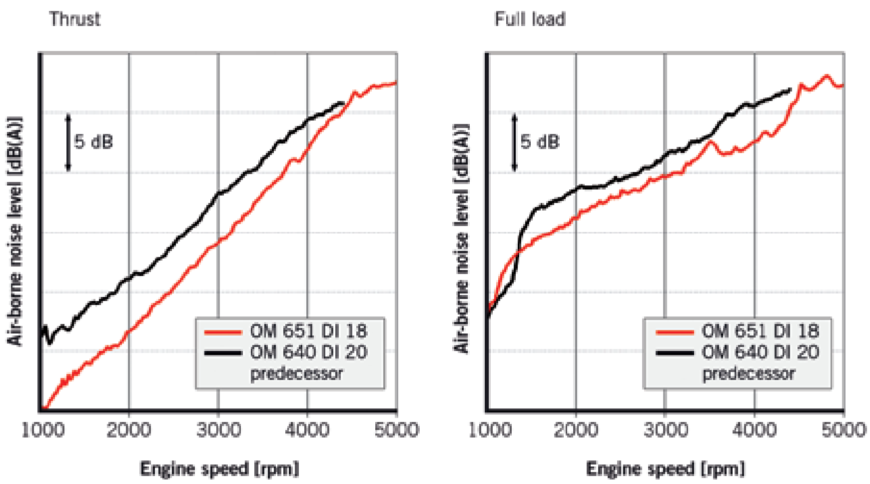
map areas particularly relevant to fuel consumption are also excellent. This balance leads to a significant decrease in fuel consumption compared with the predecessor vehicle both under weak load operation and in partially higher-load customer driving characteristics. 114 g CO_2/km for the 80 kW variant and especially 115 g CO_2/km for the 100 kW variant (NEDC, with frontal manual transmission) achieved are best values in this vehicle category, ❾.

NOISE, VIBRATION, HARSHNESS

One of the key requirement specifications for the frontwheel drive variant of the OM 651 was an optimization for the transverse installation in quiet running and vibrational comfort. To this end, acoustic optimizations were carried out by means of simulation and measurement on engine dynamometers and within the vehicle.

A main objective was to optimize the vibration level at the component bearings of the powertrain. In accordance with the engine's comfort requirements, the 1.8 l variant of the OM 651 was also equipped with Lanchester shafts. To optimize the level in the higher-frequency range, the right-hand engine mount and the upper pendulum support were attached very closely and very rigidly to the cylinder head. The lower pendulum supports were integrated into the intermediate shaft support casing. All connection elements for the component bearings were designed to have an optimum weight/rigidity ratio with assistance from optimization programs.

One key focus of the acoustic development was to reduce the flow noises. Significant improvements were achieved by means of transverse intake with a fabric hose and optimization of the clean-air line bellows. This variant meant that the package-related drawbacks in the air filter size were compensated for. All in all, the noise level of the new OM 651 four-cylinder diesel engine is again significantly improved over the predecessor OM 640 thanks to improvements in the total level as well as the reduced conspicuousness of bursts of noise, ❿. Both in terms of the air-borne noise level and the structure-borne noise level in front of the component bearings, the new OM 651 for transverse installation applications is within the very favourable range of the scatter for bench engines with the same output in accordance with the requirements of the brand.



❿ Air-borne noise compared with predecessor engine

SUMMARY

Mercedes-Benz engineers have adapted the existing OM 651 engine for the new B-Class with even more significant improvements of fuel consumption, emissions, driving characteristics and comfort in comparison with the predecessor vehicle. The design comes with further future potential for improving fuel consumption and complying with global exhaust emission requirements. Other vehicle variants based on this drive are also possible.

REFERENCE

[1] Schommers, J.; Leweux, J.; Betz, T.; Huter, J.; Jutz, B.; Knauel, P.; Renner, G.; Sass, H.: Der neue Vierzylinder-Dieselmotor für Pkw von Mercedes-Benz [The New Four-Cylinder Passenger Car Diesel Engine from Mercedes-Benz]. In: MTZ 69 (2008), No. 12

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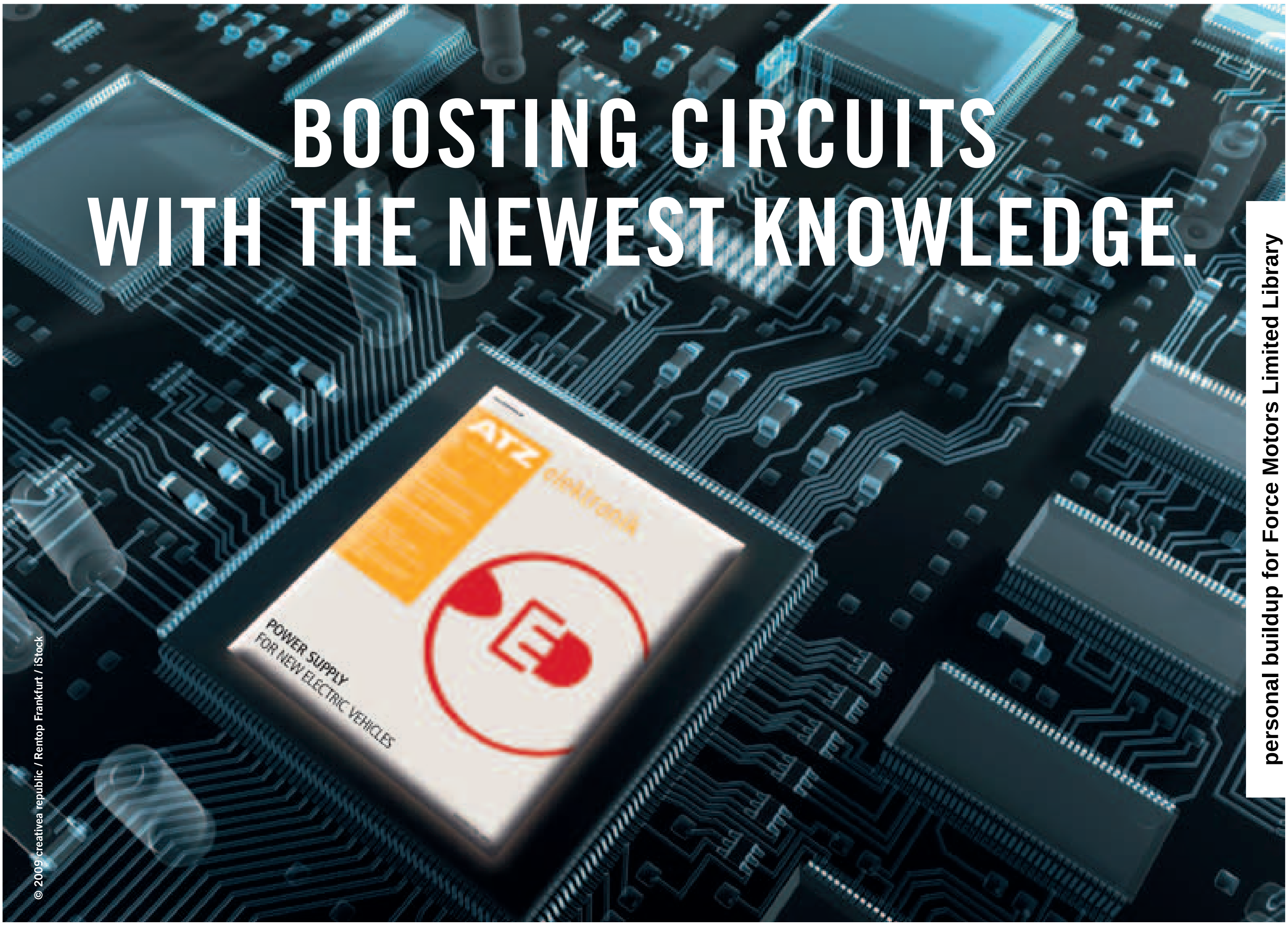

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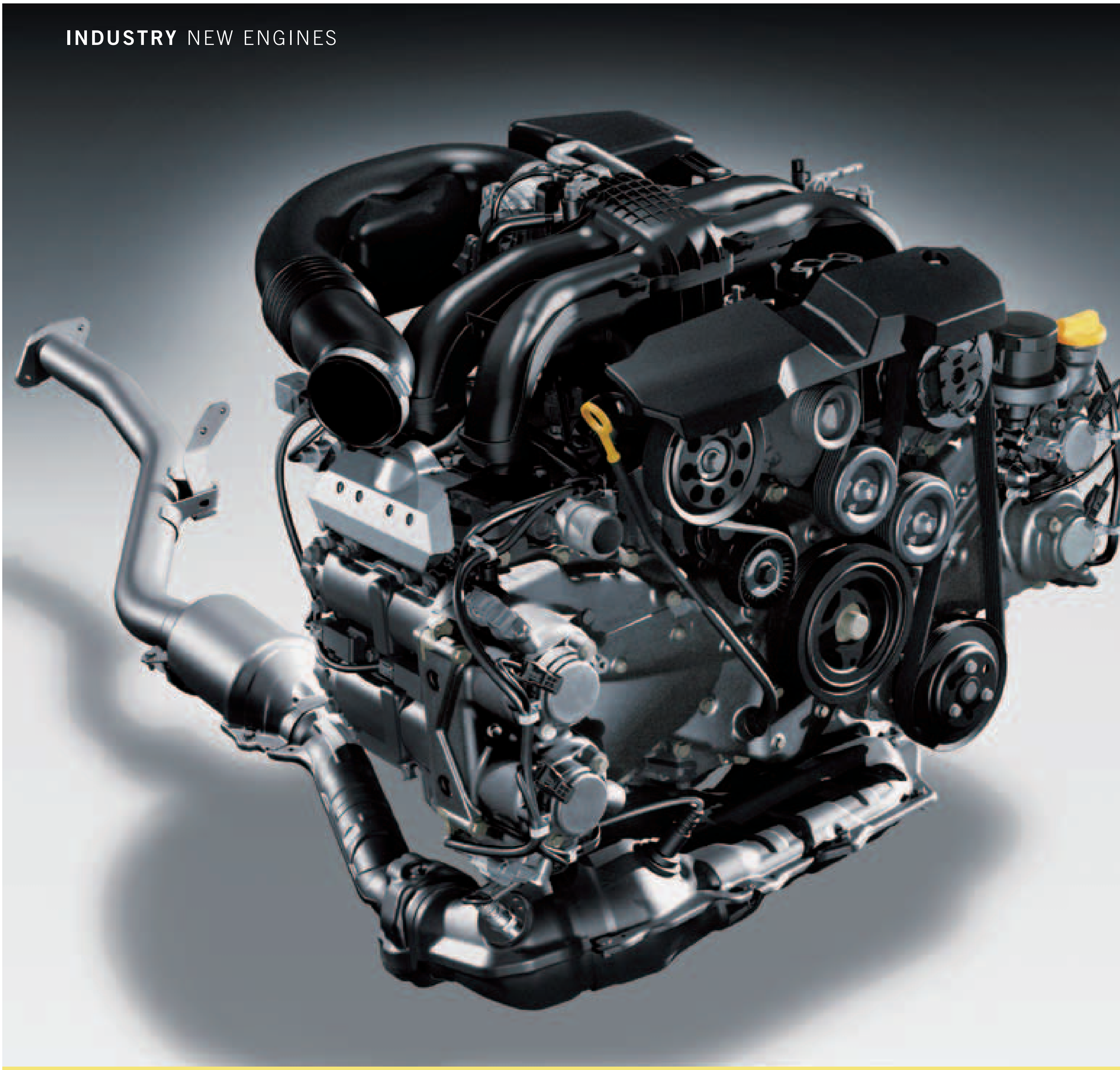

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THE NEW FOUR-CYLINDER HORIZONTALLY-OPPOSED GASOLINE ENGINE FROM SUBARU

Subaru, the automotive brand owned by Fuji Heavy Industries, has introduced its next-generation horizontally-opposed FB engine to the world in the fall of 2010. Since first developing a horizontally-opposed engine for the Subaru 1000 model of 1966, Subaru has continued to refine the characteristic features of its technology – namely, its compact, lightweight design as well as low center of gravity and vibration balance.

AUTHOR

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DEVELOPMENT CONCEPT

Developed through a process of continuous evolution over the 21 years since the second-generation Subaru EJ engine has been introduced, the new FB engine, ❶, pushes further the level of environmental friendliness. To achieve this, Subaru has totally overhauled the key bore to stroke ratio and other fundamental parameters; improved the basic combustion performance and minimised friction levels between all moving parts. Furthermore, a new active valve control system (AVCS) has been adopted among a number of other devices capable of boosting fuel efficiency and exhaust quality. In terms of drivability, Subaru sets sights squarely on performance in practical situations rather than on catalog specifications, and despite achieving maximum output levels equivalent to those of our previous engines, the new one delivers up to 4 % more torque in the low- to mid-speed ranges.

MEASURES FOR IMPROVING FUEL EFFICIENCY

In the pursuit of better fuel efficiency, FB engine development work focused on three core measures:

Enhancement of basic combustion performance:

: Flame propagation distance was shortened and the cooling surface area (S/V) reduced through the adoption of a long-stroke design and more-compact combustion chambers.
: Gas-flow resilience performance was improved through optimisation of the air intake system and of the piston head shape.

Adoption of environmentally-friendly devices:

: Pump loss was reduced and theoretical thermal efficiency improved through the adoption of a cooled exhaust gas recirculation (EGR) system.
: The new active valve control system (AVCS) also helped to reduce pump loss while making a larger expansion ratio possible; meanwhile, thermal efficiency benefited from internal EGR.
: Gas flow has improved considerably through the adoption of new tumble generation valves (TGV).

Reduction of friction levels:

: The temperatures at different locations have been optimised through the adoption of an isolated cooling system and associated modification of cooling circuits.
: The ideal cylinder bore shape was realised thanks to dummy-head machining and newly-selected head gaskets.
: Inertial mass has been reduced through lighter main drive-system components.
: Friction in the valve actuation system has been reduced through the use of roller rockers.
: The oil pump was made more efficient.

		NEW	CURRENT
ENGINE TYPE		FB20	EJ20
DISPLACEMENT [cm³]		1995	1994
BORE [mm]		∅ 84	∅ 92.0
STROKE [mm]		90	75
CYLINDER ARRANGEMENT		Horizontal 4	←
VALVE MECHANISM		DOHC Roller rocker arm	DOHC Tappet
VARIABLE VALVE MECHANISM	INTAKE	AVCS with mid position lock	AVCS
	EXHAUST	AVCS	–
VALVE ANGLE [°]		27	41
COMPRESSION RATIO		10.5:1	10.2:1
MAX POWER [kW/rpm]		110/6000	110/6000
MAX TORQUE [Nm/rpm]		198/4200	196/3200

❶ Engine specification

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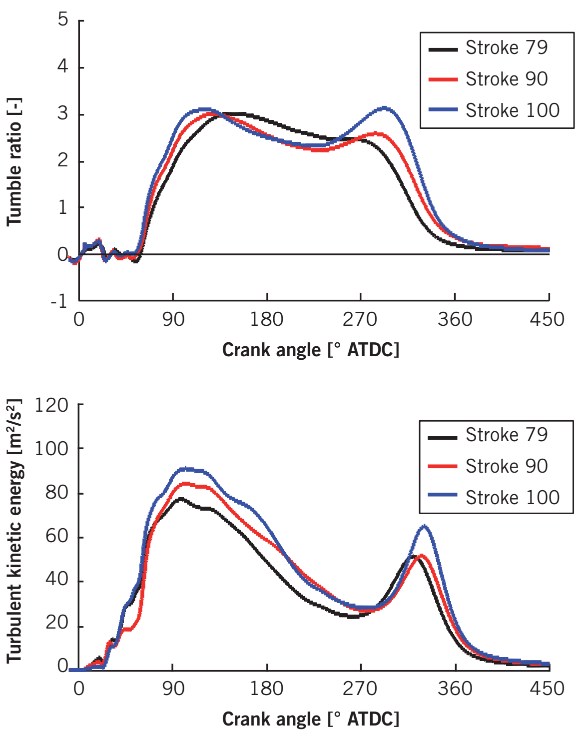
STROKE	BORE × STROKE [mm]	COMP. RATIO	PISTON SHAPE	S/V [cm⁻¹]	H/B
SHORT	∅ 99.5 × ∅ 79	10.0	Flat	2.70	0.156
MEDIUM	∅ 92.0 × ∅ 90	↑	↑	2.47	0.192
LONG	∅ 89.2 × ∅ 100	↑	↑	2.31	0.202

❷ Specification of single-cylinder engine



❸ Stroke effect by CFD analysis result

COMBUSTION PERFORMANCE

In order to endow the FB engine with the levels of environmental friendliness necessary to compete effectively, however, combustion characteristics would have to be enhanced through a complete overhaul of the key bore and stroke dimensions.

Fundamental research has shown that by increasing the amount of turbulence in the flow of gasses within the combustion chamber at between TDC and 30° ATDC, it is possible to reduce the duration of main combustion and achieve better combustion characteristics.

An effective way of achieving this in the vicinity of TDC is to maintain a large, slowly attenuating vortex – or tumble flow – until the latter part of the compression stroke, and to then convert this into turbulence just before combustion.

Meanwhile, given the correlation between the resilience of this tumble flow and both the angle of the combustion chamber's pent roof and the depth of the piston cavity, it was necessary to increase the H/B ratio – that is, combustion chamber height divided by bore – in order to improve this characteristic.

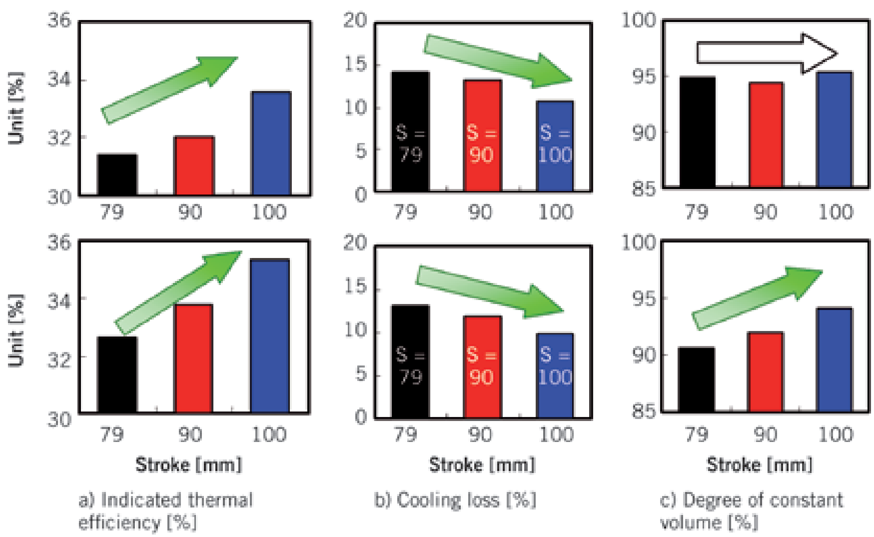
A longer stroke increases the H/B ratio, thus increasing the resilience of turbulence – or in other words, making it last longer; meanwhile, the speed of the piston also increases in this type of design, and this boosts the level of turbulent kinetic energy.

Assuming an unchanged displacement volume, furthermore, the bore becomes smaller relative to the stroke. As this reduces both flame propagation distance and the combustion chamber's surface area/volume (S/V) ratio, it holds promise for lower levels of cooling loss.

In order to verify this benefit, the three bore and stroke test dimensions have been selected as shown in ❷ below and applied computational fluid dynamics (CFD) and actual testing using a single-cylinder engine.

The results of CFD analysis, ❸, show that the turbulent kinetic energy of tumble flow in the latter part of the compression stroke increases in proportion to the stroke length, and in addition, that this increase moves the conversion point of turbulence closer to TDC.

❹ shows the results of testing on the single-cylinder engine. While no improvement in the degree of constant volume is achieved at an excess air ratio λ = 1, it can be seen that cooling loss is reduced due to the beneficial effect of a lower S/V ratio, thus enhancing combustion performance.



❹ Stroke effect on single-cylinder engine at 1200 rpm, TGV close

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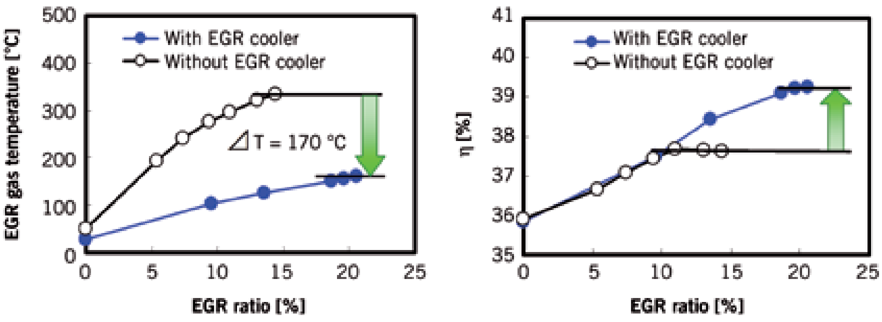
In addition, a comparison of the results obtained with λ = 1 and λ = 1.2 shows that longer strokes limit the amount by which the degree of constant volume of combustion drops. This demonstrates improvement in the flammability limit at high EGR ratios and lean burn.

On the basis of these results, it was concluded that, even for the horizontally-opposed engine, a long-stroke design would be crucial in terms of achieving improvements in basic combustion performance.

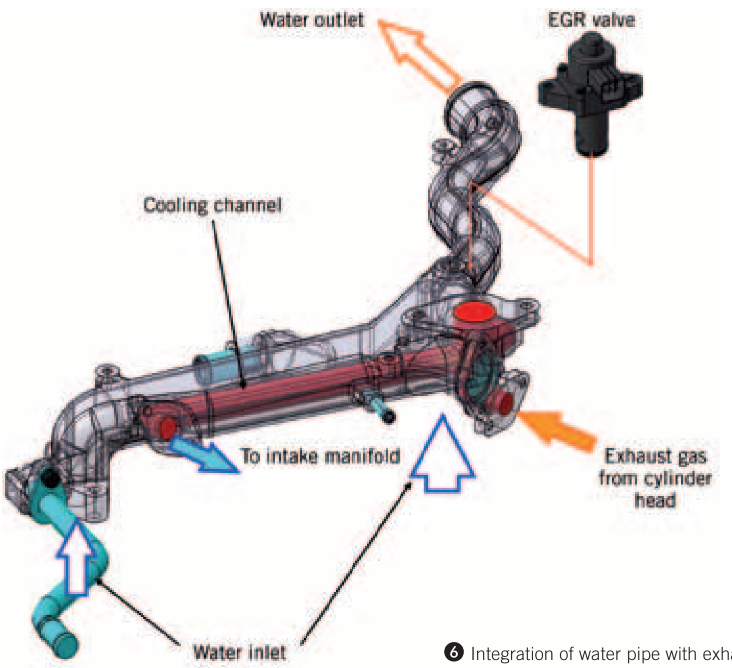
Accordingly, a 90-mm stroke for the FB engine has been selected, limiting its width to the same level as the EJ engine and ensuring its compatibility with our current platforms.

Pursuant to the selection of a 90-mm stroke, the bore diameter shrank to 84 mm. In addition, the degree of freedom with which the cams could be positioned has been increased by adopting a chain system for driving the camshaft and electing to actuate the valves using swing-arm type roller rockers, which have the added benefit of reducing friction levels. This allowed to shorten the distance between cam centers (a) and to reduce the valve clipping angle (b), thus realising more compact combustion chambers.

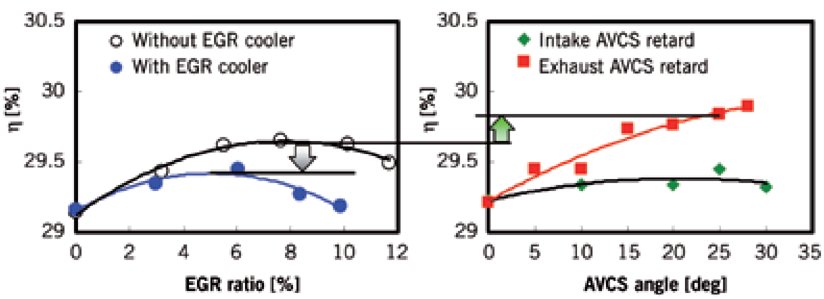
As a result, a smaller S (combustion chamber surface area) / V (combustion chamber volume) ratio was achieved, which contributes to lower cooling loss and an improved knock limit.



❺ Effect of cooled EGR at 1200 rpm, IMEP = 680 kPa



❻ Integration of water pipe with exhaust gas



❼ Internal EGR vs. external EGR at 1200 rpm, IMEP = 260 kPa

ENVIRONMENTALLY-FRIENDLY DEVICES

The FB engine's environmentally-friendly devices take the form of an EGR cooler, an AVCS and TGVs. As shown in ❺, it was confirmed that, in terms of the low-speed, high-load operation range, reduction of the EGR system temperature using a cooler or the like made it possible to limit the ignition-timing retard angle as a result of knocking, and thus, to improve combustion performance.

In order to add an EGR cooler to the engine, however, space would have to be made available, and even if this were possible, the addition of a cooler would increase the number of assembly components and make the manufacturing process much more complex.

In light of this situation, advantage was taken of the existing design of the horizontally-opposed engine and decided to integrate heat-exchanger functionality for cooling the EGR gas into coolant pipes already being used to collect coolant from the left and right banks, ❻.

Thanks to the implementation of this type of EGR cooler, operation at maximum best torque (MBT) timing became possible for practically all driving ranges at the theoretical air-fuel ratio, and this significantly improved combustion performance.

Whereas the reduction of EGR gas temperatures using an EGR cooler as described above was of considerable benefit in the high-load range, it had the undesirable effect of worsening fuel efficiency in low-load range due to its lowering of the flammability limit, ❼. However, fuel efficiency

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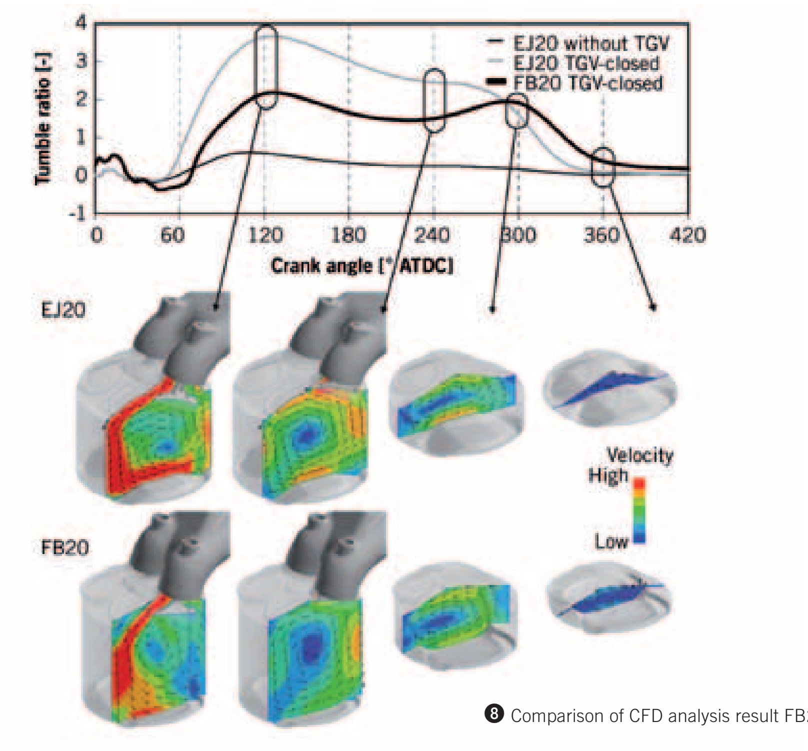

❽ Comparison of CFD analysis result FB20 vs. EJ20

could actually be improved through the use of high-temperature internal EGR gasses in these ranges.

For the FB engine, therefore, the intake-side was provided with a hydraulic, intermediate-lock type AVCS that also provides for operation at an angle retarded from the engine start-up position, and the exhaust-side with an AVCS supporting operation in the same range as previous models.

Thanks to the adoption of a twin intake/exhaust AVCS in this way, it is possible to delay the phase of both the intake and exhaust cams in the low-load range and to increase the degree of valve overlap; accordingly, fuel efficiency can be enhanced through the use of internal EGR, the realization of a Miller cycle by way of delayed intake-valve closing, and the creation of higher compression ratios by way of delayed exhaust valve opening.

While engine oil is used to perform switching operations in the same way as the FB's predecessors, the spool valve used for channel switching now features a built-in actuator, and the valve actuation solenoid has been located at the front of the engine. As a result of these changes, it has been possible to simplify the layout for engine-oil channels and peripheral components.

In addition, the newly-adopted AVCS is not limited to the use of hydraulic pressure from the oil pump alone as in previous designs; instead, it can also avail of the differences in pressures when the cams push on, and detach from, the valves, using them to induce phase differences between the cams through hydraulic action of the oil. This design not only makes it possible to make use of the AVCS from extremely low engine speeds, but it also allows intake and exhaust valve operation to be synchronised with constantly changing engine speeds and load conditions. Furthermore, the level of hydraulic pressure required for operation can be reduced, thus contributing to greater overall fuel efficiency.

With the turbulent kinetic energy of gas flow in the vicinity of TDC, which constitutes an indicator of combustion performance improvement, significantly enhanced through the adoption of a long-stroke design, the specifications of the entire intake system were modified to best suit this new flow characteristic in the pursuit of even better combustion performance.

In specific terms, a new TGV has been introduced as a starting point in order to create a powerful tumble flow in the intake stroke and a cut-out type design for better concentration of flow upon valve closure. Meanwhile, the shaft's surface area has also been reduced, adopting a low aspect-ratio design in order to limit pressure loss upon valve opening and thus ensure a plentiful supply of air at wide open throttle (WOT).

In addition, partitions were added at the intake port in order to prolong the TGV's localised flow, and by preventing any flow into the injector openings and finely tuning the shape of the valve seats and many other components. Thus, the kinetic energy of the tumble flow could be intensified further.

Next, as a means of enhancing the resilience of the tumble flow in order to ensure that it is still present in the latter part of the compression stroke, where combustion actually starts, the clipping angle of the intake and exhaust valves was reviewed and modified and also a cavity to the middle of the piston to increase the H/B ratio at the center of the combustion chamber was added. And in order to improve reflow into the piston cavity, the combustion-chamber connection was made as smooth as possible. The results obtained from CFD analysis of gas flow are shown in ❽.

The older EJ engine features a TGV that throttles the opening area to approximately 60 % of that of the FB engine when fully closed, and these results show that, even when the tumble ratio during the EJ intake stroke is increased, the kinetic engine of the flow dissipates rapidly towards the latter part of the compression stroke. In the FB engine, meanwhile, tumble flow is maintained efficiently until this point, and thanks to the long-stroke design and a range of modifications to optimise intake-system specifications, further improvements in combustion performance have been achieved.

REDUCTION OF FRICTION LEVELS

Limiting of frictional losses between the various moving parts of an engine is an effective approach in the pursuit of better fuel efficiency. The cooling circuit of the EJ engine has been totally overhauled for implementation in the FB engine. The objectives in selecting this design were as follows:

: Adoption of isolated cooling channels: The new cooling-circuit design features isolated cooling channels giving a 2:8 distribution of coolant flow between the cylinder block and the cylinder head. Thanks to this approach, high tempera-

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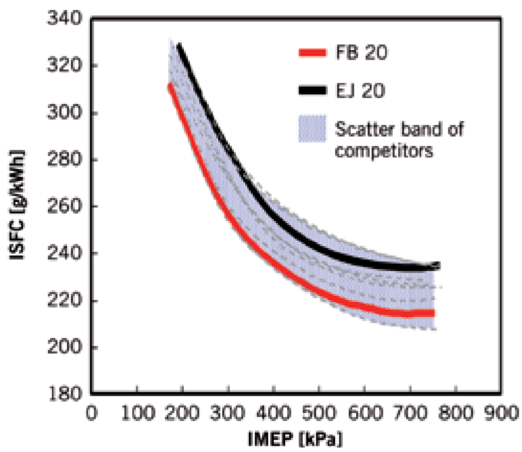


❾ Improvement of fuel consumption

tures can be maintained in the vicinity of the cylinder liners in order to reduce friction, while the cylinder heads – and the area around each spark plug in particular – are subjected to more powerful cooling, thus improving the knock limit and contributing to better fuel efficiency.

: Inclusion of a bottom bypass:
A bottom-bypass channel has been added primarily for promoting faster warming of the FB engine upon start-up. With the temperature of the engine oil increasing more quickly, and friction therefore being reduced more rapidly, this design modification has contributed to better fuel efficiency.

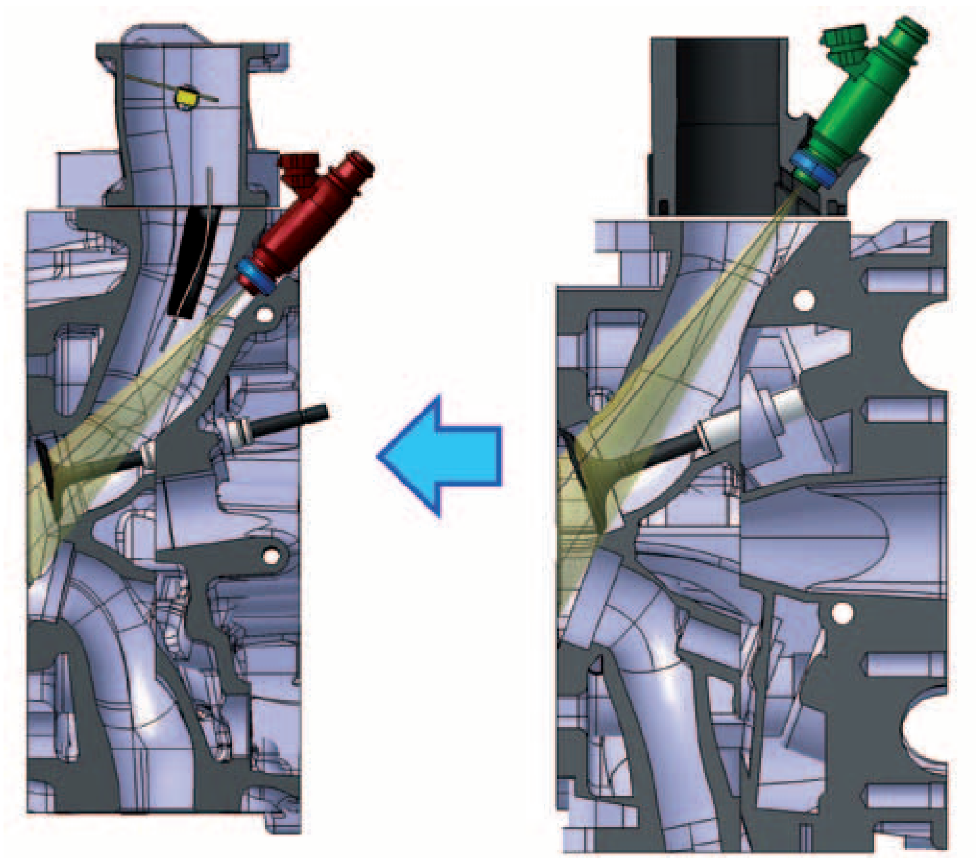
Bore distortion occurs when the cylinder head is bolted into place. Limiting of this distortion increases bore roundness during operation of the engine, which in turn reduces the resistance of the piston to sliding.

With the FB engine, the degree of bore distortion upon assembly was reduced by using a double-type cylinder head gasket and also assemble a dummy head when honing at the final stage of cylinder bore machining. The net result of these techniques is a significant reduction in distortion upon bolting of the actual cylinder head.

In order to counteract the inevitable increase in friction that comes with a longer stroke design, the weight of the main drive-system components has been reduced – namely, the pistons and connecting rods.

While the pistons had already shrunk thanks to the narrower bore, the diameter of the piston pins has also been reduced and a number of other related improvements have been made, ultimately achieving a reduction of approximately 20 % when compared with the EJ engine's pistons.

Turning to the connecting rods, whereas turbocharged-model specifications were used across the board in the EJ engine in the interests of component standardisation, a dedicated naturally-aspirated design for the FB engine has been selected. As these connecting rods no longer needed



❿ Comparison of fuel injection layout

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the same levels of strength and stiffness as the standardised components, it was possible to reduce their weight by an equivalent amount. Consequently, a reduction of approximately 20 % was achieved when compared with the weight of EJ connecting rods.

In place of the direct-acting tappet type of valve actuation system employed thus far, the FB engine uses a swing-arm type, roller rocker arm mechanism in order to reduce friction. This modification to the actuation system also contributed to smaller valve clipping angles – a critical factor in terms of making the combustion chamber more compact as described above.

The FB engine's oil pump has a modular design and is integrated into the chain cover. As previously mentioned, the AVCS selected for this new engine is capable of reducing the level of hydraulic pressure required for operation. This, combined with the comprehensive improvements made in terms of friction between sliding parts, paved the way for revision of the specifications of the oil pump itself, and its discharge pressure was ultimately reduced.

Meanwhile, the relief valve features a two-stage design that, by eliminating unnecessary pump work, contributes significantly to lower levels of friction within the pump itself.

Additionally, a wide range of fine adjustments have been made to reduce friction and weight; consequently, the FB engine boasts approximately 20 % less friction than that of the EJ engine. The fuel efficiency enhancements produced an improvement on 11.8 %. Breaking this down, better combustion performance accounted for 8.6 %; lower friction for 3.2 %. Analysis of the indicated specific fuel efficiency corresponding to these results shows that, when compared with competing engines, the FB engine delivers best-in-class fuel efficiency, ❾.

EXHAUST SYSTEM PERFORMANCE

As a result of improvement in the retard-angle flammability limit, it has been possible to increase the exhaust temperature while also keeping down HC emission volumes during high-speed idling. Moreover, Subaru optimised both the fuel and exhaust systems in order to further improve exhaust system performance.

In the FB engine's fuel system, the injectors were moved from the end of the intake manifold to a position on the cylinder head, meaning that they are now closer to the valves, ❿.

As a result, less atomised fuel adheres to the inner surface of the intake ports, and thus, less unburnt fuel is discharged as part of the exhaust. This also has a beneficial effect on fuel efficiency.

The FB engine features a newly designed exhaust system, developed in line with the following in order to simultaneously achieve high levels of output and environmental friendliness. The amount of precious metal used within the catalytic converter is down approximately 10 %, while the catalyst cost is lowered by around 20 % from the previous EJ engine level respectively.

: Exhaust gas cleaning performance was improved by optimising catalytic-converter positioning.
: Exhaust system branch lengths were shortened, the volume of converging sections was reduced, and the surface area was also made smaller in order to lower heat capacity immediately upstream of the front catalytic converter, and thus, improve catalyst heating performance. As a result, exhaust gas quality immediately after engine start-up is much improved.
: The position of the air-fuel sensor was changed to improve gas contact characteristics and reliability.
: Output performance was improved thanks to lower pressure loss and better isometry.

CONCLUSION

In the next-generation, horizontally-opposed FB engine – the first totally revamped Subaru boxer engine in 21 years – it has been done everything possible to ensure that the demands of the times can be effectively and efficiently answered. Like its predecessor the EJ engine, the FB engine features a basic design that also focuses on versatility ten or even twenty years from now, and its technologies offer potential for use in both direct injection and hybrid vehicle engines.

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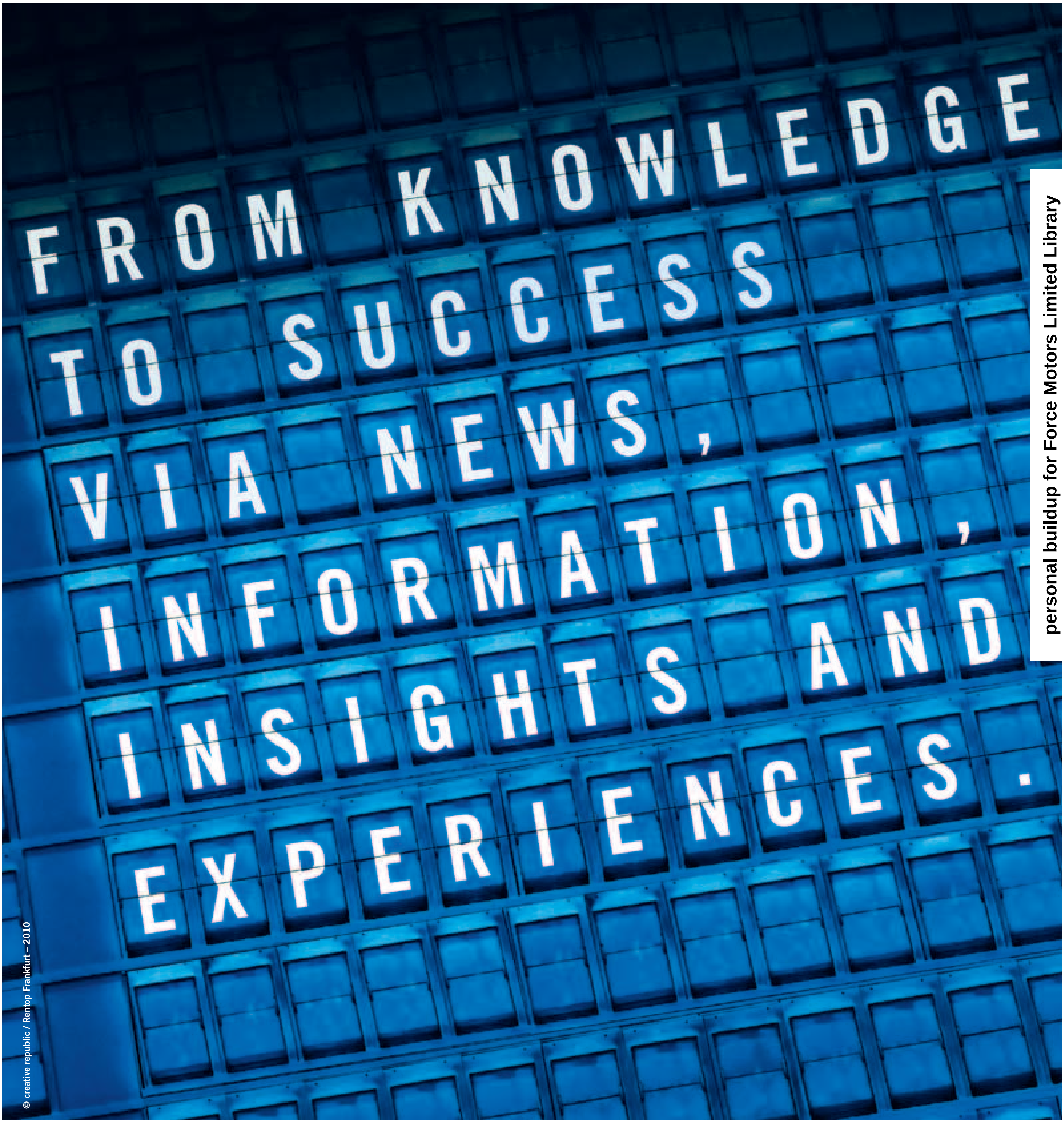

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VIRTUAL OXYGEN SENSOR IN THE INTAKE MANIFOLD OF A DIESEL ENGINE

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Currently, exhaust gas recirculation (EGR) systems for reducing nitrogen oxide emissions are generally controlled via the EGR rate. However, this fails to take into consideration the quality of the exhaust gas that is being recirculated. IAV, a leading provider of engineering services to the automotive industry, has developed a physical model which can be used to calculate the oxygen concentration in the inlet manifold. The data from the model enables the EGR process to be controlled more accurately during transient motor operation.

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CONTROL CONCEPTS FOR EXHAUST GAS RECIRCULATION

Mixing exhaust gas with fresh air through the exhaust gas recirculation system (EGR) has the purpose of reducing nitrogen-oxide (NO_x) emissions. With this approach beginning by controlling EGR only, then to be followed by controlling air-mass flow, controlling the EGR rate is now state of the art. Whereas the share of exhaust gas in total engine mass flow is unknown with controlled EGR, it can be determined indirectly by controlling air-mass flow and is given directly by controlling the EGR rate. Controlling the EGR rate, however, still only reveals an indirect correlation with the generation of NO_x: For the same EGR rate, the quality of recirculated exhaust gas can vary significantly. Knowing the concentration of oxygen in the intake manifold provides a more direct correlation with NO_x emissions. ❶ shows how this controlled variable can be used for influencing NO_x emissions directly. Although the numerical values shown in ① are engine-specific and governed by the combustion process, the quality-related characteristic is identical for every diesel engine. The area in ① is defined by three precise, calibration-related ranges. The various engine operating points are distributed as follows:

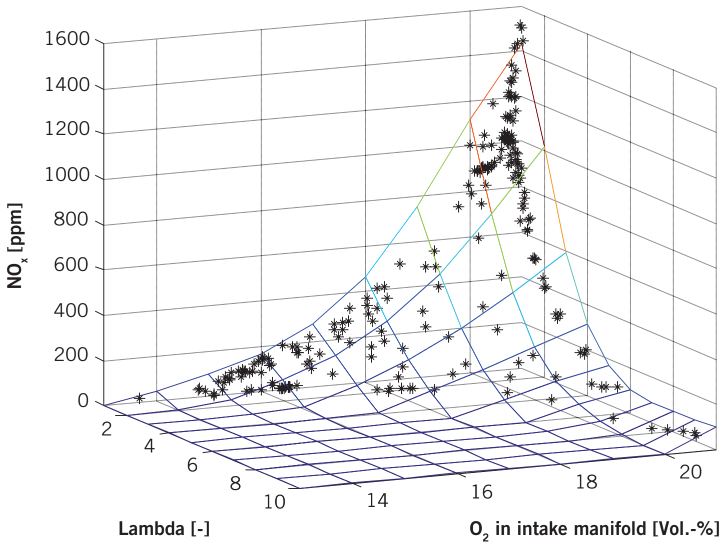
: low lambda, low O_2 concentration at low engine speed, low load
: low lambda, high O_2 concentration at high engine speed, full load
: high lambda, high O_2 concentration at high engine speed, low load.

Whereas it makes no difference whether the EGR rate or O_2 concentration in the intake manifold is used as the controlled variable in the steady state, controlling O_2 concentration in the intake manifold promises advantages in terms of NO_x emission during dynamic engine operation in particular.

MODEL STRUCTURE

Tests have shown that in modern combustion processes the temperature level in the intake manifold is too low even for heated production-level lambda probes (O_2 sensors) to deliver plausible values over the engine's target lifetime. The additional costs for mass production and the risk of condensation forming also oppose the use of a real-life O_2 sensor. This is why, as part of these investigations, a physical model of oxygen concentration in the intake manifold has been developed and implemented as a virtual O_2 sensor in the modular prototype controller MPEC. ❷ shows a schematic diagram illustrating the working principle behind the virtual sensor.

Input variables include fuel-mass flow, boost pressure, charge-air temperature and engine speed. Engine mass flow m_{eng} is initially computed in the "Engine mass flow" block. Further input variables are air-mass flow m_{air} and/or lambda λ. The availability of these input variables is adapted to suit the various sensor concepts in the "Sensor configuration" block. This block's output variables are the measured or computed air-mass flow $m_{air,mdl}$ and



❶ Influence of a diesel engine's air path on untreated nitrogen-oxide emissions

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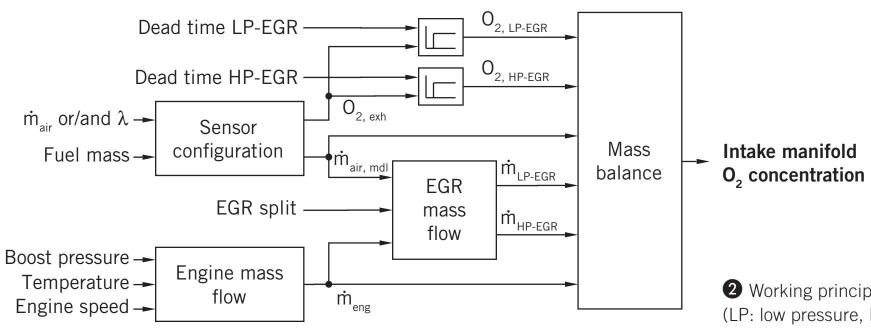

❷ Working principle behind the virtual O_2 sensor in the intake manifold (LP: low pressure, HP: high pressure)

oxygen concentration in exhaust gas, $O_{2,exh}$. The dead-time elements allow for the various gas-travel times in high and low-pressure EGR. The associated mass flows are determined in the "EGR mass flow" block. With combined high and low-pressure EGR, the EGR split is computed using the position of the high-pressure EGR valve on the basis of the flow equation for compressible fluids. Finally, the concentration of oxygen in the intake manifold is determined in the "Mass balance" block from the intermediate variables.

CONFIGURABLE VARIANTS

A total of nine different variants can be configured for the virtual O_2 sensor in the intake manifold. This means it can be adapted to suit all modern-day engine concepts. ❸ shows these variants and the differences between them. The nine variants initially differ in terms of the EGR concept for the diesel engine used. The virtual sensor can also be configured in respect of the input variables. This configuration depends on the sensor concept (A, B or C) applied in the engine under study:

: Sensor concept A is the configuration for commercial vehicle applications; only measures lambda, no air-mass sensor is provided.
: Sensor concept B is the basic configuration for the passenger car segment; only measures air-mass flow m_{air}.
: Sensor concept C is the optimum configuration for the passenger car segment; measures lambda and air-mass flow m_{air}. This variant is the best one possible. It combines the benefits of the first two concepts specified.

APPLICATION IN THE COMMERCIAL VEHICLE ENGINE

The virtual O_2 sensor is validated in the intake manifold on the engine test bench. The test engine is a commercial vehicle diesel engine with high-pressure exhaust gas recirculation. As usual in commercial-vehicle applications, no air-mass measurement is provided. The reason for this is found in the large number of different engine versions needed to cover the vast range of application conditions – this being accompanied by numerous different ways in which air-mass flow meets the mass air flow (MAF) sensor as well as far higher demands on the life of the MAF sensor. As a result, this sensor is hardly ever installed in commercial-vehicle engines.

Consequently, the virtual O_2 sensor for the intake manifold is configured in line with variant 1. Sudden load increases at constant engine speed and the European Transient Cycle (ETC) provide the test scenarios. ❹ (left) shows a sudden load increase from approximately 120 to 200 mg/stroke at t = 5 s and at a constant engine speed of 1200 rpm. The curves for boost pressure and lambda are also plotted. The EGR valve-position curve is only presented for the purpose of verifying plausibility and is not evaluated by the virtual O_2 sensor. ④ (right) shows the 1000 s ≤ t ≤ 1050 s interval in the ETC.

A good steady-state and dynamic correlation can be observed between modeled oxygen $O_{2,IM}$ (IM: intake manifold) using the virtual sensor and the value actually measured. The steady-state deviation after the sudden load increase in ④ (left) is the result of inaccuracies in modeling the EGR rate from lambda. However, the virtual O_2 sensor in the intake manifold is shown to have the potential to act as the controlled variable. Conventional control concepts can be applied as well as model-based ones that use the EGR valve for adjusting the oxygen-concentration setpoint in the intake manifold. Currently at the design-study stage, a controller for regulating O_2 concentration in the intake manifold can then be used to exert direct influence on nitrogen emissions – within the physical limits.

APPLICATION IN THE PASSENGER CAR ENGINE

Unlike application in the commercial vehicle segment, all three basic variants from A to C in ③ are conceivable options for passenger car engines. As the 2.0 l four-cylinder unit under study is a passenger car engine with an all-high-pressure EGR setup, the following discourse compares sensor variants 1 to 3.

❺ (left) shows engine behavior in response to a negative load change. Before

				EGR SETUP		
SENSOR SETUP	READING	PRO	CON	HP	HP/LP	LP
A	λ	Exact sensing of O_2 in exhaust gas	EGR model dynamics inaccurate	1	4	7
B	m_{air}	High dynamics	Inaccuracies can occur in calculating exhaust gas O_2	2	5	8
C	λ and m_{air}	High dynamic capability, high steady-state accuracy		3	6	9

❸ Variants of the virtual O_2 sensor in the intake manifold (LP: low pressure, HP: high pressure)

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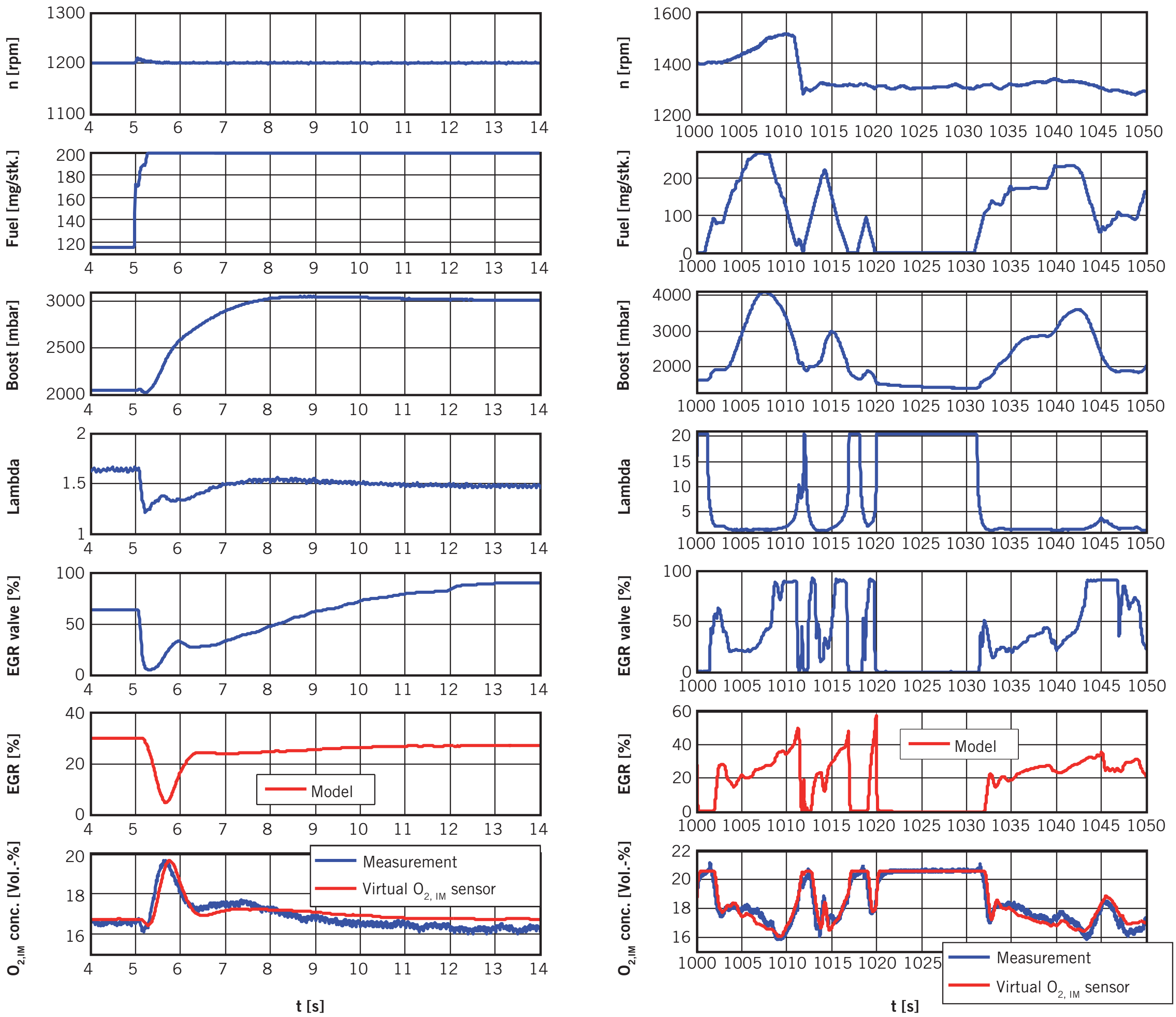
load changes, the engine is running at an operating point at which no exhaust gas is recirculated. The sudden increase in torque at constant engine speed causes boost pressure to fall and the EGR valve to open for activating and adjusting exhaust gas recirculation.

As a direct consequence of this, the intake manifold is filled with exhaust gas as clearly shown by the fall in O_2 concentration in ⑤ (bottom). By way of comparison, all variants are shown to provide good dynamic behavior and come close to the value measured. Looking at the steady-state values (as from approximately t = 9 s), variant 1 can be seen to show a permanent deviation. This is attributable to the air mass being computed from the measured exhaust gas lambda value. For this the value of the injected fuel mass is used which is subject to additional scatter. The somewhat erratic profile of the O_2 value for variant 2 can be ascribed to the fact that O_2 concentration in the exhaust manifold is computed from the air-mass signal which tends to be slightly noisy.

⑤ (right) shows the measurement results for a positive load change (t = 5.4 s), also at constant engine speed. As boost pressure starts to build, exhaust gas recirculation is briefly deactivated to enhance performance. In ⑤ (bottom), variants 2 and 3 are shown to reproduce the dynamics very well whereas variant 1, which is purely oxygen-sensor-based, takes longer to respond. It must be assumed that this effect is attributable to the oxygen sensor's dead time respectively the distance between exhaust valve and sensor. In the steady state, all three variants are initially seen to deviate. This deviation, however, disintegrates in the course of the first few seconds.

The initial deviation results from the computed engine mass flow being determined by the temperature measured in the intake manifold. As the temperature sensor in the intake manifold is somewhat sluggish, this propagates throughout the computation chain as far as the virtual O_2 value. Deviations lessen as soon as the temperature measured approaches the true temperature. However, this sluggishness on the part of the temperature sensor



❹ Sudden load increase at constant engine speed (left), details from the ETC cycle (right)

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can be extensively compensated for with an observer or by using temperature sensors of a more dynamic nature. Summarizing, it can be said that for the passenger car diesel engine with high-pressure EGR, linking information from air-mass sensor with that from the oxygen sensor gives variant 3 the edge over the other options as it is capable here of providing both the dynamics and steady-state accuracy sufficiently well.

❻ shows measurement results for variant 3 from two example sections of the FTP 75 cycle at 900 s and 1300 s. Even under these real-life dynamic test-cycle conditions, the modeled O_2 concentration follows the measured value with just slight deviations. Given the slight deviation the model is seen to exhibit, the model value can be used as the controlled variable for controlling EGR on the basis of O_2 concentration in the intake manifold.

SENSITIVITY ANALYSIS

The concept's sensitivity to input measurement-value scatter was examined. The error of the virtual O_2 sensor caused by a deviating air-mass sensor is more or less directly proportionate to the measurement error. Errors caused by inaccuracies of the computed total engine mass flow can always occur if the volumetric efficiency is modeled inaccurately or the temperature sensor in the intake manifold is too sluggish or imprecise. The influence of error from fuel mass being determined inaccurately is less since current engine concepts normally only operate with a maximum EGR rate of 50 %. At best, errors can in general cancel each other out – at worst, however, they can also amplify each other. The virtual O_2 sensor in the intake manifold can never be better than its input signals.

CONTROL CONCEPT

Generating the O_2 concentration in the intake manifold on the basis of a model or perhaps even using a real-life sensor is aimed at optimizing control of the entire air path – especially the EGR rate. An op-

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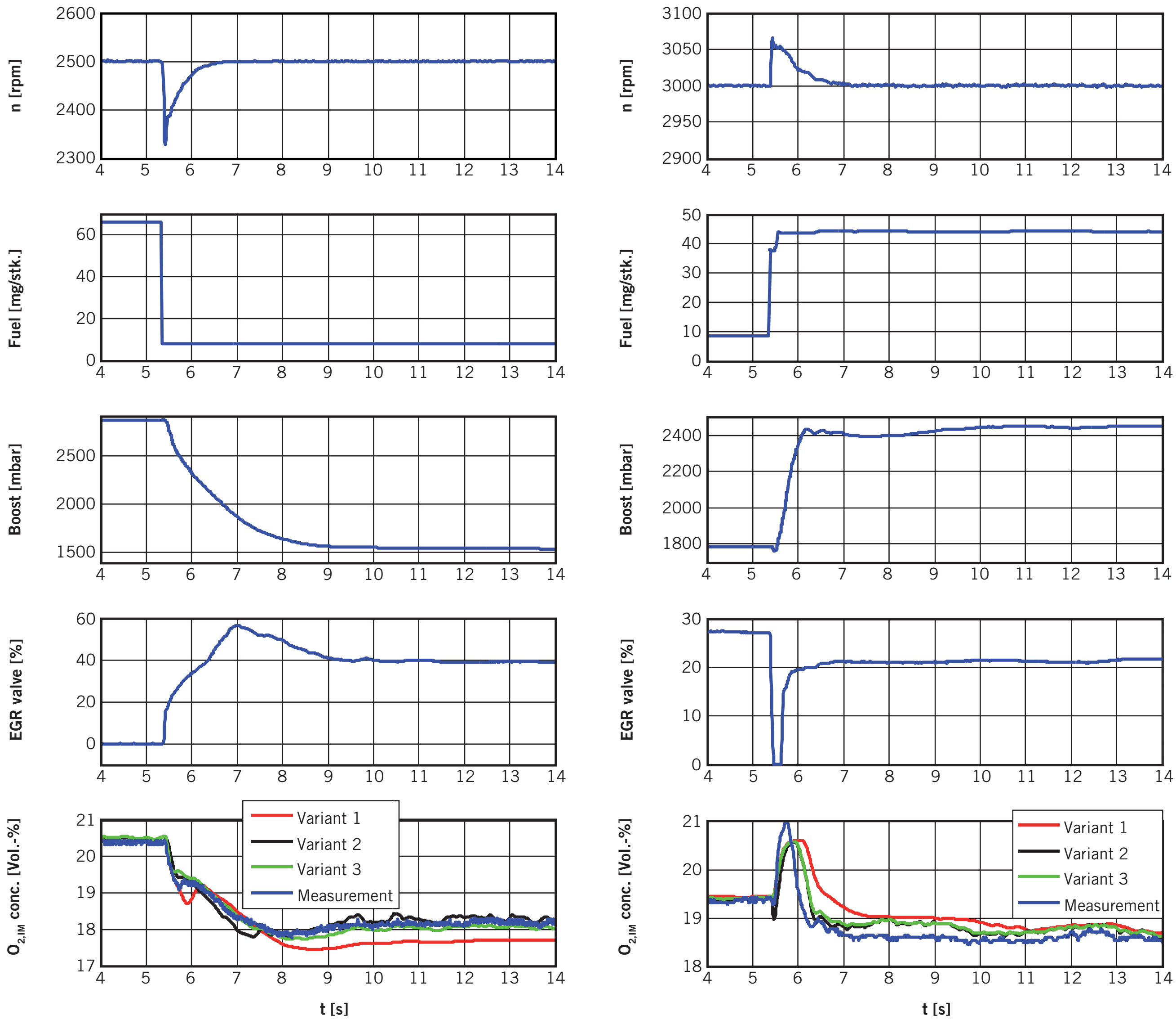
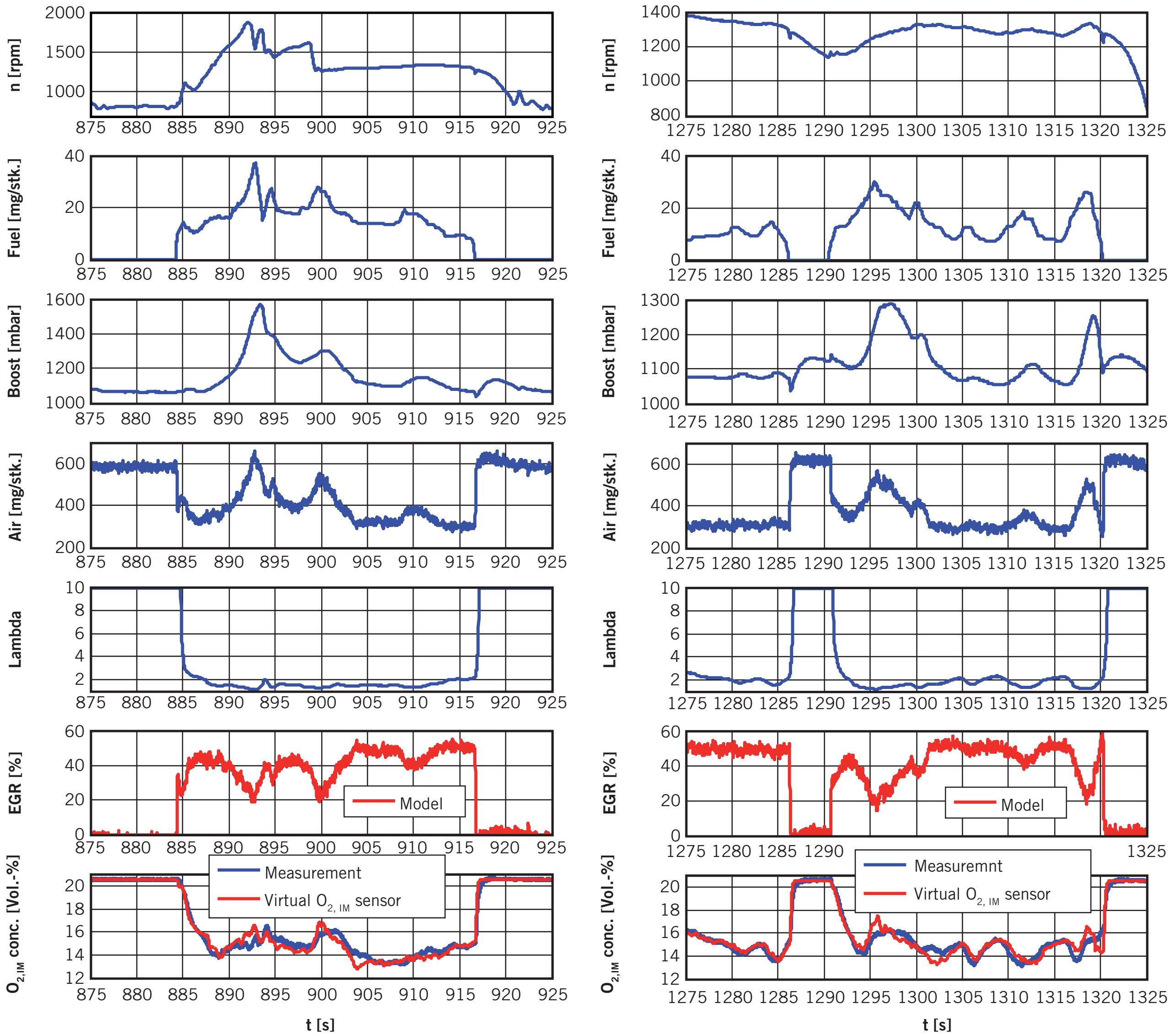


❺ Load change at constant engine speed



❻ Details from the FTP 75 cycle

timal result is achieved with a double-loop cascade control, in which the outer loop controls the O_2 concentration in the intake manifold. The virtual O_2 sensor or value measured by a real-life sensor is used here as the controlled variable. The inner control loop of the cascade structure adjusts the EGR rate. Here the O_2 controller of the outer loop provides the setpoint of the EGR rate for the inner loop. The output value of the EGR rate controller of the inner loop is the total EGR mass flow setpoint, which is converted into high and low pressure EGR mass flow using the desired EGR split. Inverse actuator models finally take the mass-flow setpoints as the basis for computing the associated valve positions. Both controllers of the cascade control are supported by open-loop controls, which are implemented with additional inverse models.

The requirement for a good working cascade control is a faster inner loop compared to the outer loop. Here, this is the case, because the inner control loop ofthe EGR rate is based on the ratio of mass flows, which are adjusted very fast. In contrast the change of the O_2 concentration in the intake manifold happens with a time delay and an additional lag.

CONCLUSION

Controlling EGR on the basis of a virtual O_2 sensor has the potential to reduce NO_x emissions from diesel engines in the passenger car and commercial vehicle segments at dynamic operating points. IAV has applied for a patent for this technique which could be used in mass production in just a few years.

REFERENCES

[1] Bessai, C.; Stölting, E.; Seebode, J.; Gratzke, R.; Behnk, K.: Emission-Orientated Control of the Air Path of a Heavy-Duty Diesel Engine with 2-Stage Turbocharging and High-Pressure EGR. 14th Supercharging Conference, Dresden, 2009

[2] Bessai, C.; Stölting, E.; Seebode, J.; Gratzke, R.; Behnk, K.: Innovative Model-Based Control Concept of the EGR Path and Virtual Sensors for a Modern Heavy Duty Diesel Engine. 9th International CTI Forum Exhaust Systems, 2011

[3] Rempel, A.; Bessai, C.; Stölting, E.; Gratzke, R.: Flexible Development Environment for Future Challenges in Engine Control. 11th Stuttgart International Symposium Automotive and Engine Technology, 2011

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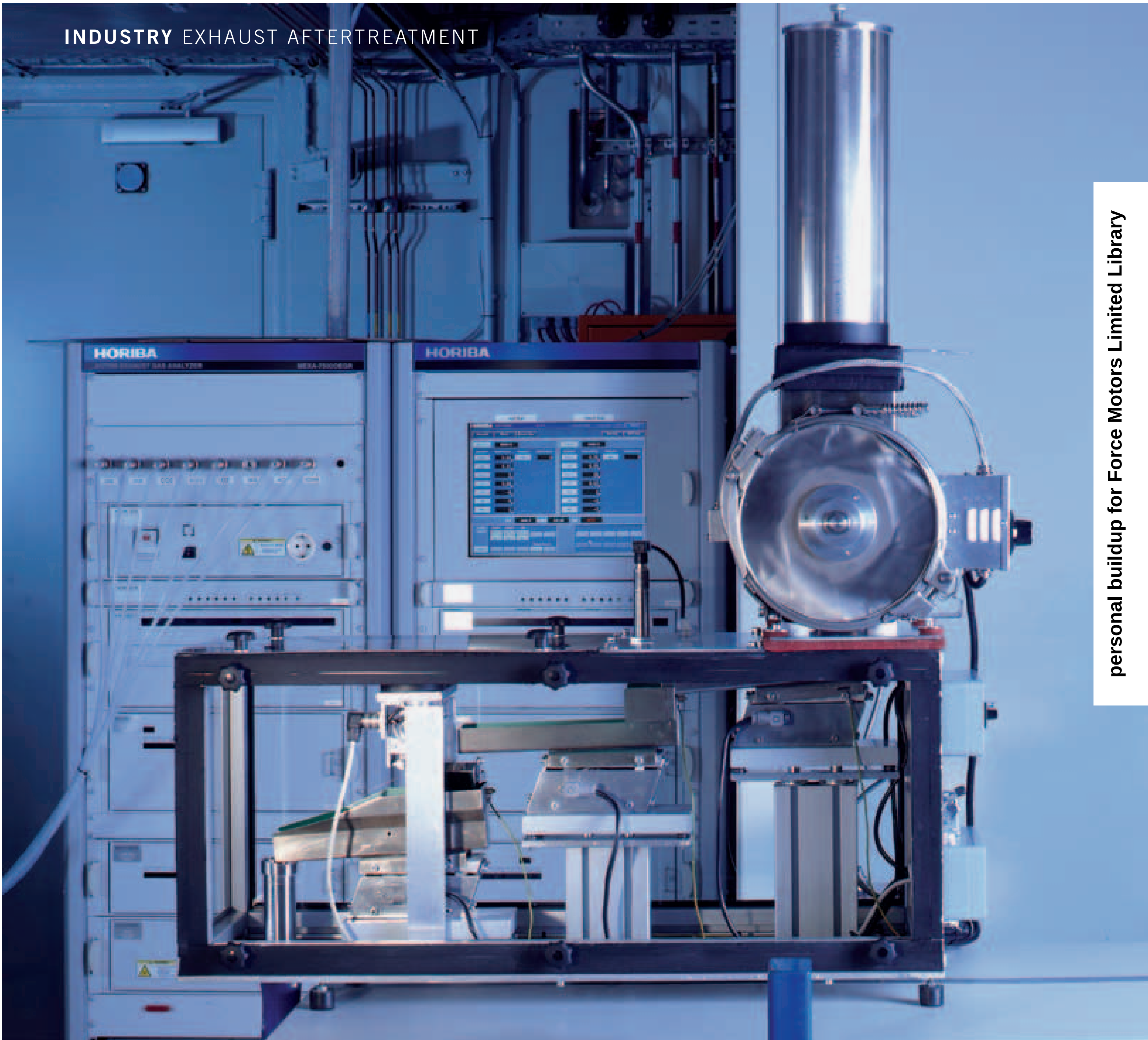

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EFFICIENT APPLICATION OF PARTICULATE FILTERS BY MEANS OF SYNTHETIC SOOT

The adaptation of a diesel particulate filter to a new engine requires a great deal of effort and takes up considerable test bench resources, particularly when it comes to loading the filter with engine soot for the tests. Elring Klinger Motortechnik has investigated whether synthetically generated industrial soot is suitable for use as a loading medium in the application of diesel particulate filters.

AUTHOR

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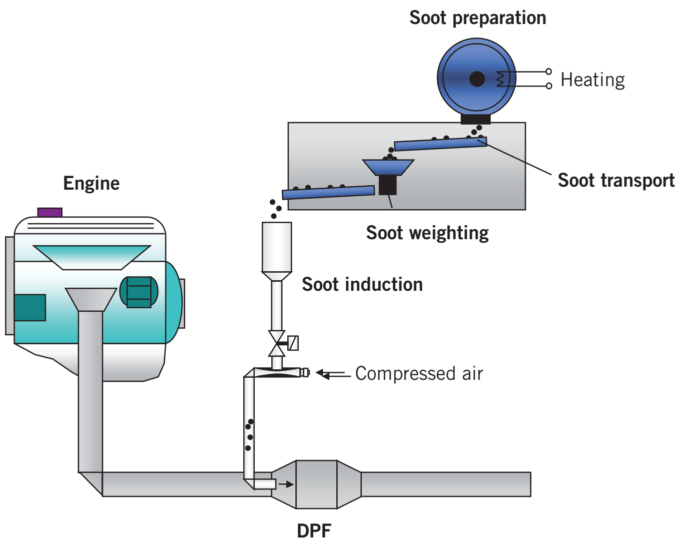
MOTIVATION

The application process of a diesel particulate filter (DPF) not only includes the programming of the ECU functions for regenerating the trap. A lot of additional investigations are also necessary, for example to determine the soot mass limit, filtration efficiencies and deterioration factors, and these occupy a huge amount of test bench time. A long time is needed especially for filling the DPF with soot before any regeneration test can take place. It is obvious that an alternative must be found. This could be filling the DPF with synthetic soot, which can be done in a very short time of approximately 20 to 30 min. In this context, it must be investigated whether the quick-filling process influences the operation behaviour of the DPF in any way. The results of these investigations are presented in this article.

ENGINE TEST BENCH

All investigations were carried out on a turbocharged 1.9 l diesel engine with direct injection and an underfloor DOC/DPF combination. All technical data can be seen in ❶ (left). ① (right) shows the system that is used for preparing, weighing and feeding the soot into the exhaust pipe. The four stations – soot preparation, transport, weighing and feeding – are marked in the Figure and will be explained in the following. The industrial soot, a synthetic soot with the product name Printex-U, is mixed, heated and dried in the mixing box. When the soot has reached the right condition, the test bench operator can choose the soot induction quantity on a user terminal. The soot can be fed in one shot or in several batches. A vibrating ramp transports the soot to the weighing unit. Once this unit has been filled with the predetermined quantity, the vibrating ramp is stopped, the weighing unit opens and the soot falls onto a second vibrating ramp to be transported to the feed pipe. The mixing of the soot with air and the feeding of the soot/air mixture into the exhaust system is performed by a venturi. To achieve a more homogeneous mixture, a mixer plate can be inserted into the exhaust pipe upstream of the DOC/DPF.

ENGINE DATA	
COMBUSTION	Diesel
DISPLACEMENT	1.9 l
INJECTION SYSTEM	Direct injection common rail
BOOST SYSTEM	Turbocharger
DIESEL PARTICULATE FILTER	Underfloor, capacity 3.5 l, coupled with DOC
POWER	74 kW
MAXIMUM TORQUE	260 Nm at 1700 rpm



❶ Engine data (left) and basic design of the soot induction system (right)

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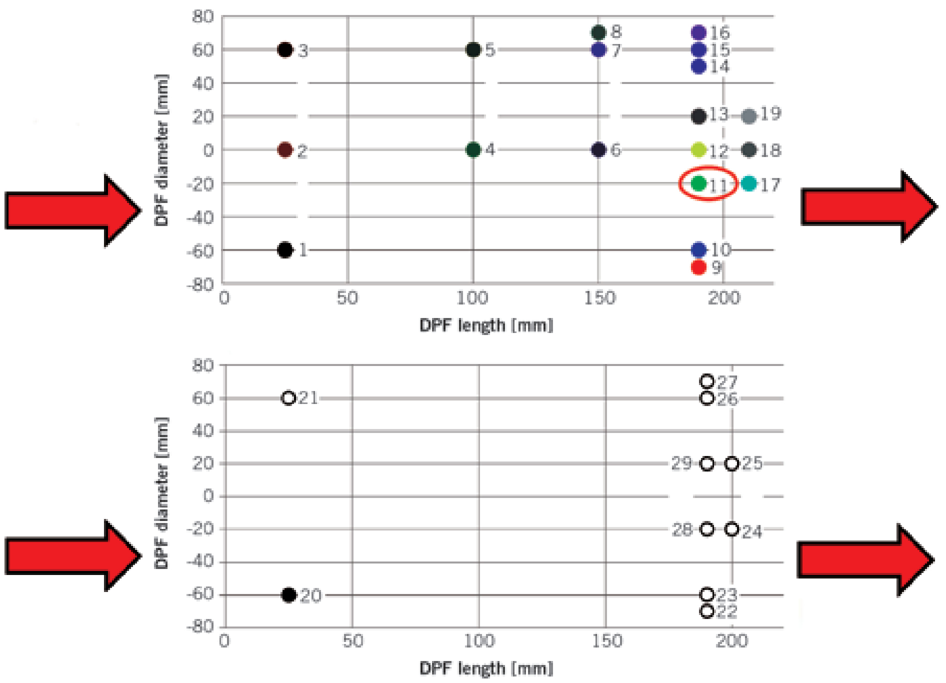


❷ Schematic diagram of the thermocouple locations; DPF cut vertically (0° to 180°) (top) and DPF cut horizontally (90° to 270°) (bottom)

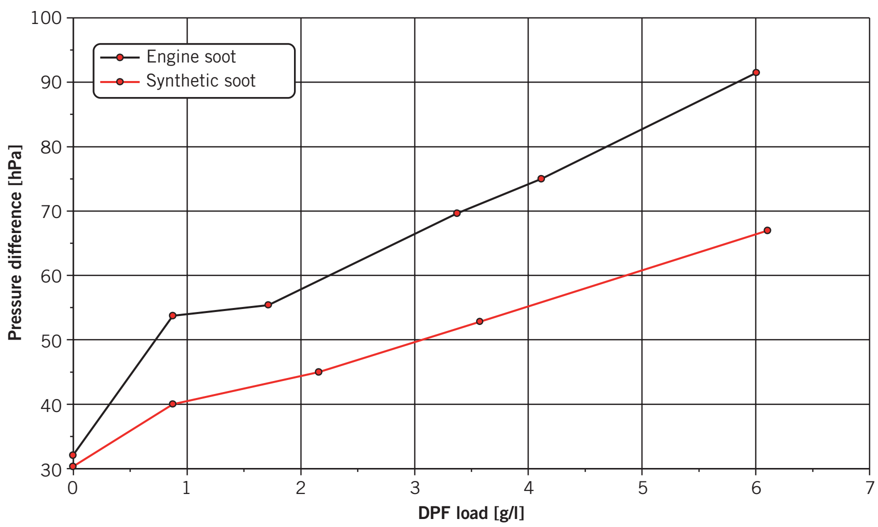
The special advantage of this construction is that the DPF can be filled either with engine soot or with synthetic soot. Alternatively, mixtures of engine soot and synthetic soot can also be used. Furthermore, the artificial soot is weighed before being fed in, which means that it is no longer necessary to weight the whole loaded filter. The particulate filter is equipped with thermocouples according to the configuration plan shown in ❷. With a limited number of thermocouples, an almost complete recording of the temperature behaviour in the DPF can be made. In all tests, sensor No. 11, which was installed approximately in the middle of the flow close to the filter exit, detected the hottest temperature of the DPF.

TEST DESCRIPTION

In order to measure the operating behaviour of the DPF, the following investigations were carried out:

- measuring the pressure drop characteristics
- drop-to-idle investigations
- measuring the active, fired regeneration
- measuring the passive CRT regeneration.

All these investigations are usually used by OEM and by suppliers in the DPF development process.



❸ DPF pressure drop curves – comparison of engine soot loading and synthetic soot loading

PRESSURE DROP CHARACTERISTICS

The pressure drop curves shown in ❸ represent the DPF behaviour when loaded with engine soot at a constant medium speed and load. The growing filter load causes a rising pressure drop as expected. The first steep pressure rise up to a filter load of 1 g/l is the typical characteristic of the filtration behaviour deep inside the ceramic cells. The pressure rise that follows has a lower gradient and represents the surface filtration in which the soot particulates are filtered by other particles gathered at the DPF surface.

When the filter was significantly loaded with engine soot, higher pressure drops were measured, both for the range of filtration deep inside the ceramic material and for the surface filtration. Theoretically, one could expect the engine soot particles to go deeper into the ceramic material, due to their smaller size, and to block the ceramic channels. However, the TEM photograph shows a different situation, ❹. The particulates of the artificial soot are smaller than the engine soot particles. The artificial soot particles do not change their consistency when being fed in and when coming into contact with the hot engine exhaust.

According to the commonly used sieve model, people may imagine that the pores of the ceramics are blocked by the particulates. This is definitely not the case in the DPF. Instead, there are four functionalities that partly overlap each other. The particulates are adsorbed by the filter wall by

- collision (the particles collide with the wall when the gas flow changes direction)
- diffusion (movement of the particulates sideways to the flow movement)
- gravity (heavy particulates sinking the wall because of their weight)
- interception (adsorption effect of the particulates when moving parallel to the surface of the wall).

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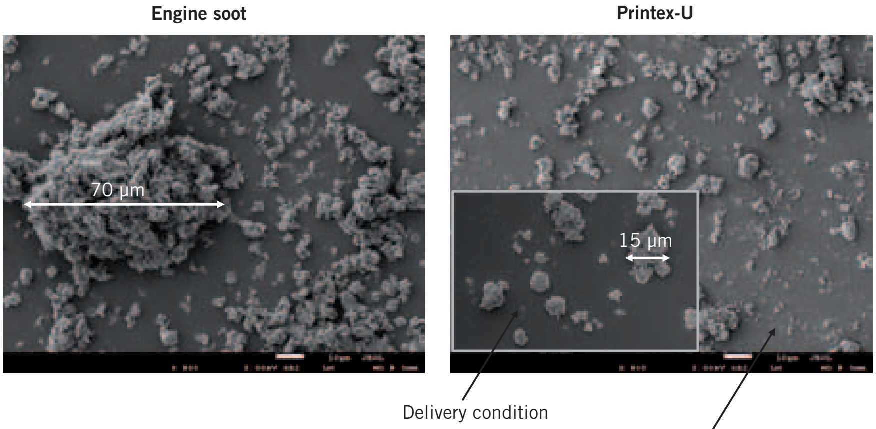


❹ TEM photograph of engine soot and synthetic soot (enlarged 800-fold)

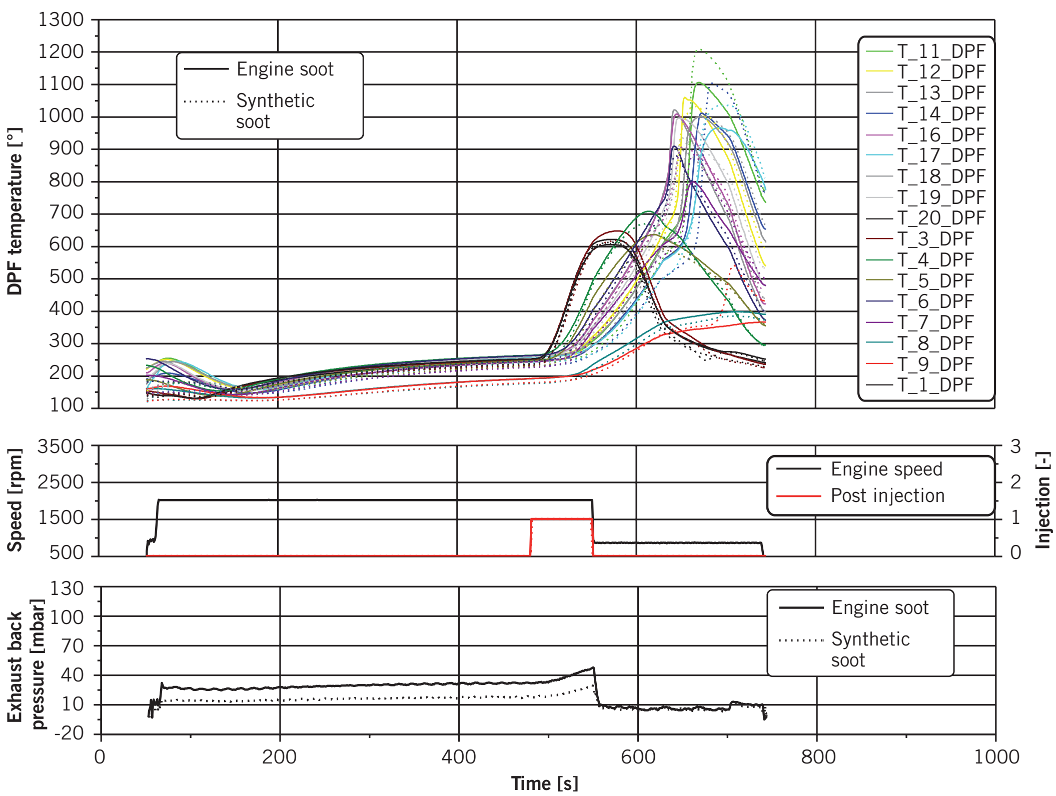
The effectiveness of these mechanisms depends on the particle size, the pore width of the ceramic material and the temperature [1]. It can be imagined that, in combination with the very small size of the synthetic particulates, the diffusion mechanism assumes a more important role in the adsorption process. The particulates can move into narrow ceramic “niches” without influencing the free flow diameter and without creating a significant backpressure.

DROP-TO-IDLE TEST

Drop-to-idle (DTI) tests include an active fired regeneration initiated by post injection under constant load and speed. After the soot has been ignited, the engine conditions drop into idle, where the gas flow through the DPF drops down to much lower values. As a result, the flow of heat-transporting gas is severely throttled. This creates a heat accumulation, which results in very high peaks in temperature and very high gradients in temperature rise.

In the DTI investigation depicted in ❺, the temperature characteristics of the variants “engine soot” and “synthetic soot” are quite similar. This statement is valid for the temperature values of the entrance area of the filter as well as the middle and exit zones. However, in the exit zone in particular, temperature differences of about ΔT = 100 °C were measured when using artificial soot. On the one hand, this is due to the smaller particulate diameter and the bigger surface/volume proportion. On the other hand, the chemical composition of the soot may also play a role (in this case, this chemical influence can be neglected).

Because the post injection is switched off when the engine drops into idle, the regeneration reaction will stop and freeze. As a result, a 100 % burning rate of the carbon cannot be achieved in that test. However, a higher burning rate of the artificial soot was also measured in the DTI investigations compared to the engine soot. Obviously, because of the smaller particulate size, the artificial soot burns better, ❻ (left). In this figure, the DTI behaviour of a 50:50 mixture is also



❺ DPF temperatures in the drop-to-idle test – comparison of engine soot loading and synthetic soot loading

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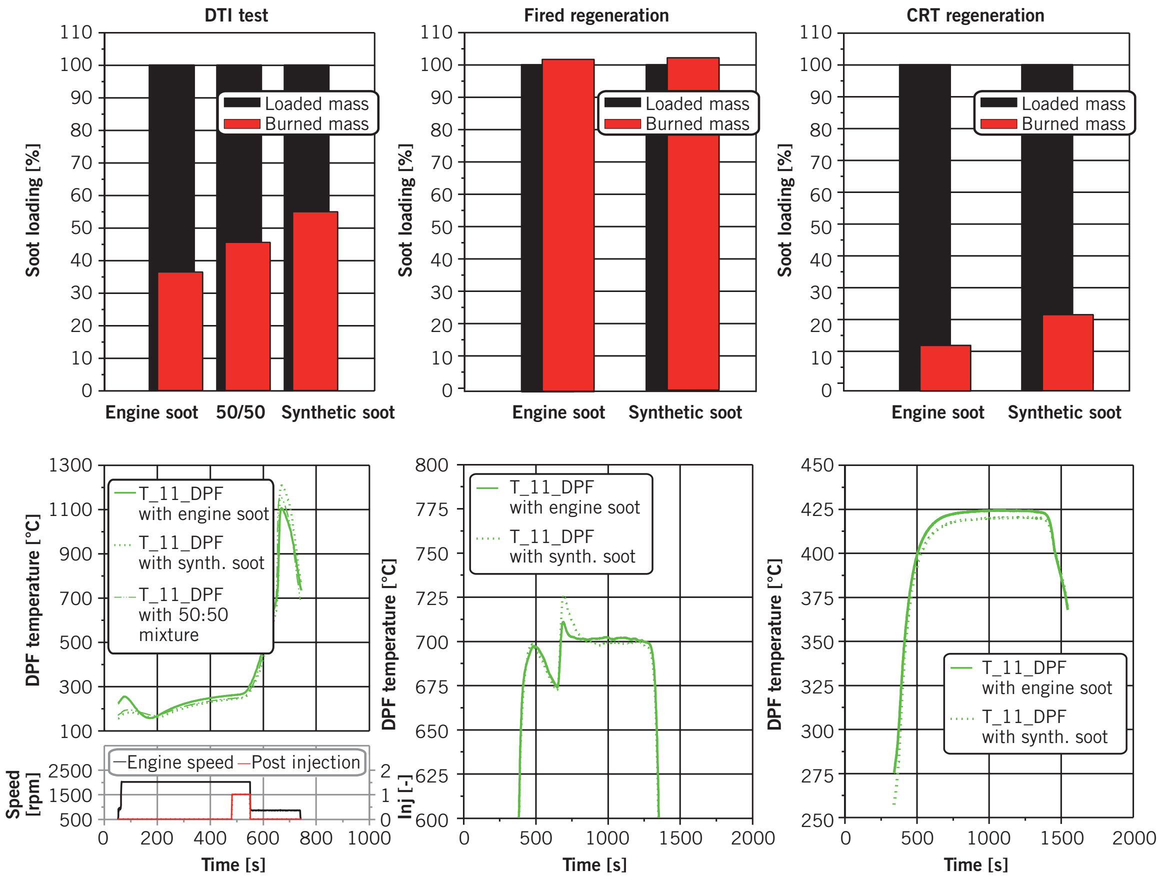

❻ Loadings, burned shares and DPF maximum temperatures in the drop-to-idle test as well as under fired regeneration and CRT regeneration conditions – comparison of engine soot loading and synthetic soot loading

depicted. Additionally, the maximum DPF temperature peaks (temperature sensor No. 11) are shown for engine soot, a 50:50 mixture and synthetic soot. The higher the share of the synthetic soot, the higher the temperature peaks are. Beside this, it should also be mentioned that, in all DTI investigations, the lower backpressure level of the filter was confirmed when using artificial soot.

REGENERATION

When a fired regeneration is performed, the speed/load point of the engine remains constant and the post injection is dosed in such a way that the whole filter burns clean (100 % burning rate). Beside the small temperature peak when the soot is ignited, no differences in the temperature curves could be detected, ⑥ (middle). The burning process for engine soot and artificial soot is quite similar.

Under CRT regeneration conditions, the filtered soot is oxidised to carbon monoxide by NO_2 molecules from the exhaust gas. Because of the EGR of the engine, the content of NO_2 in the exhaust is not very high. Therefore, the CRT burning rates are relatively low. Beside this, a better burning rate of the artificial soot can also be seen under CRT conditions. However, no differences in maximum temperature characteristics could be detected in this investigation, ⑥ (right).

CONCLUSION

The investigations with industrial synthetic soot show relatively comparable temperature behaviour. This can be stated for all different kinds of regeneration tests. Industrial soot, especially the material Printex-U that is used here, can perfectly support the DPF application for measuring the DPF soot mass limits, the filtration efficiency of ceramic substrates with cracks and the optimum temperature distribution in the DPF under fired conditions. When industrial soot is used, the test bench times can be significantly reduced because the filling times of the filter are reduced to 20 to 30 min.

Synthetic soot should not be used for special applications of the post injection algorithms. In this case, the differences in burning behaviour and filtration behaviour would create deviations and false results.

At the moment, further investigations are being carried out with a DPF in a so-called close-coupled installation. When the DPF is mounted immediately behind the turbocharger, complicated geometries with sharp bends have to be accepted. This can lead to different soot distribution behaviour on the filter surface and subsequently to different burning behaviour.

REFERENCES

[1] Vogt, C. D.; Kattouah, P.; Ruß, G.; Rothenbach, A.: Material- und Dimensionsstudie an Dieselpartikelfiltern Querschnitt 24. Hochschule Darmstadt, Februar 2010

[2] Ogunwumi, S. B.; Tepesch, P. D.; Chapman, T.; Warren, C. J.; Melscoet-Chauvel, I. M.; Tennet, D. L.: Aluminum Titanate Compositions for Diesel Particulate Filters. SAE 2005-01-0583

[3] Locker, R. J.; Gunasekaran, N.; Sawyer, C.: Diesel Particulate Filter Test Methods. SAE 2002-01-1009

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FUEL CELL DRIVE FOR A TAXI

Together with some partners Lotus Engineering has developed a fuel cell drive for a taxi. The prototype uses a Lithium Polymer battery pack as the peak power source and is analysed as an alternative for diesel drives in urban areas with stringent emission regulations.

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PROJECT DESCRIPTION

Virtually all leading automotive OEMs have, in some degree, investigated levels of electric hybridisation to reduce tailpipe emissions yet offer the same drivability and autonomy of the much established internal combustion engine (ICE) vehicle. The success of hybrid architectures is however influenced by the onboard energy conversion of choice, the vehicle duty cycle as well as the application arena. The London LTI-TX4 zero emission fuel cell taxi jointly developed by Lotus Engineering with programme leader and fuel cell system supplier Intelligent Energy, the London Taxi Company, who provided the vehicle chassis and frame and TRW Conekt, who led the safety case work of the programme, is a prime example. Although designed to operate in a congested city environment with stringent emission regulations, the taxi offers no penalty in terms of vehicle performance or restrictions to cycle regimes. With zero tailpipe emissions, a roundtrip autonomy of circa 250 km, a return-to-base refuelling model and a refuelling time measured in minutes, this technology demonstrator offers the London taxi fleet an alternative prospect to its diesel power plant variant. The vehicle is classed as an electric vehicle with a 30 kW hydrogen fuel cell system as the prime energy converter and a 14 kWh, 116 kW Lithium Polymer battery pack as the peak power source. The performance of the vehicle is superior to the conventional diesel variant, with markedly better acceleration and a higher top speed. With no engine contributing to noise and vibration, the electric driveline, fixed ratio transmission and a bespoke independent rear suspension system gives the green taxi a very smooth ride quality.

With any hybrid topology, opportunity lies in harnessing the best possible usage of energy from the onboard power delivery systems. For the taxi, the initial objective function was to simply operate the fuel cell and battery pack about their respective optimal efficiency bands to achieve minimum consumption of hydrogen. To do this, Lotus Engineering employed a modular power and energy management system within its vehicle controller. The kernel of the power and energy management coordinates the dynamics of the energy storage systems without compromising the vehicle target performance and drivability. At the supervisory control layer, the system uses a combination of rule base, efficiency maps and a consumption minimisation strategy to determine the balance between fuel cell duty cycle, battery state of charge excursions and global system efficiency. During field testing, engineers at Lotus refined the energy management algorithm to effectively optimise multi-objective parameters and addressed the necessary tradeoffs present in such a complex vehicle. The outcome; an iconic London Black Taxi with green credentials.

VEHICLE ARCHITECTURE

The vehicle hybrid power system architecture comprises a main battery pack with two additional satellite modules and a Proton Exchange Membrane (PEM) fuel cell system with the associated high pressure hydrogen storage vessel. The two power sources are coupled via a DCDC converter to a high voltage distribution bus that feeds a rear wheel drive traction drive system as well as all the ancillary loads. Specification of the main subsystems is listed in ❶ with the vehicle component layout in ❷.

The fuel cell system comprises two PEM fuel cell stacks to produce a net power output of 30 kW. The technology utilises a proprietary evaporatively cooled technique, unique to Intelligent Energy, that minimizes system size and component count, whereby water is injected directly into the PEM stack to satisfy both cooling and humidification requirements.

The largest of the vehicle design challenges posed to Lotus was to ensure the new powertrain could be installed within the vehicle space envelope with no impact on the passenger or luggage space. In fact, there are no external visual differences when compared with the conventional LTI-TX4 taxi. This meant that packaging all the subsystems around a relatively old technology ladder chassis and body system was

VEHICLE SUBSYSTEM	SPECIFICATION
PROPULSION SYSTEM	Liquid cooled 100 kW (continuous) PM motor, tri-mode inverter, 12.5 kHz switching frequency
BATTERY PACK	98 cell Li-Ion (NMC), 14 kWh, 116 kW peak discharge, 30 kW peak charge, 363 V nominal
FUEL CELL SYSTEM	384 cell Hydrogen PEM, 30 kW peak, 360 V to 250 V, 3.5 kg of H_2 capacity at 350 bar
DCDC CONVERTER	150 A continuous duty, 48.5 kHz resonant switching boost converter

❶ Specification of the main subsystems

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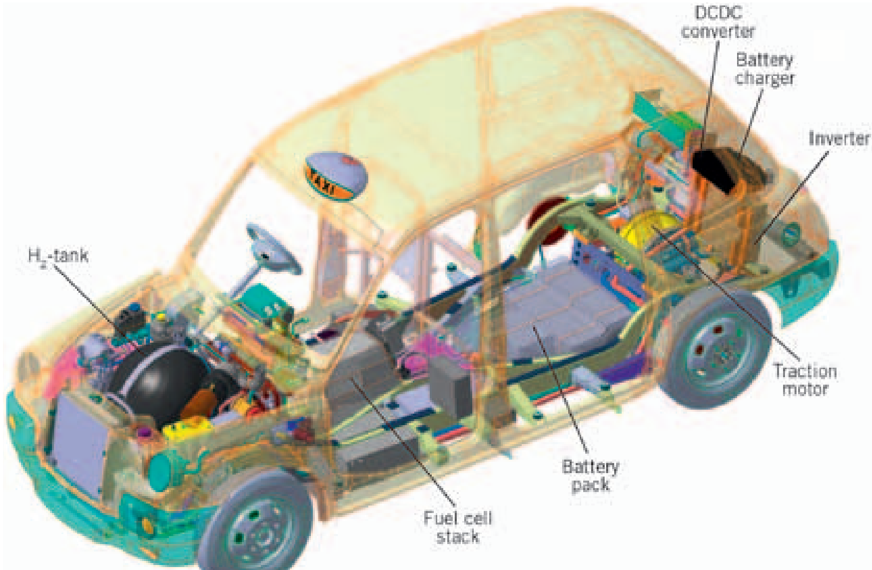
extremely challenging, necessitating some very creative thinking from the designers and build team. The engine bay houses the 154 l hydrogen storage tank weighing 84 kg. Nominal operating pressure of the tank is 350 bar at 15 °C with maximum fill pressure of 430 bar at 85 °C. This nominal pressure was chosen to be compatible with the City of London's hydrogen refueling infrastructure.

The internal tank pressure is regulated through two stages to a final delivery pressure of 4 bar to the fuel cell stacks via a flexible delivery line. External rigid pipe work serving the system includes the high pressure filling line, a low pressure degassing line for emptying the tank and a high pressure blow off valve located in the "Taxi" sign on the roof of the vehicle. This blow off valve will release gas away from the cabin should the vehicle be involved in a collision or any incident which could result in a fire around the tank, causing the tank to over pressurise. As part of the safety case for the project, extensive analysis was carried out on the tank retention system, ❸.



❷ Vehicle architectural layout

As the taxi has two power sources – the fuel cell and the battery pack, to integrate the two power sources, the power coupling devices and the electric drive system, a modular control framework was adopted. Using a combination of efficiency maps and system models, the modular architecture allows vehicle development work with flexibility for future optimisation. The modular approach, ❹, segments the control structure into an energy manager (EM), a power manager (PM) and a torque manager (TM), with structured interfaces between modules. The architecture allows decoupling of energy, power and drivability management and offers a modular and systematic development framework.

As the high level controller, the EM uses a combination of rule base, efficiency maps and a consumption minimisation strategy to determine the balance between fuel cell duty cycle, battery State of Charge (SoC) excursions and global system efficiency. With the battery SoC as the primary variable, the algorithm within the EM calculates outputs that are fed-forward to the PM. The PM observes variables that are required for instantaneous power distribution between the fuel cell, battery and the load. Regenerative braking and torque reduction are fed from the PM to the TM. Within the TM, throttle, brake signal, motor speed and brake blending commands are processed to determine traction torque and allowable recuperation based on tuned torque maps. For drivability to stay consistent with the standard taxi, a simulated engine braking torque was implemented within the TM. Lotus made this 'lift-off regen' feature selectable to enable higher energy efficiency especially on motorway driving. In addition, simulated automatic transmission creep torque was implemented by controlling the torque and speed under various road inclines.

The control of the system can be described as follows: The fuel cell is activated when the battery reaches its lower SoC threshold. It is then controlled by the EM via the PM module to operate within its maximum efficiency region to charge the battery to an upper target SoC. The fuel cell operation is twofold; the first being to operate it at maximum efficiency. To

❸ Hydrogen filling unit and undercarriage view

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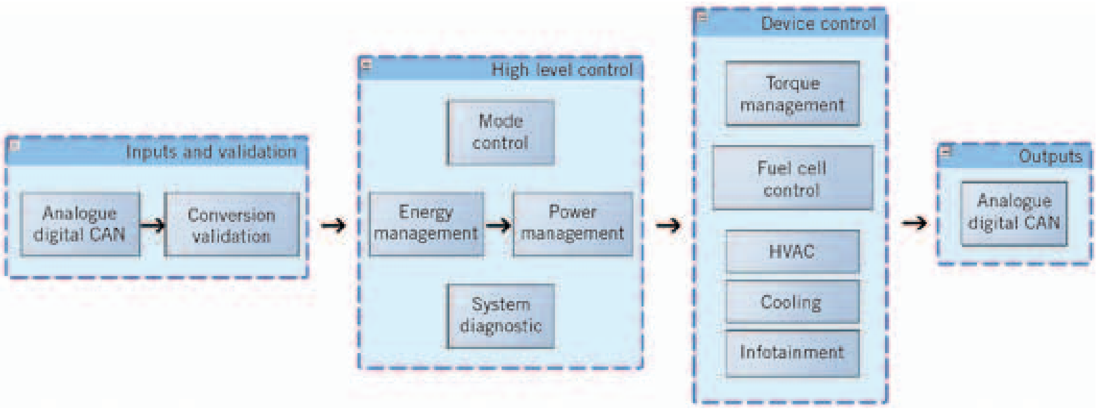
❹ Main control modules



achieve this, a minimum amount of power has to be continuously drawn from the fuel cell, therefore the EM has to determine an operating point to turn the fuel cell on to guarantee sustainable operation about its maximum efficiency point. The second criterion is to minimise the duty cycle of fuel cell operation. If the fuel cell is activated, and can be operated close to its maximum efficiency, the EM will maintain fuel cell activation for as long as possible. In effect, this forms a function to minimise hydrogen consumption and maximise fuel cell cycle life.

Apart from the main three modules described above, there are additional modules that interface with the rest of the vehicle. Calibrations and checks are carried out in the input module to ensure the control modules get valid data. They include range checks, inter-variable consistency, CAN messages validity etc. Other modules control various other power devices such as the fuel cell itself, the HVAC, vehicle cooling and driver interfaces.

VEHICLE OPERATION

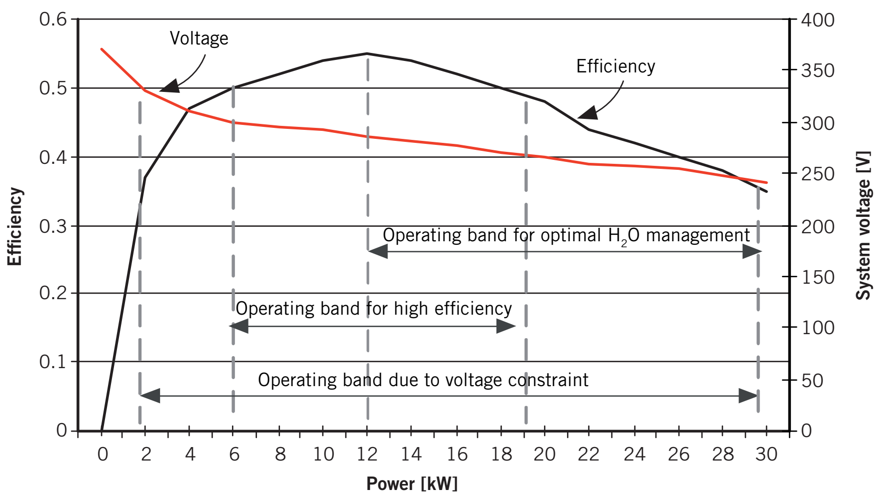
At the start of an operation cycle, the entire load demand is supplied exclusively by the battery system which is sufficient to sustain vehicle motion, auxiliary loads and acceleration demands. When the battery SoC reaches its lower boundary, the fuel cell is controlled to turn on. During the fuel cell start up period (within 3 min), the battery is still sufficient to service the vehicle power demands. When in operation, the fuel cell is regulated between 6 and 19 kW to yield 50 % efficiency whenever possible, ❺. Its evaporative cooling technology uses de-ionised water to keep the stack temperature within limits. Although this system should be self-sustainable (as the by-product of the process is water), operating the stack at a constant 48 to 50 °C proved challenging.

The control system seeks to operate the fuel cell about its maximum efficiency point while satisfying the maximum permissible battery charging current. When a positive peak power demand occurs during battery charging, the fuel cell current is limited by the DCDC converter. Load demands above this cause a voltage sag on the DC bus which then allows the battery to provide the peak power demand. When the battery SoC reaches its upper boundary, the control system will evaluate the constant power demand to determine the fuel cell operation mode. If the vehicle requires an average power greater than 25 kW, the fuel cell remains in operation to supply this average power. According to the simulated vehicle demand profile shown in ❻, this is the situation where the vehicle is cruising at approximately 60 mph on zero gradient.

FIELD TESTING

Having built two technology demonstrator vehicles, Lotus Engineering subjected the taxis to a series of real world driving scenarios. To mimic city and suburban usage patterns, the team carried out various field testing within the city of Norwich as well as surrounding suburban areas. To establish the all important real-world range, engineers at Lotus embarked on a journey from their base near Norwich to Loughborough, in the UK Midlands, where the headquarters of fuel cell provider Intelligent Energy is located. The result was a successful 210 km door to door run with hydrogen fuel and battery energy to spare, ❼.

Various routes were used to accumulate test mileage. Most of this driving was carried out during the harshest winter the UK had experienced in the past 30 years. The cold weather limitations of the vehicle dictated that that Fuel Cell would not operate with frozen coolant and the battery could not be charged below 0 °C. The solution



❺ Optimum operating boundary of the fuel cell system

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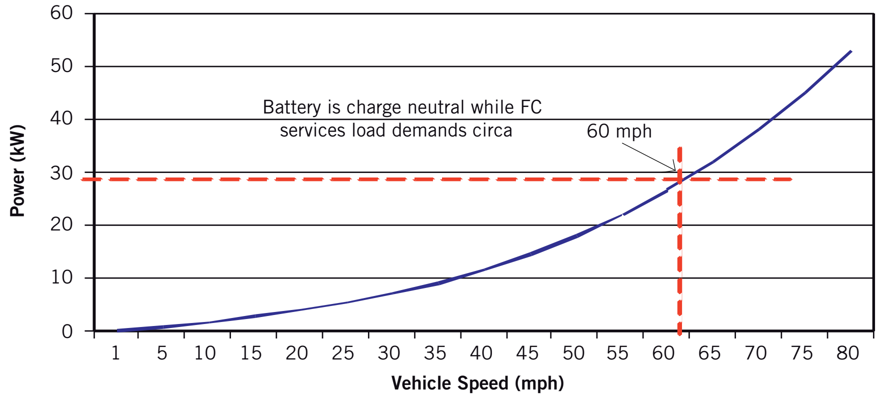


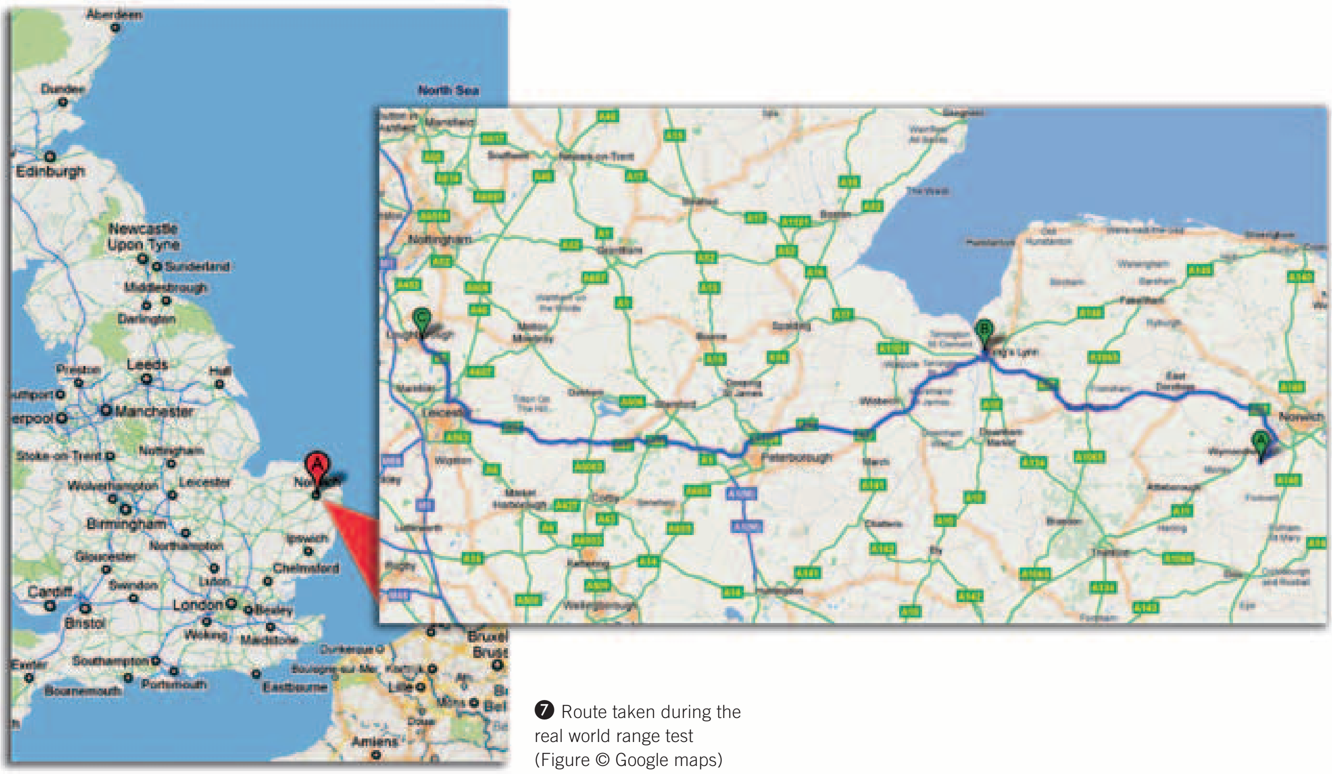
❻ Power demand as a function of vehicle speed; fuel cell maintains the battery at charge neutral after charging to upper SoC point

adopted allowed the fuel cell to warm up using electrical power from the battery. Once started, it would however only be allowed to transfer power to the motor until the battery gets sufficiently warm. Conversely, the shutdown procedure ensured that water was completely exhausted out of the stack to avoid any damage during freezing overnight conditions.

After the initial development program which was carried out on the Lotus test track, the testing moved to real world driving on public roads. Primarily, the tests started off with a mixture of urban and extra urban driving in the local area to gain confidence in the systems before electing to drive longer distances away from base. Several different routes were used around Norfolk and Suffolk, but all were aimed at covering a minimum distance over 200 km. Different fuel cell output strategies were tested, i. e. demand following/steady state output/charge sustaining and in addition, different depth of discharge states were used. Ultimately, the fuel cell control strategy was optimised to maximize the distance covered per kg of hydrogen used. Interestingly, whatever the chosen route, the real world range achieved did not vary by many kilometers. In fact the variance was found to be ± 8 km. The average range achieved on a full tank of Hydrogen (3.6 kg) was 233 km. This equates to only a 10 % decrease in range when compared to the 258 km achieved on the New European Drive Cycle (NEDC). Both test vehicles have proven to be very reliable and robust and have been demonstrated at high profile events such as the 2010 Goodwood Festival of Speed.

CONCLUSION

In addition to providing data on general vehicle durability and performance, the field tests allowed the team to gather the much needed information on general usage of a hydrogen fuelled vehicle. Opportunities for both vehicle and infrastructure improvements were identified. In general, the vehicle has demonstrated that readily available technology enablers (fuel cells, advanced chemistry batteries and power electronics) can be synergistically and successfully integrated, given the right approach.



❼ Route taken during the real world range test (Figure © Google maps)

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INFLUENCE OF GLOW TEMPERATURE ON EMISSIONS AND FUEL CONSUMPTION

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State-of-the-art diesel engines are playing a key role in plans to cut CO_2 emissions. They enable environmentally friendly driving in compliance with the more stringent Euro 6 emissions standard. In order to improve efficiency and minimize energy losses, cold-start systems can utilize a wide range of optimized modules. This paper from BorgWarner Beru Systems analyzes the New European Driving Cycle in terms of a glow system application and compares the influence of glow temperature on raw emissions and fuel consumption.

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EMISSIONS REDUCTION ON DIESEL ENGINES

In developing diesel engines to comply with the Euro 5 emissions standard, the focus of attention was on reducing particle emissions. For Euro 6, NO_x and HC emissions have been cut. Regulation 443/2009/EC additionally stipulates a reduction in CO_2 emissions by an average of 130 g/km in fleet consumption by 2015 [1]. Supplementing earlier publications [2,3], which relate primarily to the low temperature range, emissions and consumption are determined by means of standardized driving cycles such as the New European Driving Cycle (NEDC) [4]. The start conditions in the NEDC are more moderate, however, at around 20 °C.

The main objective of this new investigation is thus to assess the influence of the power consumption of the glow system – explicitly of the glow temperature and duration – on emissions and consumption for operating points at which the diesel engine is running below its optimum temperature.

CALIBRATION TARGETS FOR GLOW SYSTEMS

State-of-the-art cold-start systems such as the ISS system [5] from BorgWarner Beru Systems permit precise setting of the glow power and definition of the glow strategy. In addition to the glow control unit they also feature actuators such as intake air preheaters and metal or ceramic glow plugs.

The cold-start system was equipped with a glow control unit and ceramic glow plugs. The glow temperatures can be set as high as the temperature range typical for ceramic plugs. This is around 200 K higher than the range for glow plugs with metallic heater rods. To obtain an optimum glow system setting, opposing effects must be taken into consideration. On the one hand, the use of cold-start components consumes electric power and so produces greenhouse gas emissions. On the other hand, the glowing – especially at coolant temperatures below 40 °C – helps to keep pollutant emissions within the permitted limits in the NEDC.

To take account of the first effect, the optimum glow system setting would be extremely sparing glow activation with the lowest possible glow temperatures. The opposite approach – high glow temperature and long glow durations – would have positive effects in terms of pollutant emissions and comfort.

The description of the glow system is based on the following criteria:

: fuel consumption (including the power consumption of the glow system)
: emissions (HC, NO_x, CO and CO_2)
: comfort (engine speed stability, engine noise and start time).

CERAMIC GLOW PLUG SYSTEMS

The latest-generation ISS system from BorgWarner Beru Systems combines a performance-optimized glow control unit with newly developed ceramic glow plugs (CGPs). BorgWarner Beru Systems designed its ceramic glow plug as an outer shelf heating glow plug in order to generate the temperature directly where it is needed in the combustion chamber. The heater rod is manufactured by co-extrusion as a ceramic cable with a rotationally symmetrical construction. The cap of this glow plug, being the connection between the inner and outer conductor, is applied by injection-molding. The low nominal voltage of 5.4 V enables the full glow potential to be realized even under starting voltage drop conditions. Heat-up time up to 1200 °C is less than 2.5 s and therefore in line with all known customer demands. The glow plug is designed to glow at up to 1250 °C under nominal conditions.

The main advantages are:

: very fast heating up and reheating time because of the surface heater
: low-voltage rating (nominal voltage 5.4 V)
: possibility to implement multiple glow strategies
: longer life
: temperature directly at the required position.

The microcontroller-controlled glow control unit features new functions for which patents have been registered. They include:

: power-controlled heat-up of the CGP
: energy management during cold start based on pulse-width modulation (PWM)
: automatic recognition of glow plug type (metal/ceramic) during heat-up
: glow plug heat-up control optimized to vehicle electrical system (ramp-up function)
: nesting of glow plug current
: single glow plug energy control
: ground shift compensation

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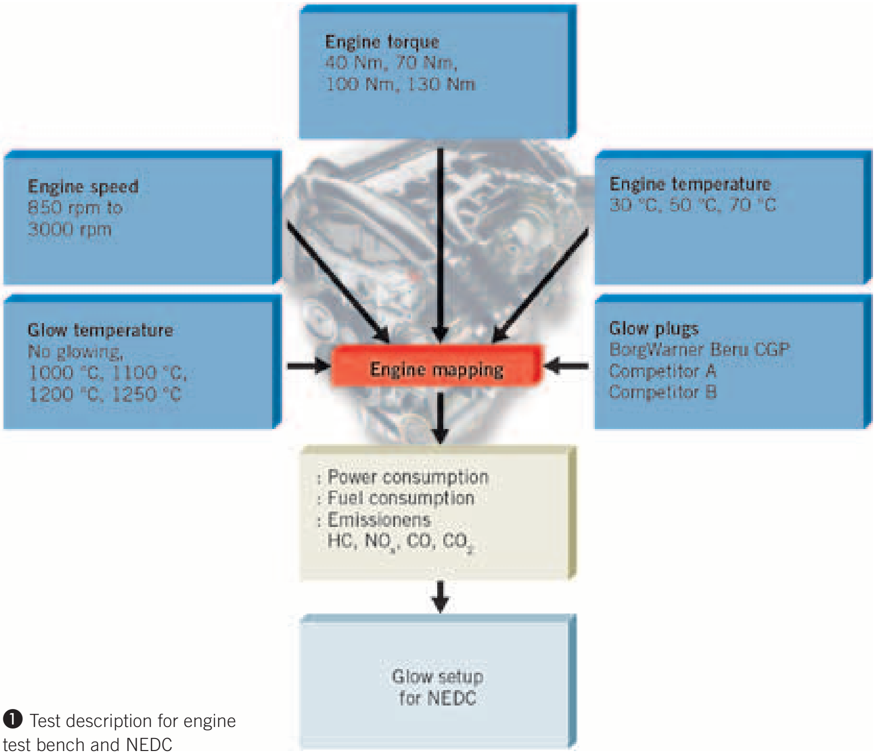
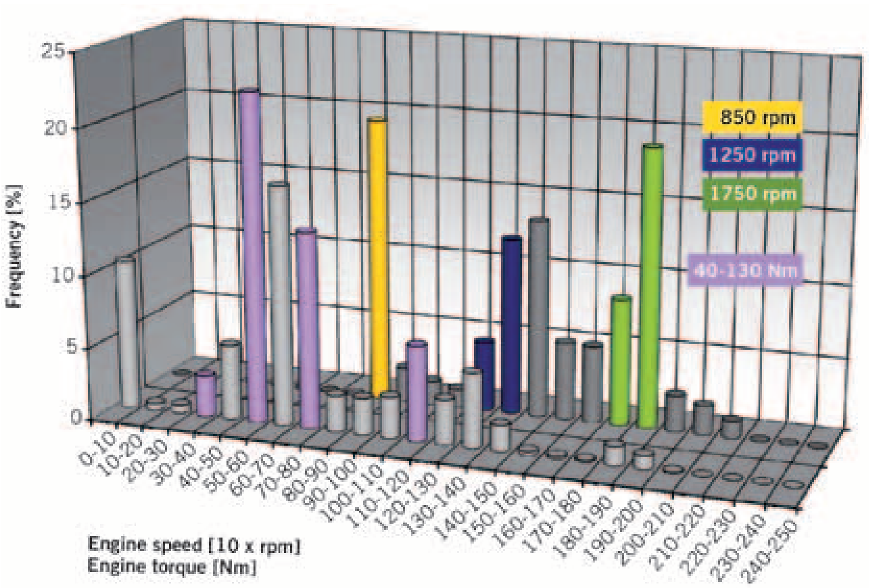


❶ Test description for engine test bench and NEDC



❷ Percentage of the engine speed and the engine torque in the NEDC

: compensation for wiring harness voltage drop
: soft load switch-off
: dynamic re-glow function specially for start/stop systems
: advanced glow plug monitoring (OBD2, CARB requirements, combination glow plug fitting)
: error memory with environmental data.

TEST RESULTS

The bases for calibration of the glow system in the NEDC were investigated with a four-cylinder common rail diesel engine on the engine test bench at the BorgWarner Beru Systems development center in Ludwigsburg. Analyzing the NEDC, a test matrix can be constructed dependent on the engine speed, engine torque output, engine temperature and glow temperature, ❶.

The results of the engine test bench measurements were reduced down to the principal driving conditions of the NEDC: The coolant temperatures of 30, 50 and 70 °C were in line with the urban traffic values of the NEDC and thus with the engine warm-up phase. The engine speed ranged between idling speed and 2150 rpm. Frequent speeds were idle (here 850 rpm) and the range between 1250 and 1750 rpm. The engine torque range was between 0 and 225 Nm. The most frequent torque points were 0, 45 and 75 Nm, and between 105 and 135 Nm, ❷.

POWER CONSUMPTION OF GLOW SYSTEM

The power consumption of the glow system was measured by means of the glow control unit. An increased glow temperature has a fundamental influence on the power consumption of the glow system. In order to attain higher glow temperatures while the engine is running, the glow voltage must be increased to compensate for the cooling effect of the gas exchange cycle and injected fuel. To increase the temperature from 1000 to 1250 °C, a 40 to 50 % higher glow power is required. Increasing the temperature from 1200 to 1250 °C resulted in a difference of a further 5 to 8 %. The outer shelf heating guarantees an optimized efficiency of the CGP.

FUEL CONSUMPTION

The fuel consumption correlates with the power consumption of the glow system. The results with no active glow system serve as reference values for the depiction in ❸. Dependent on the engine speed, torque and temperature, fuel consumption with glowing active was as much as 4 % higher. The influence of the higher power consumption of the glow system on fuel consumption is more marked at lower torque or with smaller fuel injection quantities. Especially future legislation [1], which focuses particularly on CO_2 emissions, will demand the devising of innovative glow strategies.

RAW EMISSIONS

❹ shows the emission measurement results at one selected engine speed,

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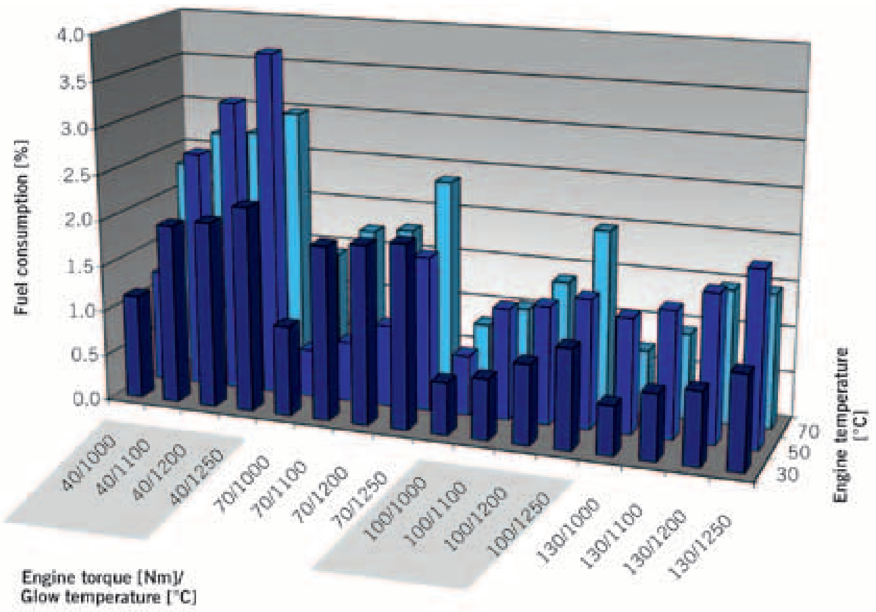
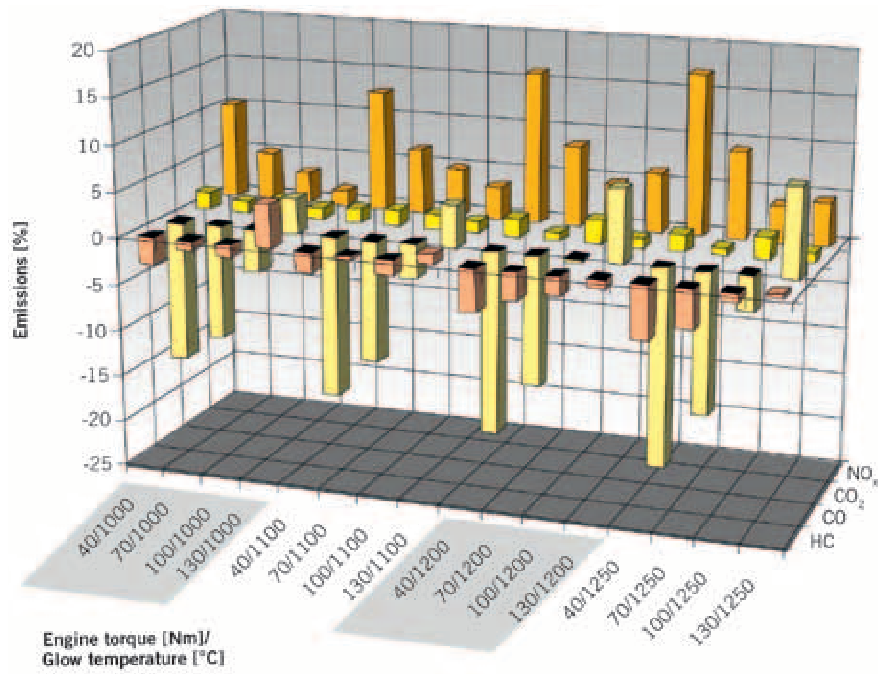
relevant torque and exemplary glow plug temperatures. The results without active glowing provide the reference values for all the data presented in this section. Higher emissions compared to the reference values are depicted as positives; lower emissions are depicted as negatives. The higher glow plug temperature reduced CO and HC emissions but increased NO_x emissions. The CO_2 emissions correlating with the fuel consumption were slightly increased. In order to utilize the positive effects and compensate for negative effects, therefore, an optimized glow strategy in terms of glow temperature and duration is required.

❺ shows the influence of the glow plug temperature on HC and NO_x emissions in a speed/torque graph. Only minor improvements were seen between 1200 and 1250 °C at some operating points. Higher glow temperatures resulted in significantly higher NO_x emissions, with a disproportionately higher rate of rise between 1200 and 1250 °C.



❸ Variation of the fuel consumption dependent on engine temperature, engine torque and glow temperature at 1250 rpm



❹ Emissions dependent on engine torque and glow temperature at engine speed 850 rpm and a coolant temperature of 30 °C

VEHICLE VALIDATION

For the driving cycle the vehicle was fitted out with an engine of identical design to that used in the engine test bench testing. Based on the engine test bench results, the following three glow strategies were developed and validated during the NEDC.

Reference calibration as basis:
- maximum glow temperature of 1250 °C at engine start
- glow temperature reduced to 1100 °C dependent on coolant temperature while engine running
- glow duration according to production calibration of engine.

Comfort calibration (reduced engine noise):
- maximum glow temperature of 1250 °C at engine start
- no reduction in glow temperature while engine running
- glow duration according to production calibration of engine.

Economy calibration (reduced glow duration and glow system power consumption):
- reduced glow temperature of 1100 °C at engine start
- glow temperature rapidly decreasing to 1000 °C while engine running
- reduced glow duration.

❻ shows the results of these glow strategies for the NEDC. The basis (100 %) of the data is the reference calibration. The comfort calibration reduced HC and CO emissions but, as expected, resulted in an increase in NO_x and CO_2 emissions and in fuel consumption. The economy calibration delivered good results in terms of fuel consumption but resulted in an excessive increase in HC and CO emissions.

SUMMARY AND OUTLOOK

State-of-the-art diesel engines are playing a key role in plans to cut CO_2 emissions. They enable environmentally friendly driving in compliance with the more stringent Euro 6 emissions standard. Cold-start systems can utilize a wide range of optimized modules in order to improve efficiency and minimize

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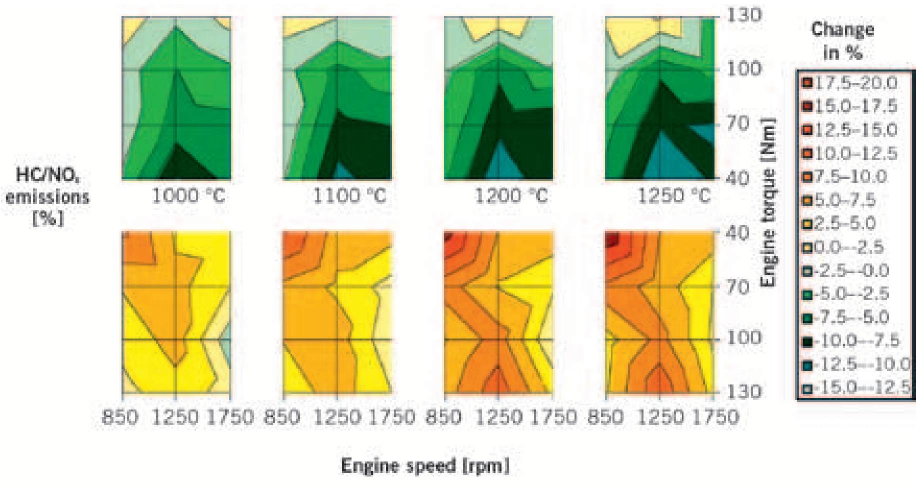
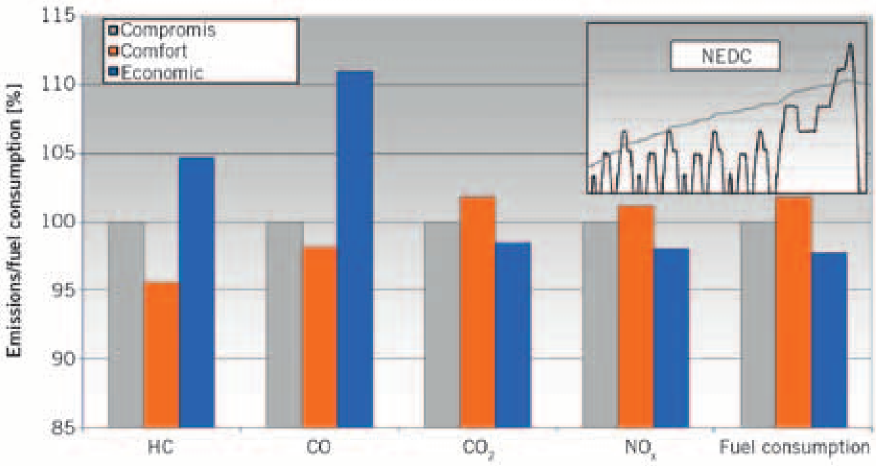


❺ HC and NO_x emissions dependent on engine speed, torque and glow plug temperature; the coolant temperature is 30 °C



❻ Comparison of emissions and fuel consumption during NEDC (urban traffic)

energy losses. The interaction of the glow controller, its adaptation to the energy management system and the corresponding glow plugs are a component element of the overall glow system application.

This investigation analyzed the standardized NEDC driving cycle in terms of a glow system application and compared the influence of glow temperature on raw emissions and fuel consumption. In general, between 1200 and 1250 °C no significant influence on raw emissions was seen, though there certainly was an increase in power consumption resulting in higher fuel consumption.

A glow strategy must therefore represent a compromise between ride comfort requirements and fuel consumption caused by the power demand of the glow system. The decision as to the required glow power of an application at the various operating points depends heavily on the engine design and the general calibration strategy.

Intelligent glow systems can be adapted to the engine strategy while at the same time influencing fuel consumption and raw emissions. Using algorithms to minimize the current changes and power losses, the glow power can be set precisely to the desired level of the application.

REFERENCES

[1] Regulation setting emission CO_2 emissions from light-duty vehicles performance standards for new passenger cars as part of the Community's integrated approach to reduce. Regulation (EC) No. 443/2009 of the European Parliament and of the Council of 23 April, 2009

[2] Last, B.; Houben, H.; Rottner, M.: Influence of modern diesel cold start systems on the cold start, warm-up and emissions of diesel engines. 8th Stuttgart International Symposium, March 2008

[3] Grütering, U.; Pischinger, S.: Stable running of diesel engines at very low ambient temperatures. 8th Stuttgart International Symposium, March 2008

[4] Directive relating to measures to be taken against air pollution by emissions from motor vehicles and amending Council Directive 70/220/EEC. Directive 98/69/EC of the European Parliament and of the Council of 13 October 1998

[5] Blanc, M.; Geiger, S.; Houben, H.; Hovestadt, T.; Toedter, O.: Diesel-Kaltstartsystem ISS der zweiten Generation mit Ansaugluft-Vorwärmung [ISS second-generation diesel cold-start system with intake air preheating]. In: MTZ (67) 2006, No. 5

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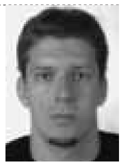

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APPLICATION OF AN OPTICAL FLOW METHOD FOR FLOW ANALYSIS IN ENGINE COMBUSTION

The application of optical flow method for the determination of flow fields in engine combustion is illustrated by the spray propagation of gasoline direct injection valves in an injection chamber as well as swirl-determination in a rapid compression machine. The potential of this measurement technique as an alternative to particle image velocimetry (PIV) is demonstrated.

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1 INTRODUCTION

Meanwhile, Imaging Measurement Techniques are an indispensable part of engine combustion process development. Optical metrologies are used more frequently for the characterization of injection sprays, the analysis of mixture formation and combustion as well as for the investigation of exhaust gas before and after its aftertreatment. Due to their nonintrusive operation, combined with a high temporal and spatial resolution, they permit the examination and measurement of complex processes. For example, the geometrical spray structure of injection valves is analyzed by means of the Mie-scattering technique [1], the mixture formation process is evaluated with laser-induced fluorescence [2] and the chemiluminescence of combustion in the ultraviolet and visible spectral range is visualized [3, 4]. In general, the methods used provide a statement on the current moment of recording, without being able to determine the vector motion. If information on flow fields and its local motion distribution is needed, currently PIV is used. This measurement technique provides reliable results. However, from the technical point of view or for financial reasons, its use is not reasonable in some cases. Nevertheless, for realizing the aimed studies with such tasks, a measuring technique is required which permits a reliable flow analysis using less amount of equipment. In this context, the optical flow method implies a high potential for realizing such measurements.

2 FLOW ANALYSIS USING PIV

The determination of flow fields using PIV is a recognized and reliable technology. The flow under investigation is usually provided with solid particles or liquid droplets that follow the flow [5]. On the basis of two successive exposures, the flow motion can be determined by means of the imaged particle displacement. Image recording and analysis have to, however, be adapted to each other with respect to the flow conditions. Thus, the choice and number of added particles is of crucial importance for the successful use of this measurement technique. If the particles are too heavy and thus too slow, they do not follow the flow with sufficient accuracy. If too little or too many particles are added, the analysis based on correlation algorithms does not provide any useful results. Furthermore, the particles can contaminate the optical access and may lead to increased mechanical abrasion or even blockages in the technical facility. In order to effect a PIV measurement at least the following components are required:

: device for adding particulates
: laser with optics to form a light-sheet
: camera system to acquire the illuminated particles
: unit for timing control
: calculator for evaluating image data.

After the recording of the image data of the examined object, they are evaluated by correlation functions which must be conditioned by the experimenter on the basis of the image features. The image pair is divided into image segments which are subsequently evaluated by the correlation function. As a result, the function provides a displacement vector for each image segment. The velocity can be calculated from the time difference of the two images. The smallest size of the evaluated image segments depends on the number of particles in the image. This results in a defined number of vectors that can be determined for the overall image. In order to increase the vector density, an overlap of the image segments have to be selected that increases the required evaluation time. In general, the calculated flow field also includes vectors which have not been determined correctly. For this reason, today's PIV software packages work with complementary methods such as multiple assessment, image segment adaptation and vector plausibility checks in order to improve the quality of the results.

3 OPTICAL FLOW METHOD

Optical flow is the seeming motion of brightness patterns in an image sequence, with the movement being determined by assessment methods for each pixel in the image. The following boundary conditions for the use of optical flow methods can be derived:

: Brightness patterns (intensity difference) must be present in the image sequence.
: Brightness patterns should only change moderately from image to image.
: The sequence must consist of at least two images.

These boundary conditions also permit the flexible use of this analytical method. Thus, the optical flow method can be used for characterization of spray analysis using an illumination, but also permits for example the investigation of flame fronts without a light source. In both cases a camera is needed which is able to record at least two images in a short time interval. As high-speed cameras have been available in various performance classes for some years, their application suggests itself in this context.

Different approaches for calculating the optical flow, which are more or less suitable in regard to the respective image feature, are found in the literature on this subject. The technique used in this paper is founded on the method of Horn and Schunck [6]. It is essentially based on the assumption that a brightness pattern does not change during motion and the motion of adjacent pixels only differs slightly.

EQ. 1
$$f(x + u, y + v, t + 1) - f(x, y, t) = 0$$

In this equation, x and y denote the position within the image and t refers to time dimension. The displacements u and v are to be found.

By a first-order Taylor expansion, Eq. 2 can be derived from Eq. 1. Thus, the linear optical flow condition is obtained which is known as data term of first order.

EQ. 2
$$f_x u + f_y v + f_t = 0$$

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For determination of the displacement vectors *u* and *v* this single equation is not sufficient. Horn and Schunck worded this problem by taking into account global smoothness of the vector field and introduced a so-called smoothness term (Eq. 3).

EQ. 3

$$|\nabla u|^2 + |\nabla v|^2$$

The idea is to penalize differences of neighboring motion vectors. On the assumption of moving object surfaces which are represented by a larger number of image pixels and which show a small displacement between images, neighboring motion vectors should not differ severely. However, large problems occur with object borders that move in the image. In this case undesirable smoothing of the motion vectors occurs. The formulation of the smoothness term is, hence, crucial and should take into account structure properties in the image. In flow analysis variable structures are considered in which translation, rotation as well as change of size can be observed. Thus, in this paper a smoothing term is used which judges the borders of image structures [7, 8]. A criterion for identification of structure borders is the evaluation of the magnitude of the gradient in the image.

EQ. 4

$$|\nabla f| = \sqrt{(f_x^2 + f_y^2 + f_t^2)}$$

A structure border is often related with a strong change in gray level value. Hence, the magnitude of the gradient in such areas shows large values and can be used to determine the intensity of smoothing. A so-called image-based smoothing term has the form

EQ. 5

$$g(|\nabla f|^2)\ (|\nabla u|^2 + |\nabla v|^2)$$

For a suitable choice of $g(|\nabla f|^2)$ Charbonnier et. al. [8] introduced the function

EQ. 6

$$g(|\nabla f|^2) = \frac{1}{\sqrt{1 + \frac{|\nabla f|^2}{e_s^2}}}$$

which is meanwhile well established. Here e_s as a small positive contrast parameter can be chosen arbitrarily. The introduction of $g(|\nabla f|^2)$ implies that the smoothing term is not only dependent on the current calculated field of motion but also depends on the original image. With this approach only the magnitude of the image gradient takes effect on the smoothing and thus acts isotropically. According to Horn and Schunck the data and smoothing term can be combined in an energy functional after its definition.

EQ. 7

$$E_{(u,v)} = \int_\Omega \left((f_x u + f_y v + f_t)^2 + \alpha g\ (|\nabla f|^2)\ (|\nabla u|^2 + |\nabla v|^2) \right) dxdy$$

Minimization of the energy functional in a certain neighborhood Ω supplies the motion vectors. In regard to this, α denotes a regulation parameter of the smoothing term. The functions $u\ (x, y, t)$ and $v\ (x, y, t)$ are to be determined in such a way that the value of the integral is minimized. The solution of this minimization problem can be obtained using variational methods and can be found with the Euler-Lagrange-Equations. As a solution, a system of coupled non-linear differential equations is obtained

EQ. 8

$$\partial_u F_{ux} + \partial_y F_{uy} + F_u = 0$$

EQ. 9

$$\partial_v F_{vx} + \partial_y F_{vy} + F_v = 0$$

which, however, has no algebraic solution and thus has to be solved numerically. The choice of the iterative method for solving the equation system governs the time needed for obtaining a solution [10]. The use of unidirectional multigrid methods is a promising class of methods which relies on an advantageous setting of the initial grid values. By a predefined number of sub-sampling factors the computational load of the minimization problem can be reduced significantly. After each calculation level the result is interpolated into the next higher level. As a result, a refined estimate is obtained through each level. This strategy enables the evaluation of large image sequences with low computing time.

The result is a vector field of velocities for each image sample in the sequence. Using such an approach for data and smoothing term, combined with an image sequence which comprises more than two individual images, a post-processing of the results is not necessary, as through the optimization problem the best-possible solution throughout the complete image sequence is calculated.

The key to successful use of the optical flow method is therefore the suitable choice of the two terms that should be established taking into account the following image features [11]

- types of motion and resizing
- intensity fluctuations
- noise.

3.1 ANALYSIS OF SPRAY PROPAGATION OF A BDE-INJECTOR USING OPTICAL FLOW

The characterization of spray propagation of injection valves becomes increasingly important, as particularly with direct injection the distribution of fuel in the combustion chamber determines the starting conditions for subsequent combustion. Typically, the analysis of the spray is performed in an optically accessible injection chamber in which the operating parameters such as chamber pressure, chamber temperature, fuel pressure and fuel temperature can be adjusted separately. ❶ shows the schematic design of the injection chamber and the equipment used for recording the images.

The spray images are generated as a shadow process. A simple, continuously operated light source (halogen lamp) in combination with a high speed camera (Photron Fastcam APX 120 K) represents the entire acquisition system. A diffuser plate is mounted in front of the halogen lamp in order to homogenize the intensity distribution. When the spray enters the injection chamber, the image

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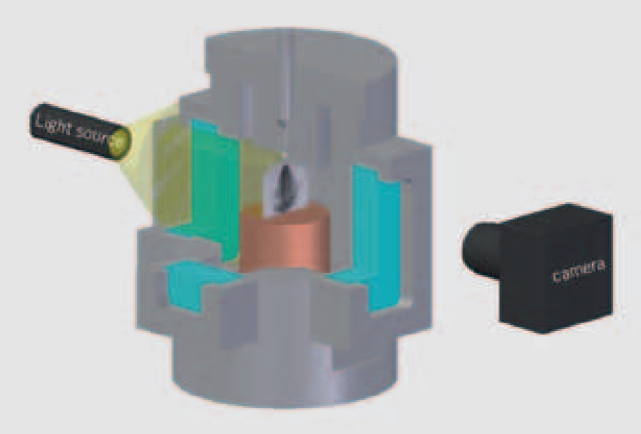


❶ Schematic assembly of the injection chamber with measurement equipment

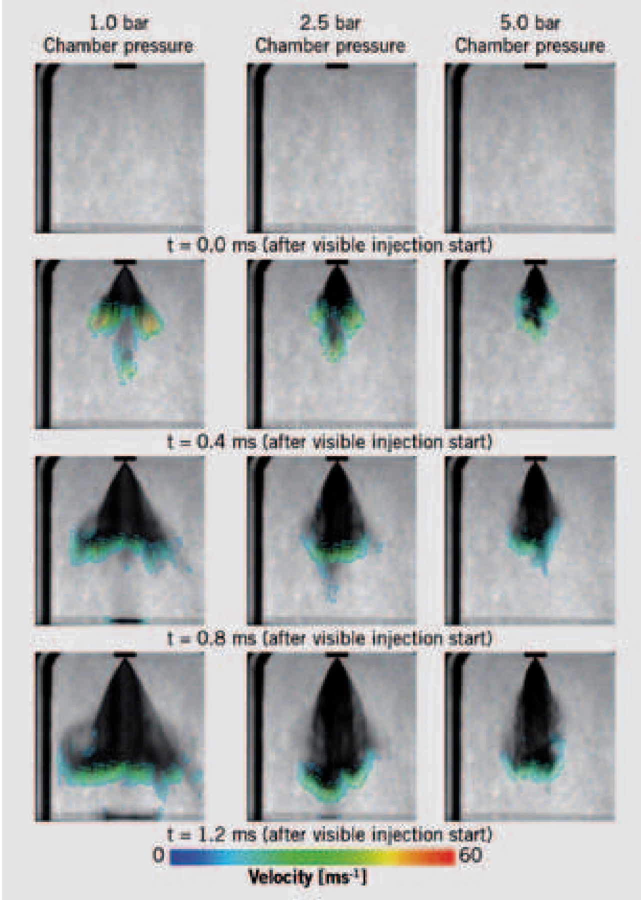
intensity will be reduced at the locations where the spray crosses the way of the light between the illumination and the camera. The image acquisition rate for the visualization of the injection is 15.000 frames per second at a resolution of 256x256 pixels. ❷ shows the velocity vectors of the spray propagation of a swirl injector calculated by means of the optical flow method at selected recording times after start of injection for a variation of the chamber pressure. The reduction of the intensity within the images due to the spray penatration can clearly be seen. Its change from image to image is very obvious especially at the spray front wherby the optical flow analysis provides corresponding velocity vectors mainly at these locations. In the spray core and in the background only slight intensity changes can be found. At these locations the evaluation shows only very small velocities which are not displayed in the illustrations.

For the interpretation of the results it should be pointed out, that this recording technique delivers projected illustrations. The entire three-dimensional spray is converted into a two-dimensional image. Therefore, the locations of velocity determination can only be reported in two coordinates. Nevertheless, using this very simple acquisition technique in combination with the optical flow method, the flow field of spray propagation can be calculated and a quantitative comparison of the results at different operating conditions is permitted.

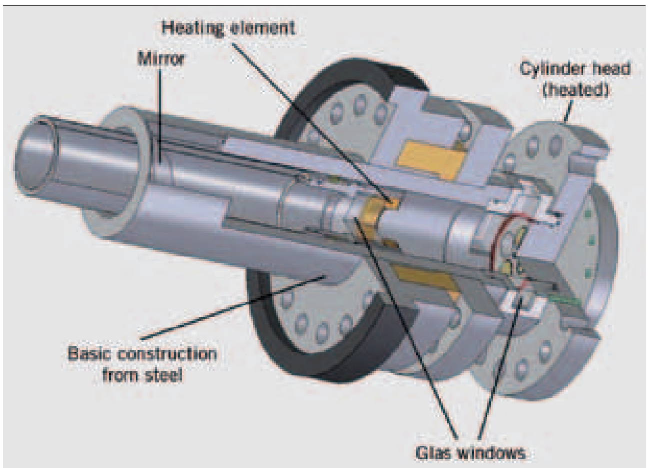
3.2 ANALYSIS OF SWIRL MOTION IN A RAPID COMPRESSION MACHINE USING OPTICAL FLOW

With the use of rapid compression machines for a dynamic simulation of engine strokes it is possible to study the influence of different parameters on mixture formation and combustion. Swirl for example, can decisively affect the ignition and combustion behavior. The knowledge of swirl motion provides an important contribution for a better understanding of the processes. ❸ shows an optically accessible compression machine of the type TeRCM-K8401. The main feature of the unit is a dynamic simulation of a freely selectable engine stroke curve.

In order to visualize the swirl motion, the cylinder load was doped with oil vapor. As a light source, a continuous wave laser was used to illuminate the combustion chamber through a glass window which is located at the side of the chamber. A laser is basically not necessary, but was used for this study due to its availability. As before in the spray characterization, again a high-speed-camera (Photron Fastcam APX 120K) was used. The optical access to the combustion chamber roof was realizedby means of an output mirror and a glass window embedded in the bottom of the piston.



❷ Optical flow evaluation of the spray propagation at various chamber pressures



❸ Schematic illustration of the rapid compression machine

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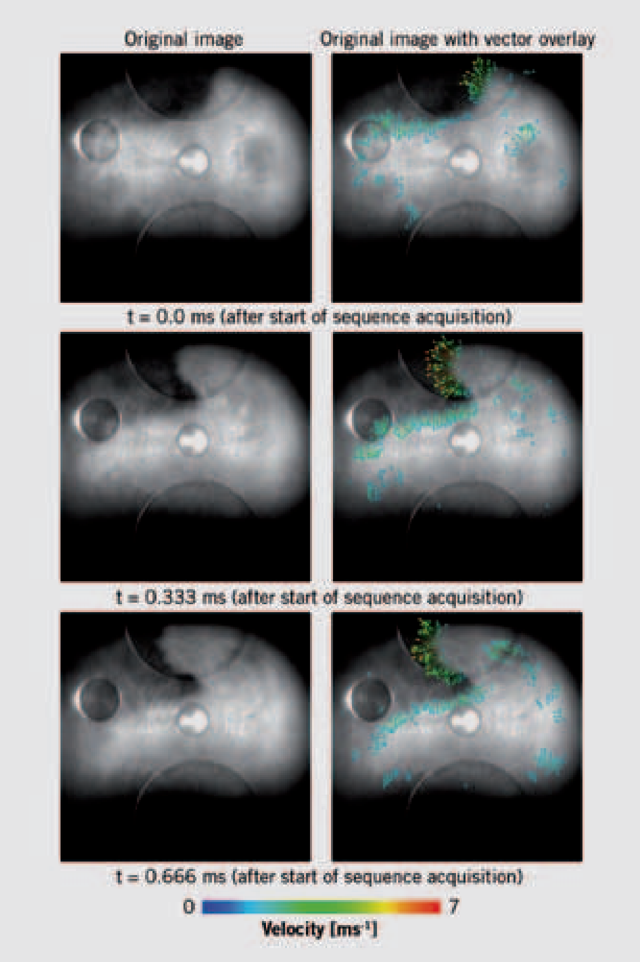

❹ Optical flow analysis of the in-cylinder swirl motion

An exemplary analysis of swirl motion using optical flow analysis is shown in ❹. For a better understanding both original images and analyzed images with overlaid velocity vectors are shown. The cylinder head with the intake and exhaust valve as well as the centrally located injector can clearly be seen. The swirl motion can be visualized due to the inserted oil vapor, as there are intensity gradients resulting from the mixing of unloaded and loaded air. As expected, the optical flow analysis provides velocity vectors at the places where strong intensity changes can be observed from image to image. Time-constant intensity values do not produce any motion vectors.

4 CONCLUSION

The method of optical flow analysis provides a quantitative analysis of visual motion from image sequences as it can be observed e.g. in spray propagation or in-cylinder swirl motion. A pre-condition of this methodology are differences in brightness in the acquired motion sequence which can be assigned to the examined movement. For this reason, the optical flow analysis provides for the spray propagation mainly vectorial velocity information at the spray front. In order to determine swirl motion, the intensity gradients are used which arise at locations where oil-loaded and unloaded air are mixing. In contrast to the PIV measurement technique, the optical flow method is in principle not dependent on additional particles for flow analysis. If the flow shows not any valid intensity gradients, particles are added for the visualization. In contrast to PIV, the dosage has no affect on the calculation. Another advantage compared to the PIV-method is the possibility of using inexpensive light sources. The use of a Laser is only necessary if light intensities are required which are not realizable with other light sources. The results presented in the article show that a reasonable combination of several from the literature known approaches of the optical flow method allow a quantitative determination of flow fields with a lower technical expense in comparison to the PIV measurement technique. First preliminary tests of the application of the presented method for e.g. the analysis of flame fronts in technical combustion or the characterization of the ignition spark propagation also show promising results.

REFERENCES

[1] Rogler, P.; Grzeszik, R.; Arndt, S.; Aigner, M.: 3D analysis of vapor and liquid phase of GDI injectors using laser induced exciplex fluorescence tomography in a high pressure/high temperature spray chamber. SAE, Technical Paper Series 2007-01-1827, 2007

[2] Scholz, J.; Wiersbinski, T.; Beushausen, V.: Planar Fuel-Air-Ratio-LIF with Gasoline for Dynamic Mixture-Formation Investigations. SAE, Technical Paper Series 2007-01-0645, 2007

[3] Dec, J.; Espey, C.: Chemiluminescence Imaging of Autoignition in a DI Diesel Engine. SAE, Technical Paper Series 982685, 1998

[4] Drake, M. C.; Haworth, D. C.: Advanced Gasoline Engine Development Using Optical Diagnostics and Numerical Modeling. Proc. Combustion Inst., pp. 99-124, 2007

[5] Adrian, R. J.: Twenty years of particle imaging velocimetry. Exp. Fluids, 39, pp. 159-169, 2005

[6] Horn, B.; Schunck, B.: Determining Optical Flow. Artifical Intelligence, 17, pp. 185-203, 1981

[7] Alvarez, L.; Deriche, R.; Sánchez, J.; Weickert, J.: Dense disparity map estimation respecting image derivatives: a PDE and scale-space based approach. Journal of Visual Communication and Image Representation, 13(1/2):3-21, 2002

[8] Charbonnier, P.; Blanc-Féraud, L.; Aubert, G.; Barlaud, M.: Two deterministic halfquadratic regularization algorithms for computed imaging. Proc. IEEE International Conference on Image Processing, Volume 2, pp. 168-172, 1994

[9] Weikert, J.; Bruhn, A.; Schnörr, C.: A theoretical framework for convex regularizers in PDE-based computation of image motion, International Journal of Computer Vision, 45, pp. 245-264, 2001

[10] Black, M. J.; Anandan, P.: Robust dynamic motion estimation over time, Proc. 1991 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, pp. 292-302, 1991

[11] Black, M. J.; Anandan, P.: The Robust estimation of multiple motions: parametric and piecewise smooth flow field, Computer Vision and Image Understanding, 63, pp. 75-104, 1996

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AGING OF AUTOMOBILE FUEL CELLS – PRINCIPLES AND ANALYSIS METHODS

Three of the most important hurdles faced by automobile fuel cell systems in the upcoming market launch are forming nationwide infrastructures for hydrogen fuelling stations, reducing manufacturing costs and increasing lifetime. This article from the Fraunhofer Institute for Transportation and Infrastructure Systems IVI in Dresden introduces a new method for analysing state-of-health of automobile fuel cells.

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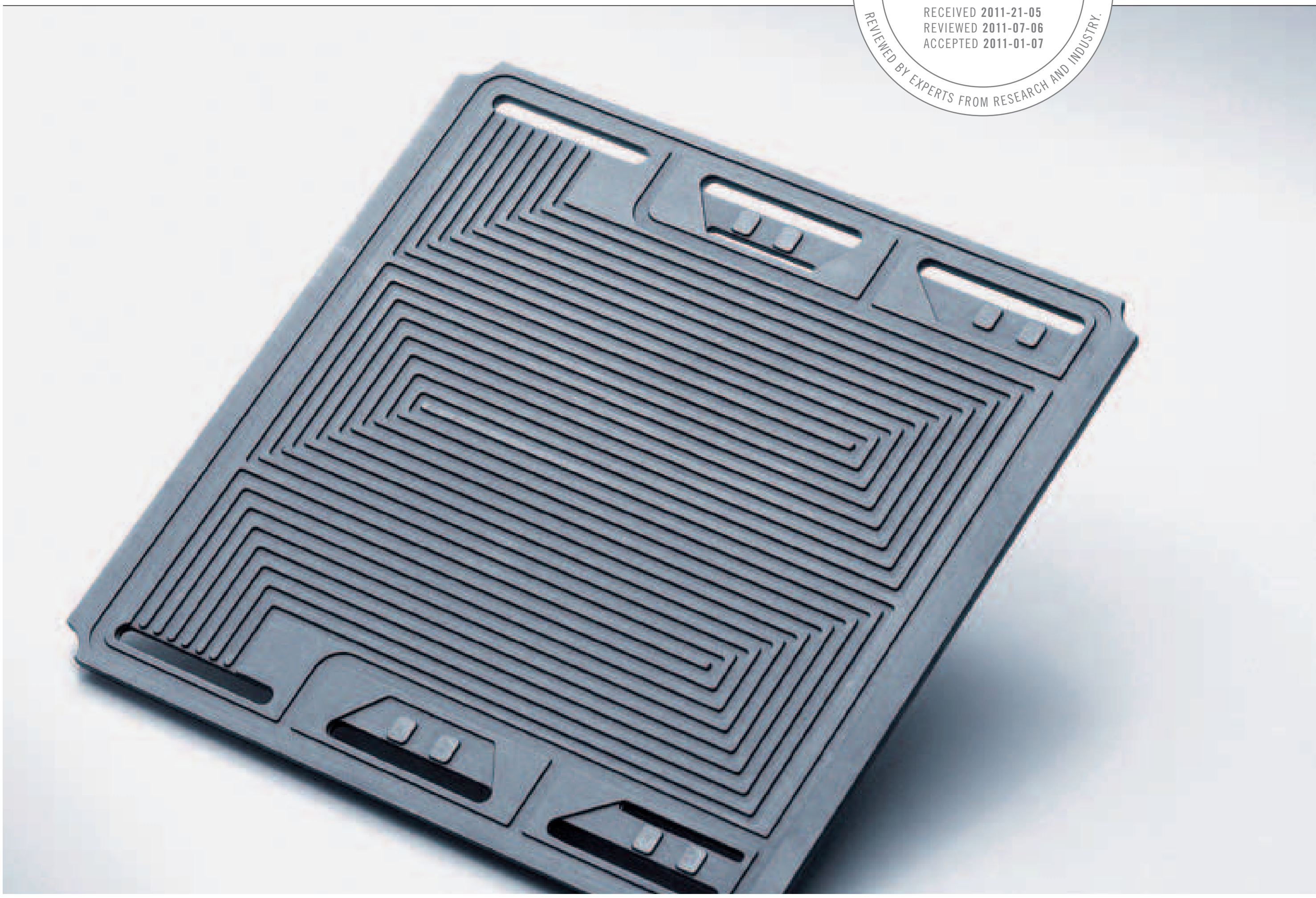


1 FUEL CELLS IN AUTOMOBILES

Fuel cells systems today offer a promising option for changing over to a CO_2 neutral energy supply in transportation by converting hydrogen into electrical energy in an efficient and emission-free manner. Almost all well-known automobile manufacturers are currently developing fuel cells. In the process, fuel cell vehicles will allow significant market opportunities in the long term, especially in the middle and upper class segment, despite the current hype about lithium-ion battery technology. The reasons for this are larger ranges, shorter refuelling times and lower system costs in the long run, in comparison to battery systems [5].

In addition to infrastructural hurdles in the way to launching automobile fuel cell systems in the market, manufacturers consider the requested service life of over 5000 hours as a great challenge. Diagnosis and analytic methods that monitor the state-of-health specific to the fuel cell components have special importance in the development and testing of fuel cell vehicles. In particular, post-mortem analysis helps to understand aging processes that are highly complex and to evaluate their influence on the performance of the fuel cells.

1.1 FUNCTIONAL PRINCIPLE

The functional principle of fuel cells is based on the direct electro-chemical conversion of chemical energy into electrical energy, similar to batteries. However, in contrast to batteries, the reactants of the fuel cells are fed continuously. The main components are two electrodes coated with catalyst material and one electrolyte separator. The electrolyte provides the spatial separation of the educts and simultaneously enables the charge transfer between the electrodes.

For automotive polymer electrolyte fuel cells, the educts are hydrogen and atmospheric oxygen. A proton-conducting polymer membrane serves as the electrolyte. The anode is continuously supplied with hydrogen, which is adsorbed and oxidised on the catalyst, during operation. At the same time, oxygen is catalytically reduced on the cathode. As the H+ ions are released at the anode reaching the cathode through the membrane, the electrons flow to the cathode via a closed circuit. There, they combine with oxygen and protons to form water.

The fuel cell delivers a useful cell voltage because of the different Galvani potentials of the reactions on anode and cathode. Several voltage drops occur in operation depending on the current flow, which reduces the useful cell voltage. These overpotentials describe voltage losses due to fuel crossover and internal currents across the membrane, activation losses, charge transfer (Ohmic losses) and mass transport (concentration losses). If you apply the cell voltage over the current density, then the typical polarisation curve of the fuel cell appear, as shown in ❶.

1.2 COMPONENTS AND STRUCTURE

Polymer electrolyte fuel cells have a sandwich-like structure and consist of the components anode, membrane and cathode, two gas diffusion layers and two end plates, in which flow channels for gas supply are incorporated. Membranes and both electrodes are combined in the membrane electrode assembly. The voltage level can be increased through the series connection of individual cells. To do so, fuel cell stacks are set up. Bipolar plates inserted between the cells serve to drain electrons and ensure gas supply and removal of product gases, ❷.

2 AGING BEHAVIOUR OF FUEL CELLS

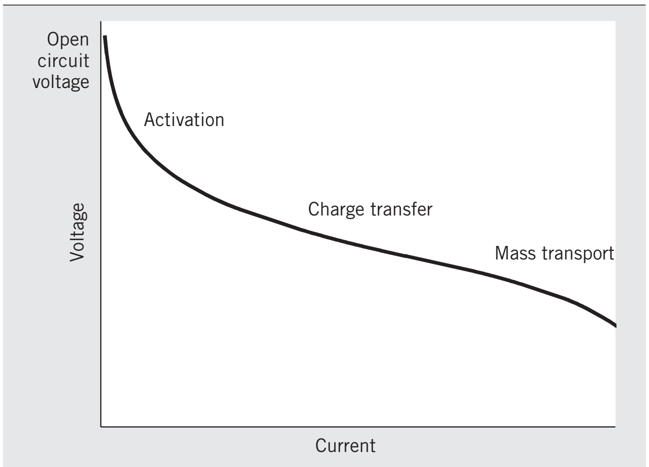
The lifetime of electrochemical systems is limited by different aging processes that are strongly influenced by the specific load profile. In fuel cell systems, the start and stop processes, long idle phases and quick load changes primarily create conditions that lead to an accelerated aging on the electrodes, the gas diffusion layers, the bipolar plates and the membrane.

2.1 AGING PROCESSES

The main aging processes on the electrodes are based on change in the catalyst structure. Here mainly the active catalyst surface is reduced by agglomeration of catalyst particles or by absorption of contaminants. Furthermore, the porous supporting structure in the gas diffusion layers is being deteriorated. The reason for the processes is primarily a shortage of media on the anode or cathode, which leads to potential displacements and corrosion processes. On the membranes, aging processes have been observed which lead to a loss of proton-conducting properties but also cause material thinning and drying-out the membrane. In particular free radicals in the membrane environment negatively affect the conductivity and the supporting structure of the membrane. Corrosion, impurities of the media and thermal strain can lead to functional damages on the bipolar plates.

2.2 EFFECT ON FUEL CELL PERFORMANCE

The damage described directly affects the evolution of the polarisation curve. Aging on the catalysts leads to altered activation



❶ Polarisation curve of a fuel cell

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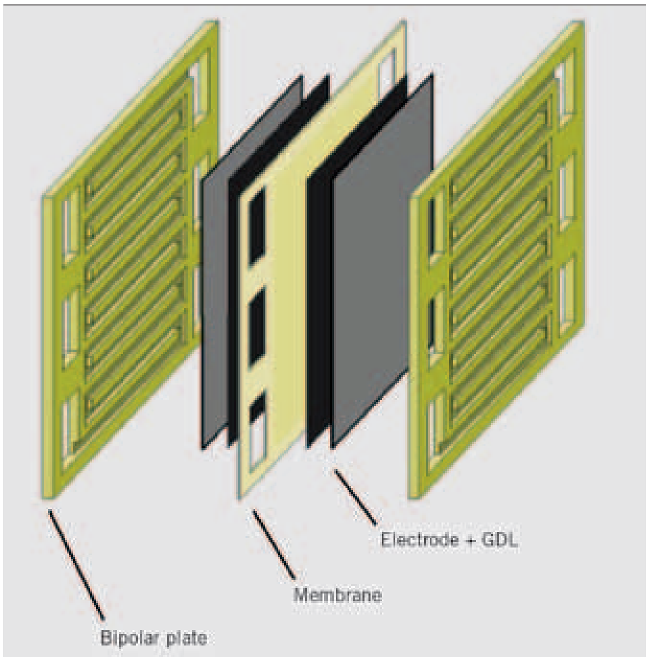

❷ Fuel cell components

overvoltages on the cathode and anode and specifically affects the lower current range. Membrane aging and aging processes on the bipolar plate bring about a changed cell resistance that shows in the middle range of the curve in particular. Here, the loss of proton-conducting membrane properties mainly leads to a more sloped curve. However, the depletion of the membrane thickness due to the chemical aging processes brings about a smaller resistance and a lower slope as a result. In addition, membrane aging is evident in a reduced open circuit voltage. The aging of the porous structure of the gas diffusing electrodes influences the shape of the polarization curve in the upper current range. Effects that complicate the diffusion processes lead to greater voltage losses in the case of high currents.

3 ANALYSIS METHODS

Different diagnostic methods are used in order to analyse the aging processes. Methods in which the properties are directly determined on the materials can be used usually only ex-situ. The components must be separated out from the fuel cells and analysed electrically, chemically or electrochemically. However, in the case of in-situ methods, the aging condition is derived indirectly from the behaviour of the fuel cell. They are used without having to disassemble the system.

3.1 MODEL-BASED AGING DIAGNOSIS

① shows the voltage characteristic of the fuel cell depending on the current. The voltage-current relationship is generally shown as a parametric model in which the parameters describe the material and structural properties of the different fuel cell components. If one parameter changes because of aging, this change affects the polarisation curve. Conversely, a change in the parameter set can be closed from the deformation of the voltage characteristic.

The actual development of the polarisation curve can be determined from the measurements. Normally, the course does not exactly follow the model setting since the observations generally have errors. In case of a parametric model with K parameters and a test series with N > K observations there is an over determined system of equations that is inconsistent due to measurement errors. The parameters can be estimated with mathematical standard methods.

Applying a parameter identification method the unknown parameters of a given model can be evaluated for a series of measuring data. The goal of this kind of mathematical optimisation problem is to adjust the model parameters (and the slope of the function with it) to the observations in the best possible manner. However, it is not possible to estimate any given number of parameters. In fact, attention must be paid to a clear identification of individual parameters. Following Beck et al. a parametric model is not fully identifiable if its sensitivity coefficients $S_{P_n} = \frac{\partial E}{\partial P_n}$ are linearly dependant [1]. In this case the concerning parameters P_n have to be replaced by parameter groups or constants.

3.2 MODEL APPROACH

The method for model-based aging diagnosis presented here is based on a simplified parametric model as per Eq.1.

EQ. 1

$$E = E_0(p, T) - \eta_{D+int} - \eta_R - \eta_K$$

Therein, the single overvoltages η develop as following:

EQ. 2

$$\eta_{D+int} = b_A \ln\left(\frac{i_{int+i}}{i_{0,A}}\right) + b_K \ln\left(\frac{i_{int+i}}{i_{0,K}}\right)$$

$$\eta_R = \left(r_E + \sum_n r_{K,n} + \frac{\partial}{\kappa}\right) i$$

$$\eta_K = m \exp\,(n\, i)$$

with the measurable state variables

: E: cell voltage
: p, T: pressure, temperature
: i: current density

and the structural and material parameters

: b_A, b_K: Tafel parameter on anode und cathode
: $i_{0,A}$, $i_{0,K}$: exchange current density on anode und cathode
: i_{int}: internal equivalent current density
: r_E, r_K: electrode resistance and contact resistance
: ∂: membrane thickness
: κ: membrane specific conductivity
: m, n: empirical Kim parameter.

Except for the Tafel parameter every parameter is subjected to aging processes and changes in the course of time.

The parameter set cannot be identified completely. The sensitivity analysis shows that it is not possible to clearly identify both, anode exchange current density and cathode exchange current density. Hence, the model approach is simplified by linking anodic and cathodic exchange current density by a constant factor $i_{0,A} = X_1 i_{0,K}$.

Furthermore, the single membrane resistances, thickness and conductivity cannot be clearly identified. Corrective measures is the simplified internal resistance $r_i = \left(r_E + \sum_n r_{K,n} + \frac{\partial}{\kappa}\right)$, which ac-

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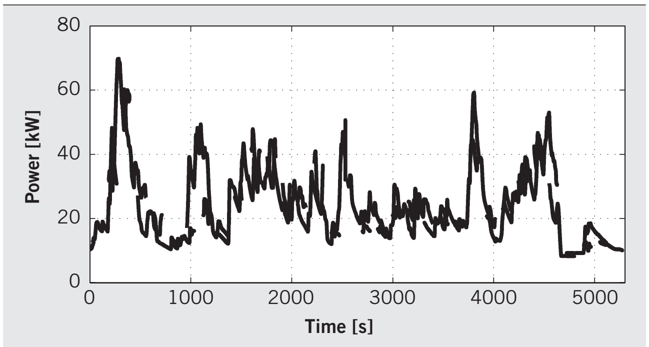
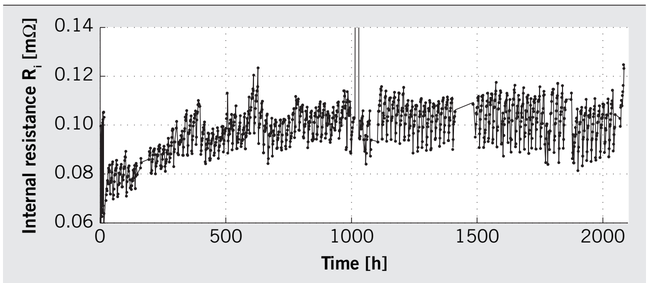
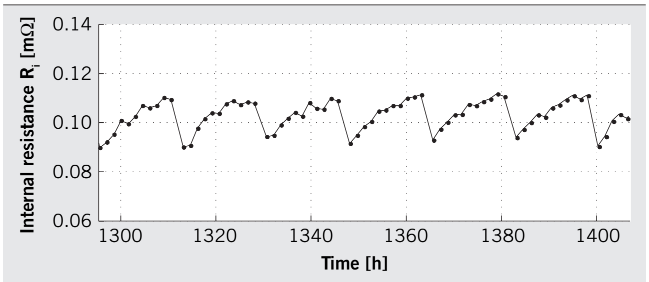


❸ Load cycle during the eight-month service life test



❹ Slope of the internal resistance



❺ Slope of the internal resistance (section)

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counts for both, contact and specific resistances on electrodes an membrane.

With the proposed simplifications the model approach is fully identifiable. Since each parameter describes the special properties of the components electrode ($i_{0,K}$), membrane (i_{int}, r_i) and gas difusion layer (*m, n*), the method allows a component-specific observation of the aging effects.

4 APPLICATION

Comprehensive tests series can be evaluated just on the basis of current, voltage, pressure and temperature signals and analysed with regard to aging with the analysis method. As the signals are usually not measured space-resolved but metered globally for single cells or whole fuel cell stacks the aging parameters can be determined only on cell and stack level, respectively.

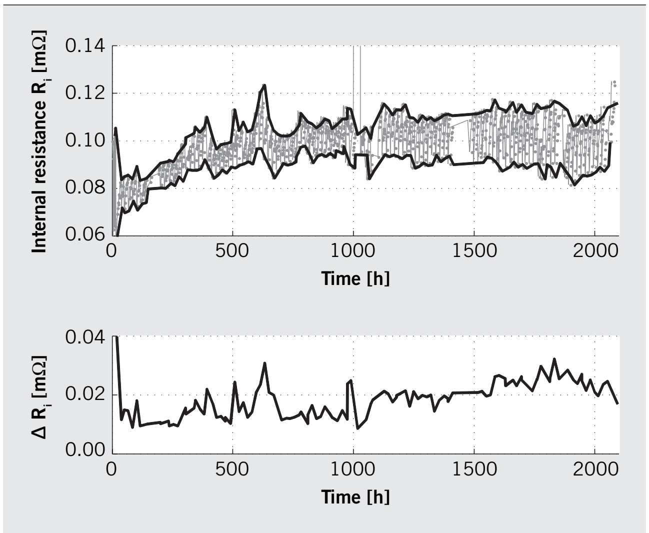
An 80-kW fuel cell system has been evaluated at the Fraunhofer Institute for Transportation and Infrastructure Systems IVI within the scope of the European Fuel Cells Project Felicitas, in cooperation with the Nucellsys GmbH. The eight-month service life test consisted of eleven 1.5-hour long load cycles every day, followed by a 7.5 hour break. With the load profile the performance requirements for a hybrid fuel cells bus have been recreated on bus line 42 in Stuttgart (Germany), ❸.

The corresponding aging parameter set is determined for each load cycle in a downstream post-mortem analysis. ❹ shows an example of the slope of the stack's internal resistance. Each point shown in the figure corresponds to a complete parameter identification of a 1.5-hour long cycle.

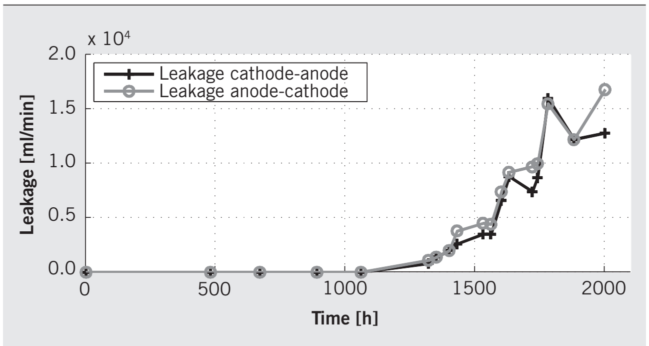
The interpretation of the results provides a deeper insight into the aging process of the fuel cells. Three significant aging processes should be described here as an example, a detailed discussion of the parameter's development can be found in [6].

- Membrane dehydration
  During the entire testing time period, a periodic oscillation of the parameter Ri has been observed. The oscillation period in the process is 17.5 hours and thus corresponds to the duration of a daily test procedure. As an example, ❺ shows the slope of the internal resistance, magnified in the 1300 to 1400 hours time interval.

The resistance value of the first of the eleven test cycles carried out daily is always the lowest. However it increases with every additional test. At first the increase is high, after that it will decrease continuously with progressive tests. At the end of a test day, the



❻ Cyclic slope of the internal resistance – envelope curve and amplitude



❼ Measured membrane leakage

value approaches a stationary value. The variations of the internal resistance are mainly attributed to the membrane resistance, which bears the largest part in the internal resistance [3]. Since the membrane resistance is directly dependent on the water content of the membrane, the membrane humidity can also be inferred from the slope of the resistance values. It declines sharply, the higher the resistance [4]. The resistance values increasing through the day show that the membrane has dried up over the course of the daily test sequences. Diffusion processes during the 7.5-hour long break ensure that the water content is normalised again before the start of the following day.

: Membrane contamination
The effect of cyclic membrane dehydration described above increases over time. The oscillation amplitude increases to double the original value, ❻, during the service life test. The observation is explained by the slow membrane enrichment with metallic cations. On one hand, it leads to a strengthening of the electro-osmotic effect and thus an increase in the water transport through the membrane on the cathode. On the other hand, it weakens the water diffusion coefficients and thus slows down the back diffusion of the water towards the anode direction caused by the concentration difference over the membrane [2]. Both effects lead to an accelerated dehydration of the membrane during operation.

: Chemical aging
In addition to influencing the water content, the absorption of contaminants also negatively influences the proton conductivity of the membrane. This effect leads to a long-term increase of the internal resistance. This increase has however been observed only up to 1000 hours in ④. From here on, the influence outweighs the chemical membrane aging that has a reverse effect: The membrane resistance decreases overall through the loss of membrane material. The overlaying effects lead to a stagnating slope of the averaged resistance values toward the end. Measurements of membrane leakages carried out in parallel confirm the assumption: As shown in ❼, the membrane thinning starts from 1000 hours onwards and with it, the gas transfer.

5 SUMMARY AND PROSPECTS

Service life and aging speed of fuel cells strongly depend on the respective load profile. The model-based analysis method presented here provides a complete insight into the aging processes and helps to understand complex aging processes and to evaluate their influence on the operating behaviour of the fuel cell.

REFERENCES

[1] Beck, J.; Arnold, K. J.: Parameter Estimation in Engineering and Science. John Wiley & Sons, 1977

[2] Okada, T.: Effect of ionic contaminants. In Vielstich, W.; Lamm, A.; Gasteiger, H. A. (editors): Handbook of Fuel Cells – Fundamentals Technology and Application, Volume 3: Fuel Cell Technology and Applications, Part 1, Chapter 48. John Wiley & Sons, 2003

[3] Stumper, J.; Stone, C.: Recent advances in fuel cell technology at Ballard. In: Journal of Power Sources, 176, pp. 468–476, 2008

[4] Büchi, F.; Scherer, G.G.: Investigation of the Transversal Water Profile in Nafion Membranes in Polymer Electrolyte Fuel Cells. In: Journal of The Electrochemical Society, 148, A183–A188, 2001

[5] McKinsey & Company: A portfolio of powertrains for Europe: a fact-based analysis. The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles. Accessed on http://www.iphe.net/ on 26.04.2011

[6] Jonas, K.: Online Aging Diagnosis and Load Dependent Service Live Prognosis of Polymer Electrolyte Fuel Cells. Dresden, Technical University, Dissertation, 2009

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