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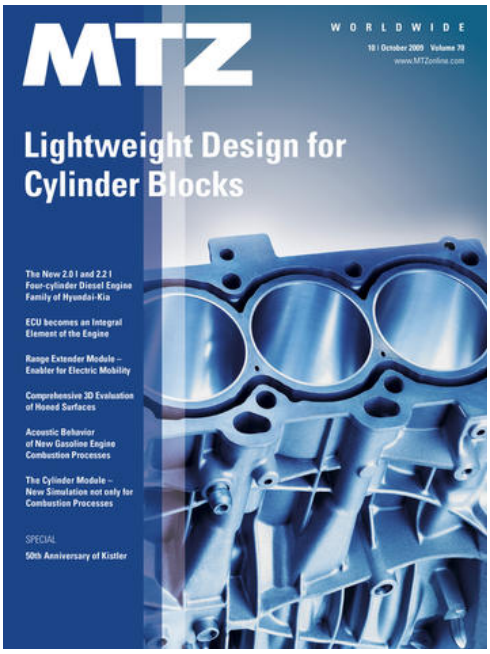

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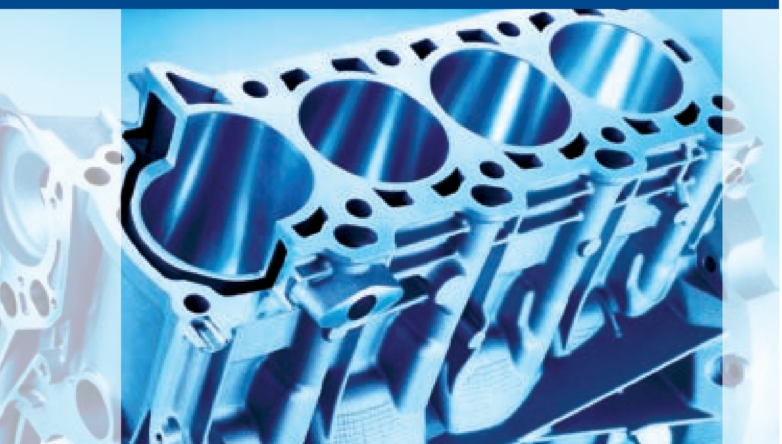

4
Innovative concepts for **Cylinder Blocks** are in the focus of KS Aluminium-Technologie. The "Modular High-Pressure Die Casting Concept" is the response to the challenges of downsizing. The gravity inversion die casting process comes up to the highest strength demands. PTWA technology is enhancing the cylinder bore surface competence.

COVER STORY

DEVELOPMENT

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Onwards and Upwards!

Dear Reader,

Among young engineers, the concept of efficiency, which was once a key topic for a close-knit community of thermodynamics experts, no longer seems to be „in“. This is surprising, because improving the efficiency of technical systems is one of the most important tasks facing the engineering sciences. Ernst Ulrich von Weizsäcker, a scientist and the nephew of the former president of Germany, maintains that energy-efficient technologies will provide the crucial stimulus for future economic growth. According to Weizsäcker, these technologies will replace IT and telecommunications as the driving force behind the growth of the world economy.

Hardly a day goes by without a prominent scientist somewhere announcing the start of a new project. For example, I discovered recently that Dr. J. Craig Venter, one of the scientists responsible for sequencing the human genome, has teamed up with Exxon Mobil on a 600 million dollar research programme to develop genetically modified algae for fuel production.

While it is not difficult to grow algae that produce fuel, the partners are aiming to solve the problem of the output being completely disproportionate to the area needed for production.

However, new methods of developing energy will not resolve the difficulty that energy supplies will become increasingly scarce and expensive in the long term. Every technology which aims to improve efficiency will also contribute to safeguarding the future of the human race.

These are good times for those of you who are engineers and scientists. The fate of our civilisation is in your hands! It is essential that you take a proactive approach, because you have one of the most exciting jobs in the world.

Johannes Winterhagen
Frankfurt am Main, 24 August 2009

Johannes Winterhagen
Editor-in-Chief

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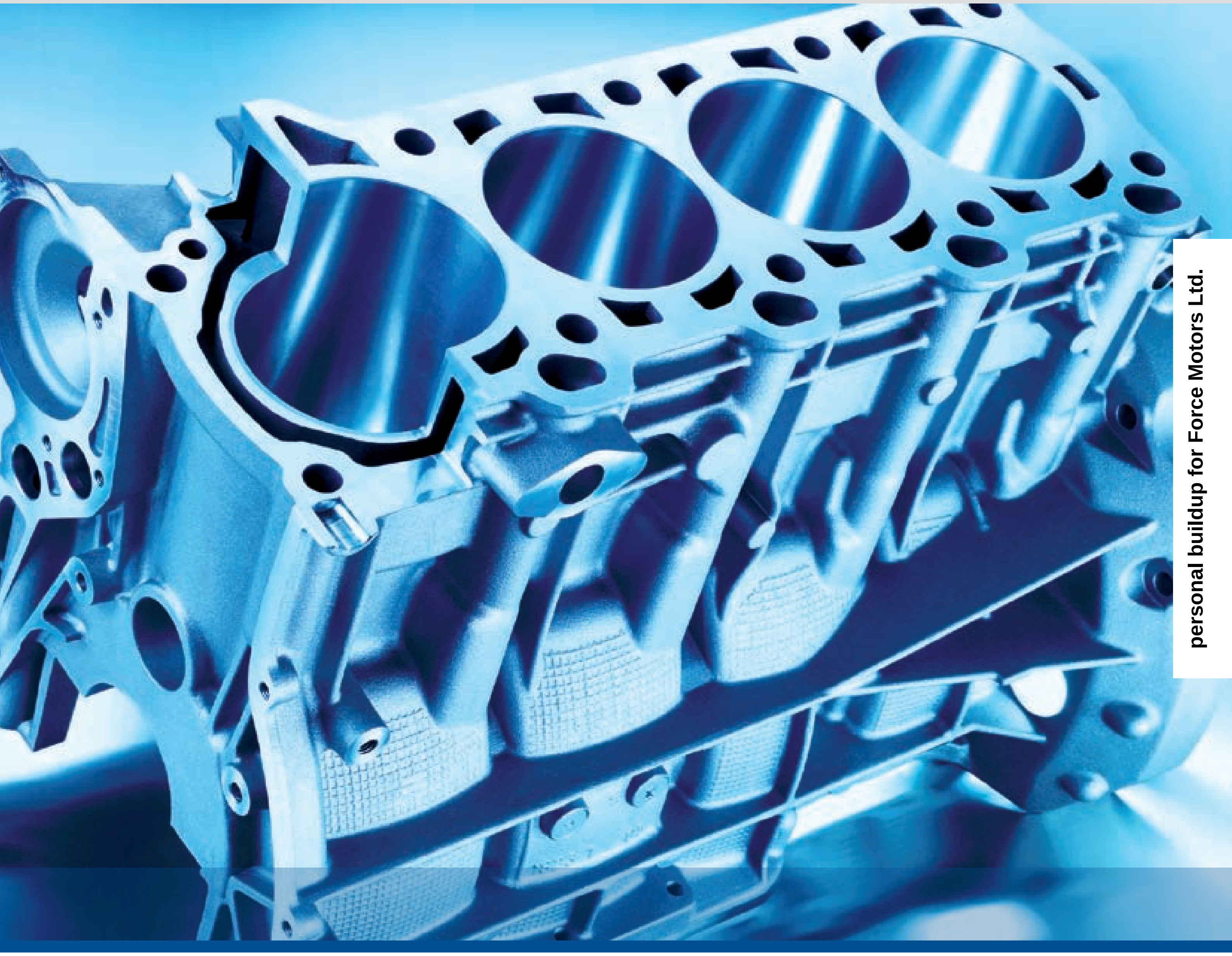
Cooperation with the STG, Schiffbautechnische Gesellschaft e.V., Hamburg, in the area of ship drives by combustion engines



Lightweight Design for Cylinder Blocks
in Response to Current and Future Requirements

KS Aluminium-Technologie has an annual output of one million aluminium cylinder blocks with a high percentage of blocks for diesel engines. Innovative concepts are in the focus. The "Modular High-Pressure Die Casting Concept" is the response to the challenges of downsizing. The gravity inversion die casting process comes up to the highest strength demands on diesel engines. PTWA (plasma transferred wire arc) technology is enhancing the cylinder bore surface competence.

1 Introduction

Lightweight design is based on three pillars which impose the need for tradeoffs:

- lightweight structure in compliance with load, material and fabrication method
- affordable material of minimum density
- cost-effective fabrication process.

In the light of high material concentration, meanwhile nearly half of the passenger-car engines produced in Europe is equipped with cylinder blocks made of aluminium, **Figure 1**. So far, the Al lightweight design has succeeded in keeping abreast with development progress for petrol engines and, what is more, for DI diesel engines.

2 Changed Engine Environment for Cylinder Blocks

Current as well as future fields of action [1] relate to

- fuel consumption for petrol engines
- nitrogen oxide emissions for diesel engines
- alternative (regenerative) fuels as an overriding issue.

From 2012 onwards, the EU is (gradually) limiting the CO_2 fleet emissions to 130 g/km. This calls for downsizing, i.e. the reduction of displacement and number of cylinders with a focus on petrol engines. Compensation in terms of performance output is achieved with the aid of direct injection by supercharging. Savings in fuel consumption result from load point shifting, efficiency boosting and lightweight construction.

The characteristic of the mechanical stress to which cylinder blocks are exposed is the ignition pressure and that of the thermal stress, the specific performance. The target conflict between lightweight design and mechanical-thermal load is heightening under the impact of the following current technical specifications:

- petrol engine:
  ≤ 150 bar, approx. 120 kW/l
- passenger-car DI diesel engine:
  ≥ 200 bar, approx. 90 kW/l.

The reduction of engine friction loss and cylinder wear as well as compact design for hybridisation/electrification of the drive train complement the catalogue of requirements. In this environment, it is comforting to learn that at least small range extenders will safeguard the existence of internal combustion engines in the longer term [2]. Developments are generating the need for building small, lightweight, rigid, high-strength cylinder blocks under extreme cost pressure, **Figure 2**.

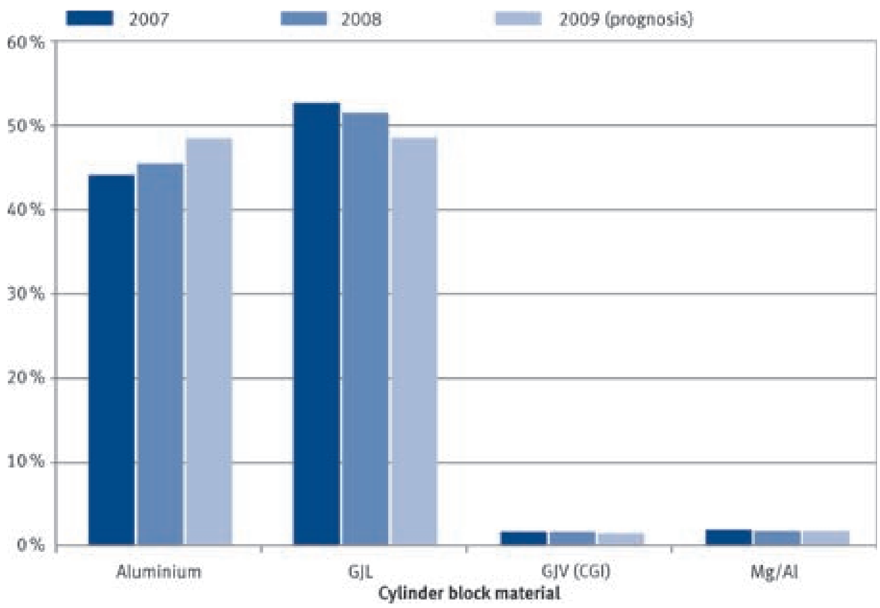


Figure 1: Market shares of passenger-car engines produced in Europe, according to cylinder block material

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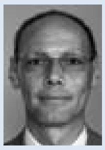

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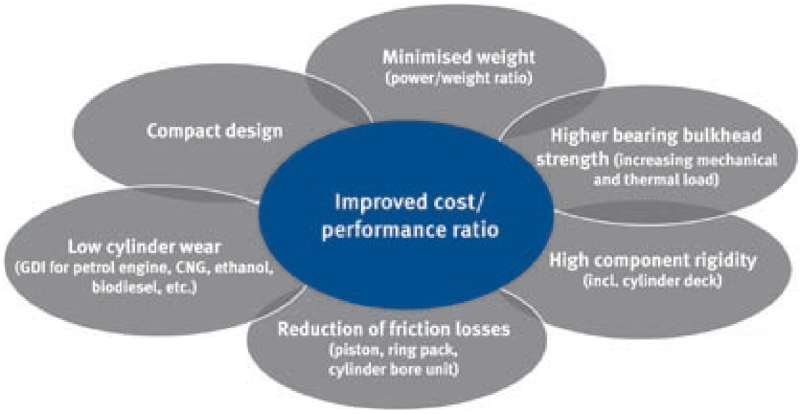


Figure 2: Challenges for cylinder block design development

3 Top Limit of Application of Al Cylinder Blocks in Retrospect

The last-mentioned point does not necessarily mean a contradiction for Al cylinder blocks although the rapid diesel ignition pressure rise has concretised prognoses with respect to the top limit of application. Initially this limit was seen to be 150 bar – disregarding composite casting solutions that are detrimental to lightweight design [3]. Growing experience then led to more favourable predictions [4]. Accordingly, optimised component design concepts can withstand ignition pressures of up to 200 bar, but above 160 bar only with a certain hybrid character. Reality is in the process of, at least, confirming the prognoses.

4 Current Lightweight Design Potentials for Cylinder Blocks

Under the present boundary conditions applicable to petrol engines, the replacement of cast iron (CI, GJL) by Al still offers a weight reduction potential of up to a good 40 %, and still of up to 35 % for diesel engines, in the most favourable case, also 40 %. Indications vary because absolute comparability is not always given. Neutral sources [4] quote up to 5 to 10 % for compacted graphite iron (CGI, GJV) compared to GJL, OEMs recognise 15 %. This means that also in the case of GJV despite higher material potential the minimisation of wall thickness is subject to casting-technique constraints.

5 Aspects of Selection of Materials

Material profiles [3, 4, 5, 6] and Cumulative Energy Demand (CED) are referred to by all parties with different lines of argumentation. Al boasts the following benefits:
- high heat transfer coefficient (thermal release)
- favourable specific Young's modulus (E/ρ)
- strengths in between GJL250 and GJV are realisable with some effort.

The cost-benefit aspect is decisive for the selection of a material. Weight savings have a virtual value, to be set off against higher production cost. When spreading the engine range, the engine weight is also a corrective factor for the axle weight rating. In a specific case, cylinder block lightweight construction is declared as the strategic target jointly with the whole diesel engine range [7, 8]. In most cases, both Al and GJL/GJV are deployed selectively. A minority takes a sceptical attitude towards Al cylinder blocks. **Figure 3** illustrates contrary viewpoints.

6 Further Development and Optimisation of Al Cylinder Blocks

6.1 Component Engineering

The wide variance of design options for Al cylinder blocks imposes the need for

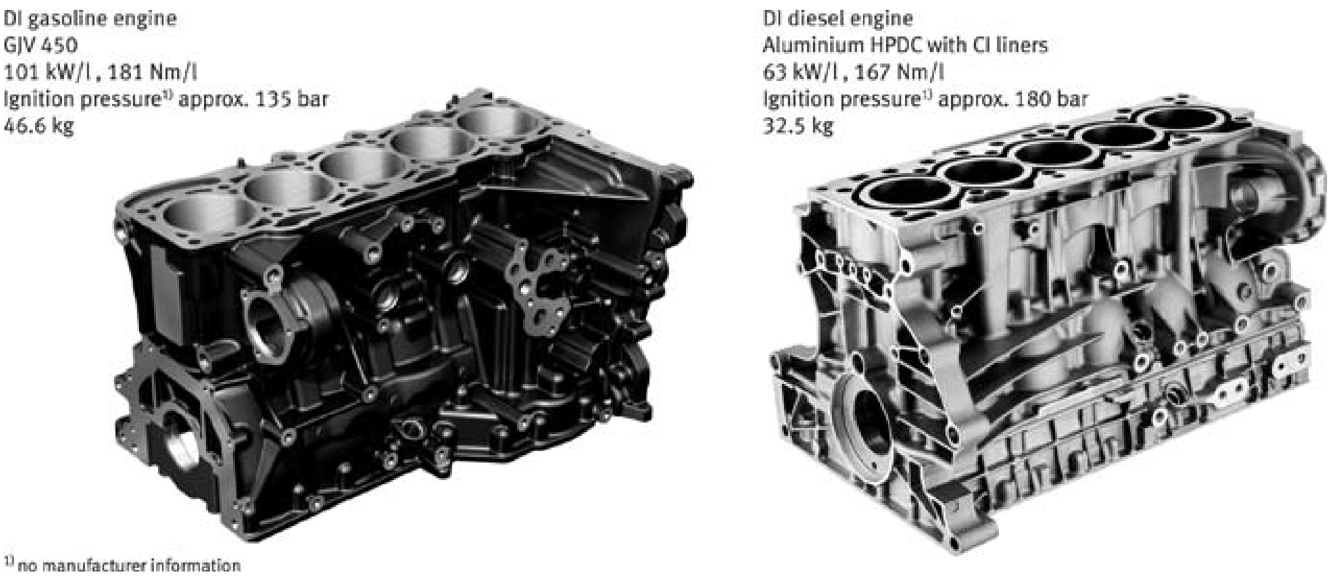


Figure 3: Concept comparison with the example of mass-produced five-cylinder inline engines

Figure 4: Water jacket sand cores with distribution and collector duct as well as cast cylinder land cooling

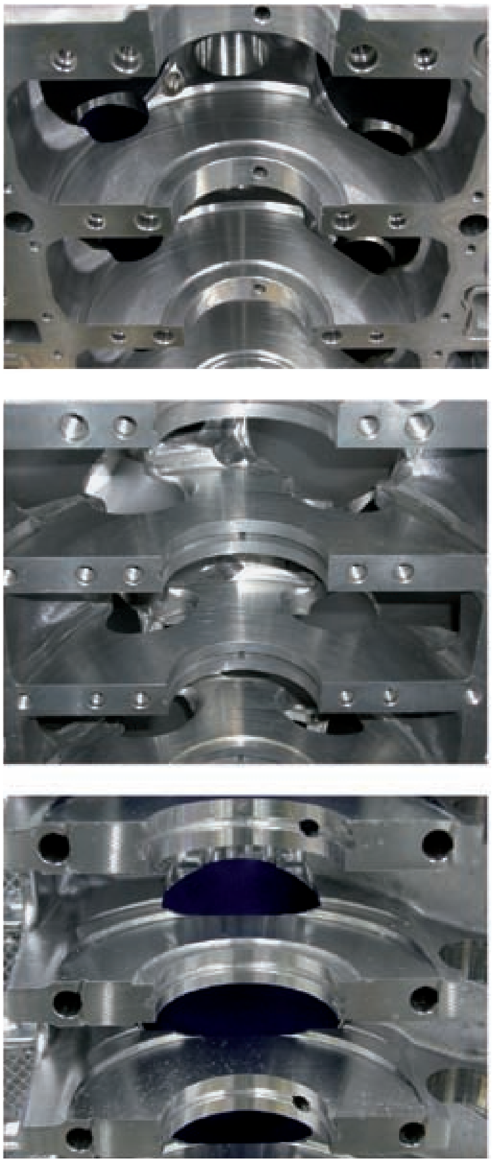


Figure 5: Pulsation pressure equalisation in the crankcase; drilled (above), sand-core cast (centre), milled (bottom)

taking account of suitable concepts whose four pillars are component design, casting method, alloy with heat treatment and cylinder bore surface technology [5]. The first-mentioned comprises basic prerequisites in terms of material- and casting-specific design, structural rigidity and acoustics as well as, in particular, shape stability.

In the following, only a few examples of ingenious problem solutions are quoted:

- tie design for VW R5 TDI [9]. Elegant circumvention of the thread strength problem
- embossed positive-fit transverse force absorption of main bearing cap in BMW diesel engines [8], lateral relief
- composite design for VW V10 TDI [10], bearing bulkheads with recesses on the casting side, bolted GJS crankshaft carrier (bearing bulkhead load through cylinder pair, weakening through cylinder bank and deflection of flow of forces render the realisation of the V cylinder arrangement in diesel engines difficult)
- Mg-Al composite cylinder blocks in BMW R6 petrol engines [11], a technological master piece but an expensive concept with a limited potential.

Current design trends relate to complex coolant routing for transversal passage through the cylinder head, for example, or cast cylinder land cooling systems, **Figure 4**. This requires an evermore elaborate sand core technology. Design freedom and "high integration" – a sand casting domain [12] – continue to be the subject of strict cost-benefit analysis. The targeted integration of additional sand cores solves functional problems also for die casting applications and prevents mass concentrations.

In a diesel engine, dimensioning of the cylinder land constitutes a special problem area for achieving a compact design in the case of cast-in and shrunk-on cylinder liners. The main bearing threads in the bulkhead are becoming a general neuralgic zone. In this area, shape stability is impaired by:

- decreasing main-bearing width
- limited thread turn depth and
- large bearing bulkhead openings (pulsation pressure compensation) near the thread, **Figure 5**.

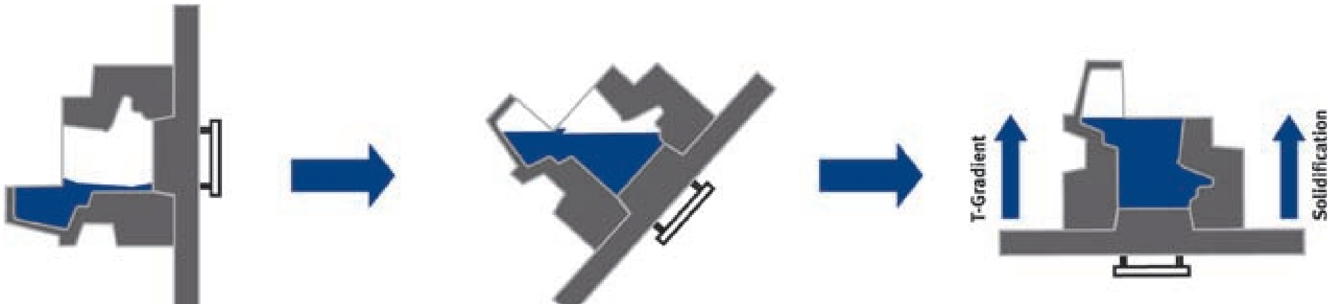


Figure 6: Principle of gravity inversion die casting process

6.2 Casting Methods

6.2.1 Gravity Die Casting

For Al cylinder block mass production, high-pressure die casting is competing with gravity die casting/core package process (CPS with local chill mould), and with low-pressure die casting in the premium sector. What is new in this context is gravity inversion die casting with especially low-turbulence mould fill at layerwise rising level during inversion and rapid, controlled solidification of the bearing bulkheads, **Figure 6**. The sprue on the cylinder head side is used as a feeder area. A fine bearing bulkhead casting structure (DAS values around 25 µm) imparts extremely high tensile strength (lattice parameter AlSi7Mg / T6: R_m = 300 to 330 MPa). The casting concept tailored to the inline design caters to diesel engines.

6.2.2 "Modular High-pressure Die Casting Concept"

The innovative "Modular high-pressure die casting concept" has been developed for small high-performing engines to enhance downsizing [13, 14]. Independent technologies applicable for high-pressure die casting render the concept flexible and economic, **Figure 7**.

- Favourable production costs:
  Small cylinder blocks are subject to increased cost pressure. High-pressure die casting mass production offers cost benefits. The concept modules compensate the principle-inherent disadvantages of conventional high-pressure die cast cylinder blocks. The objective is to attain the features and properties of high-grade low-pressure die cast cylinder blocks.
- Low weight:
  With near net shape and low wall thickness (3.5 mm), high-pressure die castings allow lightweight construction. Slimming down to 15 % (without cast-in parts) compared to low-pressure die casting is realisable. Although high-pressure die casting appreciably constrains the freedom of design, it comes very close to sand casting in lightweight construction.
- High component strength:
  In high-pressure die castings, porosity and feeding problems typically depress the strength level in the thick-walled bearing bulkhead area. Gas inclusions under high pressure which are inherent in the casting principle preclude a strength-enhancing T6/T7 heat treatment (blistering during solution heat treatment, therefore usually used in ascast condition F). Process optimisation – essentially an evacuated high-pressure casting die – is opening the access to unrestricted heat treatment as well as the use of artificial ageing alloys. By suppressing porosity, static and dynamic bearing bulkhead strengths are boosted, **Figure 8**.
- Closed-deck design:
  When applying the high-pressure die casting method, the geometry attainable in steel imposes constraints on component rigidity of the cylinder area in open-deck design. Warmbox water-jacketed sand cores with special double coating finish allow realising the closed-deck design, e.g. for high-performance options. This technology is also appropriate for the balance-shaft housing of 4-cylinder inline cylinder blocks.
- LOKASIL or sprayed coatings:
  High-silicon LOKASIL cylinder bore surfaces [15] can be beneficially integrated into the concept: compact design, low long-term cylinder distor-

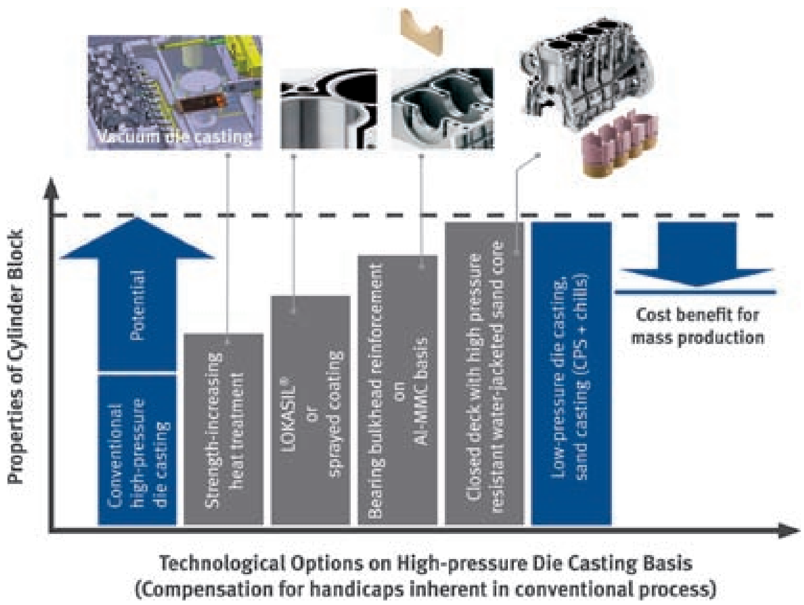


Figure 7: Concept modules of "Modular high-pressure die casting concept"

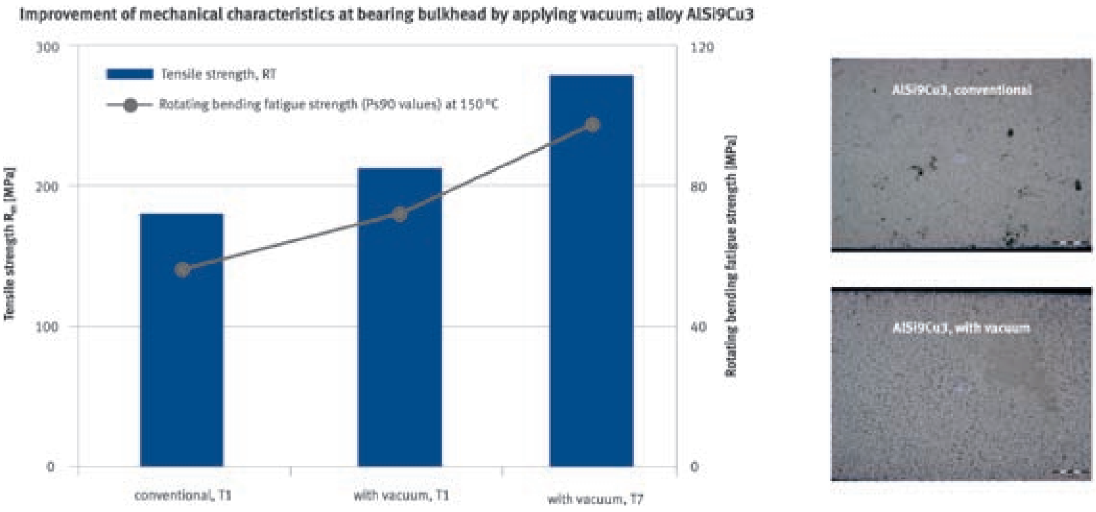


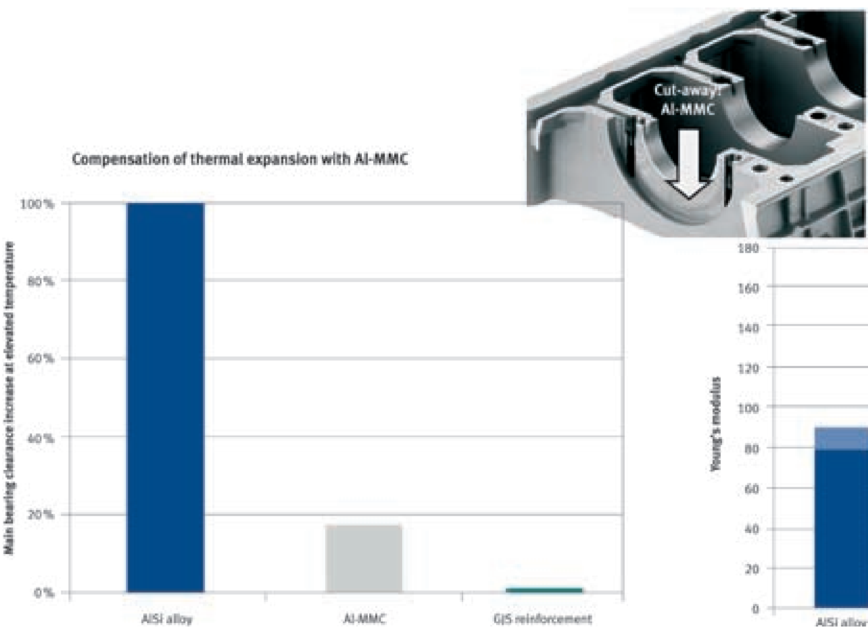
Figure 8: Reduction of porosity by vacuum application in high-pressure die casting; improvement of casting quality and increase in tensile strength R_m and tension/compression fatigue strength σ_{zdw} of high-pressure die cast bearing bulk-heads with vacuum application

tion rate, high thermal stress relief, low weight and now also competitive costs. It works without saying that grey-cast liners and, in view of their low porosity, cylinder bore surface coatings, are further options.

- Metal-matrix composite bearing bulkhead reinforcement:
  Similar to LOKASIL, the Al-MMC bearing bulkhead reinforcement is based on pressure-infiltrated preforms composed of ceramic particles/fibres. Lightweight substitution for heavy cast-in GJS parts for the bedplate is combined with compensation for increased play due to thermal expansion at operating temperature (oil pump losses, noise excitation) and increase in Young's modulus, **Figure 9**. A gapless composite structure will prevent leaks of the main-bearing lube oil supply. The weight benefit ranges from about 1.5 kg (4-cylinder inline engine block) to 4 to 5 kg (12-cylinder V-engine block).

6.3 Al Alloy Castings

Al casting alloys distinguish between the AlSiCu and the AlSiMg family [5], where the latter only used in artificially aged condition, **Figure 10**. Cylinder blocks of AlSiCu are often only heat-stabilised (T5). High strength requires a fine, low-pore structure, favoured by the casting process, as well as a strength-increasing heat treatment. What is new is a low-cost alternative heat treatment option which can be applied both locally and integrally (T5mod), **Figure 11**. In the abbreviated process, solution heat treatment (T6/T7) is avoided by quenching the casting directly in the casting cell after hot forming by means of a high-pressure water-air mixture, followed by artificial ageing. The highest strength values are obtained by means of combined solution heat treatment with hot isostatic pressing (HIP) [16].



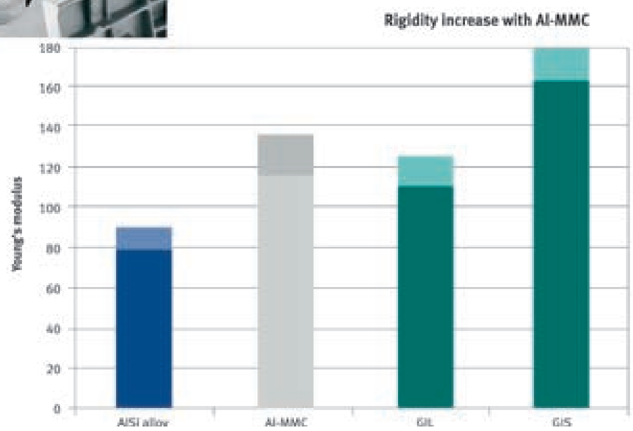


Figure 9: Main bearing thermal expansion clearance compensation and increase in Young's modulus on Al-MMC basis

Alloy Family	Benefits	Handicaps
AlSiCu	· Cold-hardening (T1), fully stabilisable (mostly T5), age-hardening viable (T7/artificial ageing) · Excellent long-term stability at elevated temperature (strength, hardness) · Cost (secondary alloys)	· Low ductility (breaking elongation) · Moderate heat conduction · Corrosion (depending on application)
AlSiMg	· High ductility (breaking elongation) · Excellent heat conduction · Low sensitivity to corrosion	· Hardens only at elevated temperature (T6) (extra cost), not fully stabilisable · Limited long-term stability at elevated temperature (strength, hardness) · Cost (primary alloys)
AlSiMg(Cu)	· Better long-term stability (good tradeoff)	· Comparatively low ductility loss

Figure 10: Pros and cons of alloy family AlSiCu and AlSiMg

Bearing bulkhead failures in petrol engines, in contrast to the permanently tolerable 180 bar ignition pressure in diesel engines, sometimes relativise strength demands, specifically when the quality of low-pressure die castings competes with high-pressure die castings. A key to success is the great thread depth of the main-bearing bolts. Starting points for incipient cracks are the last bolt thread turn and the notch of the thread run-out. In the case of Al, the creep behaviour will shift the load on the individual thread turns to this point. A sufficient number of thread turns will stop this process. Of corresponding relevance is the thread quality. Pre-cut and subsequently formed threads will increase the fatigue strength by about 30 %.

6.4 Cylinder Bore Surface Technology

There are diverse cylinder bore surface technologies to compensate for the tribological shortcomings of conventional Al casting alloys, [5, 9, 10, 15, 17, 18, 19]. Elevated cylinder wear hazards result from direct gasoline injection and from corrosion caused by alternative (natural gas) and/or regenerative fuels (ethanol and biodiesel admixtures). Cylinder bore surfaces on AlSi basis are to be rated as being more sensitive [20].

Monolithic V-arranged cylinder blocks of large gasoline engines with non-reinforced cylinder bores are frequently

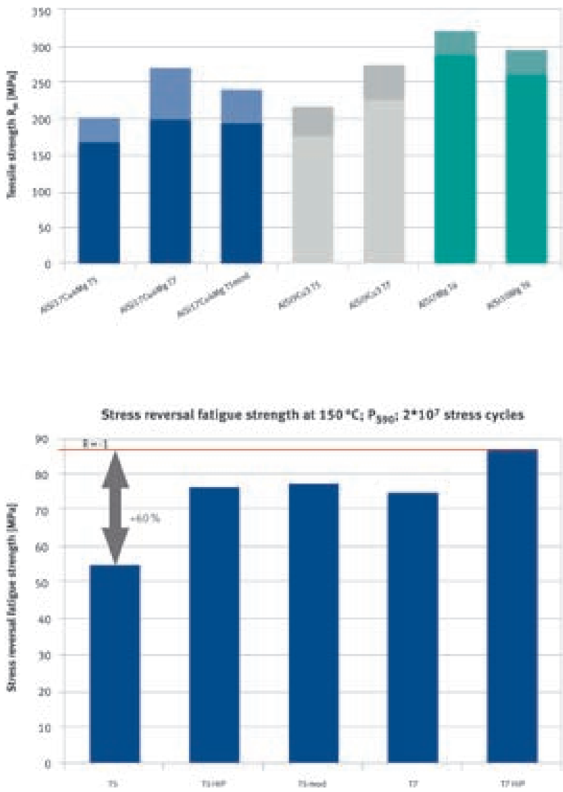


Figure 11: Tensile strengths R_m achieved with different heat treatment modes including HIP; high-pressure spraying system for casting quenching

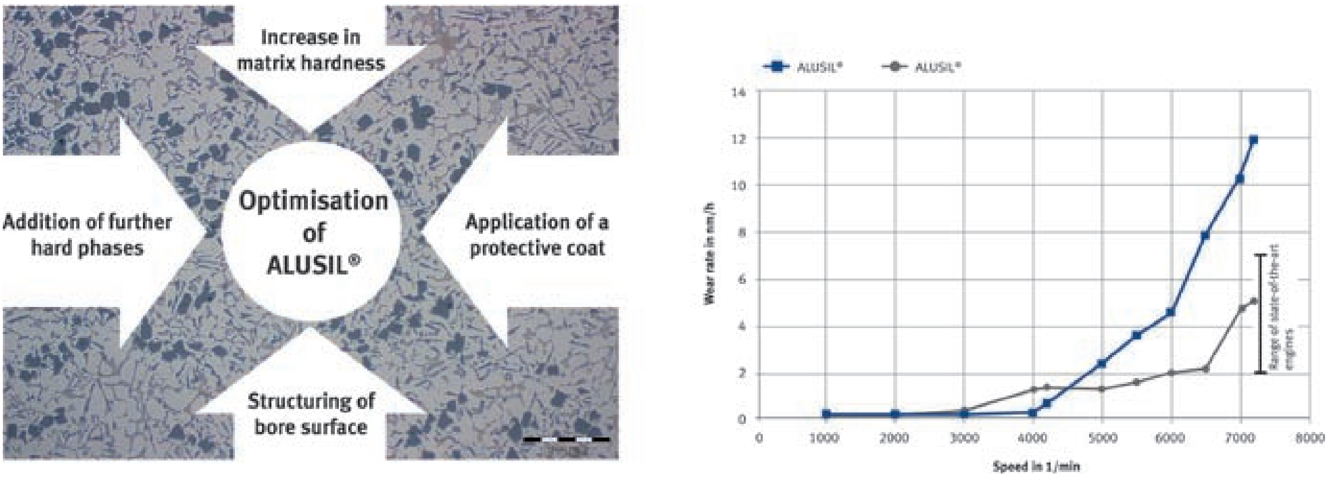


Figure 12: Strategies for the further development of ALUSIL; significant reduction of RNT wearing rate in the high-rev range

based on the tried and tested ALUSIL technology (hypereutectic alloy AlSi-17Cu4Mg [17]). Flaring-up wear phenomena have prompted the development of suitable alloys to ensure a sustainable improvement in wear resistance. With simultaneous distinct hardness enhancement on T7 basis, the following strategies were pursued: a) conventional optimisation (raising the Si and Cu contents); b) additional inter-metallic hardness phases; c) mixed crystal hardening by adding suitable elements. The latter approach – ALUSIL3+ – meant the breakthrough. The progressive wear rate observed in a demonstrative engine by means of a radionuclide wear test (RNT) at extremely high rev numbers/full-load operation was significantly reduced, **Figure 12**. A higher oil retention volume which mitigates wear in the case of unfavourable lubricating conditions requires a modified honing process. The respective tests are underway.

The core competency in cylinder bore surface technology is strengthened further by the PTWA technology [21]. By means of thermal spraying methods, thin surface coats are applied to the cylinder bore with cylinder blocks of quasi monolithic characteristics. Additional potentials are thus generated with respect to friction loss and wear reduction as well as fuel compatibility. Coating materials in the form of wire exhibit advantages over powder. Moreover, PTWA only requires one wire (against a fixed electrode). A rough surface is decisive for safeguarding the adherence of the coat. A dovetail profile, developed by Institut für Werkzeugmaschinen und Fertigungstechnik, Technical University of Braunschweig, **Figure 13**, introduced by means of a purpose-designed cutting plate, will improve coat adhesion compared to blasting methods. Despite close tolerances, the coating can be applied to the premachined blank part. This means that the coating work can be outsourced to a contractor.

7 Summary and Outlook

The Al cylinder block also defies competition with GJV material for diesel engines. Always provided that all-round optimised concepts are available, the currently demanded ignition pressure of 200 bar need not mean a “ceiling” which

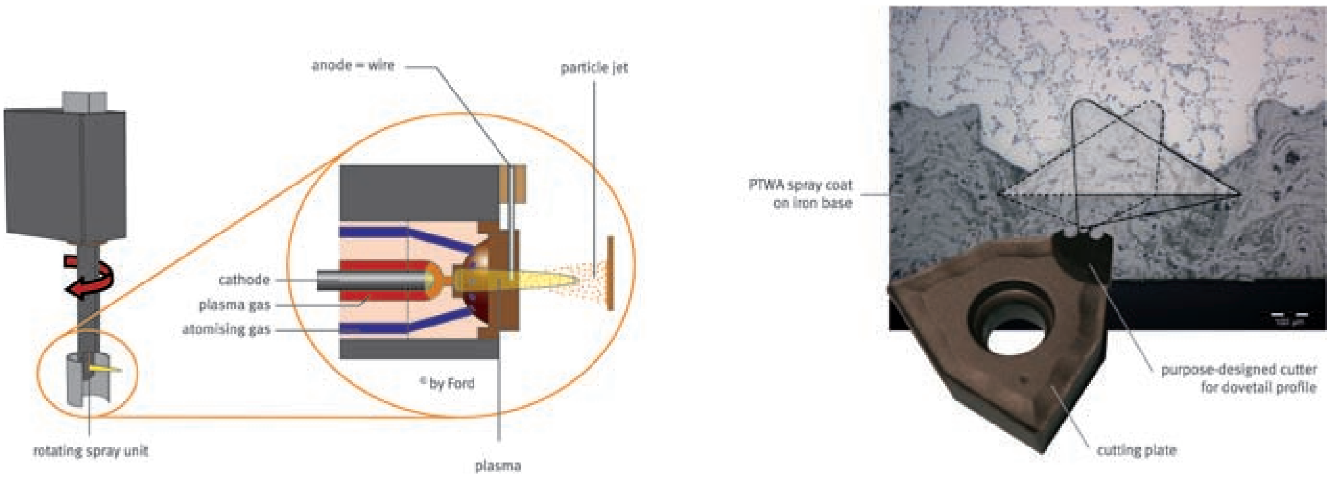


Figure 13: Principle of PTWA cylinder bore surface coating; improved coat adherence through dovetail profile

cannot be surpassed. Downsizing calls for small, cost-effective, but high-strength cylinder blocks. This is just the application where heat-treatable high-pressure die castings offer interesting potential. Thermally applied cylinder coatings allow a wider range of application in mass production and are thus available for meeting extended tribological requirements.

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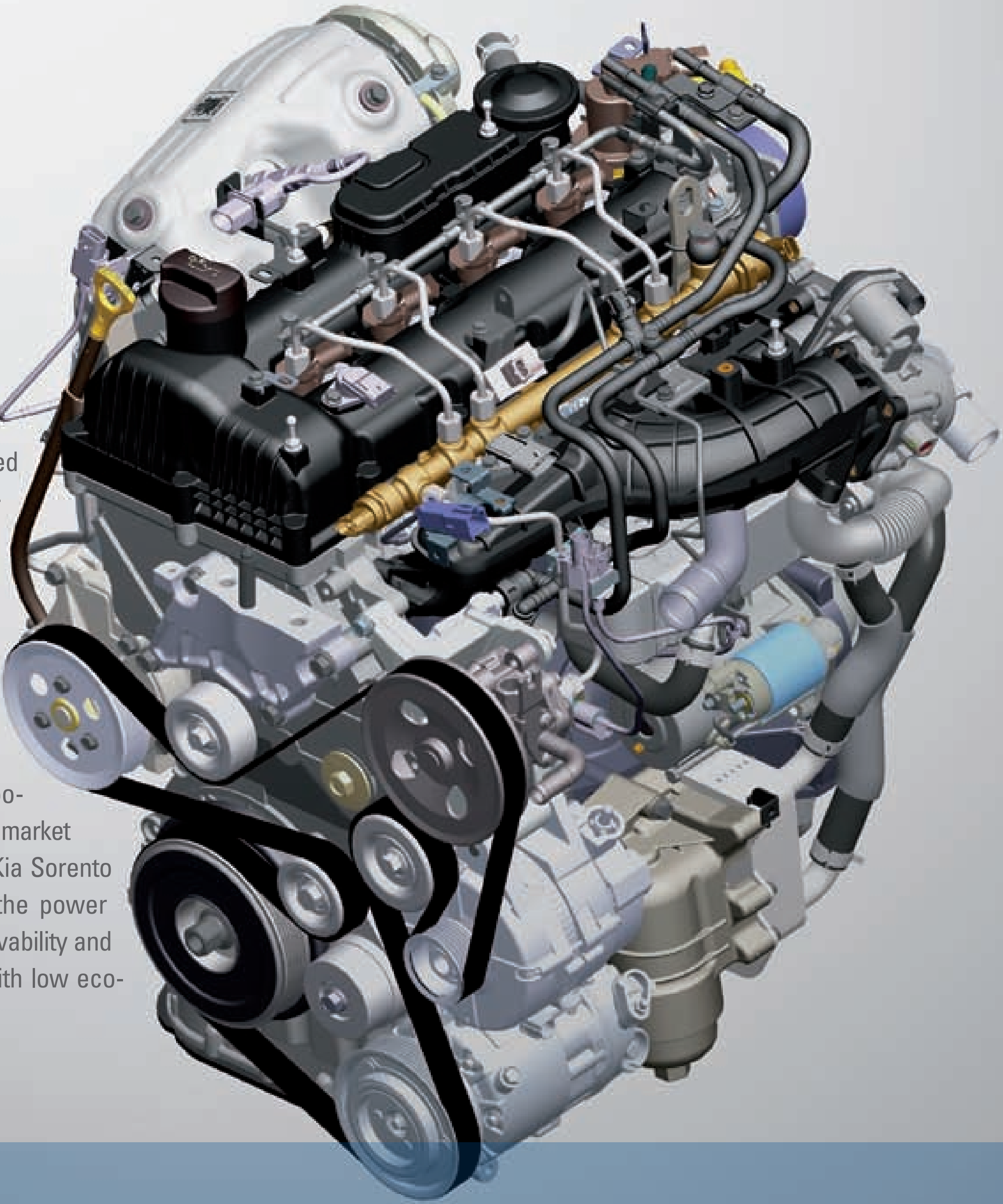
The New 2.0 l and 2.2 l Four-cylinder Diesel Engine Family of Hyundai-Kia



With the newly developed 2.2 l diesel engine Hyundai-Kia introduces the first model of the R-family to fulfil the Euro 5 emission legislation. The power unit marks with its specific performance of 66 kW/l and 200 Nm/l, the top range of single turbocharged engines. With the market introduction in the new Kia Sorento and Hyundai Santa Fe the power pack enables sportive drivability and high acoustic comfort with low economic fuel consumption.

1 Introduction

Emission substances generated from a compression ignition engine, mainly Particulate Matter (PM), nitric oxide and nitrogen dioxide (NO_x), cause serious environmental problems. As environmental awareness is growing considerably, CO_2 emission has also emerged as a social and engineering priority. As the CO_2 levels became an important factor in rating the value of vehicles, a worldwide competition has been triggered to reduce the CO_2 and fuel consumption.

Alternative powertrains, such as hydrogen-fuelled, fuel cell electric and hybrid electric engines have recently been highlighted among the possible countermeasures for compliance with stricter emission regulations and reduced fuel consumption. However, the demand from the market for higher performance of the engine and vehicle is still continuing, thus performances of alternative powertrains are far from satisfying customer's expectation. From engine performance and fuel economy points of view, a diesel engine is still attractive but numerous technical hurdles must be cleared to achieve higher performance with lower fuel consumption, better acoustic comfort and compliance with stringent emission standards. Hyundai-Kia's new R-engine family is expected to offer a promising response to the demands of the marketplace.

2 Development Guideline

With the upcoming Euro 5 legislation the new R-family will replace stepwise three existing engine families (D-2.0 l to 2.2 l, A-2.5, J-2.9) for passenger car applications and will handle a wide fleet from midsize vehicles up to the SUV-segment. Coming from this aim the following development targets have been derived:

- reduced fuel consumption by dropped engine friction
- enhanced and competitive performance by 27 % from 114 kW to 145 kW, and torque from 343 Nm to 436 Nm
- Euro 5 emission classification at all vehicle derivates without $DeNO_x$ system
- high engine stiffness for very good NVH

Table 1: Engine specification of the R-2.2 l in comparison to its predecessor

Engine		R22 (new)	D22 (current)
Type		R4	
Valvetrain		DOHC 4V	SOHC 4V
Displacement	ccm	2199	2188
Bore pitch	mm	94	96
Bore	mm	85.4	87
Stroke	mm	96	92
Stroke/Bore ratio		1.12	1.06
Conrod lenght	mm	145	145.8
Compression ratio		16	17.3
Peak pressure	bar	180	160
Power	kW	145	114
at speed	rpm	3800	4000
Torque	Nm	436	343
at speed	rpm	1800 – 2500	1800 – 2500
Injection system		Bosch CR Gen. 3	Bosch CR Gen. 2
Injection pressure	bar	1800	1600
Emission level		Euro 5	Euro 4

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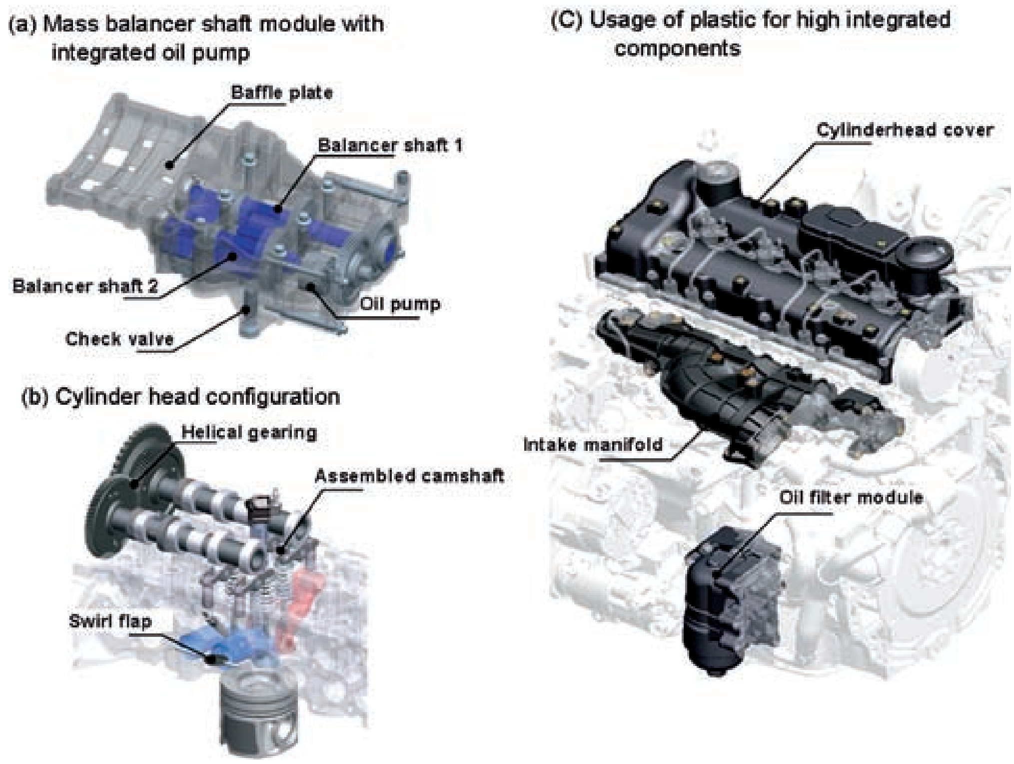


Figure 1: left top: mass balance shaft module; left bottom: cylinder head; right: plastic parts

- extended service interval at all applications
- compact package close – coupled Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF)
- maintenance-free DPF.

3 Base Engine Concept

The new 2.2 l engine was designed with the aim of achieving the highest performance with low fuel consumption over the entire operating range. Acoustic comfort and potential for compliance with future exhaust emission limits were also considered. The first variant of new R-engine family is the 2.2 l version which is compared to its predecessor in **Table 1**. The R-engine family has a "closed-deck" crankcase (grey cast) in common, which has a "deep skirt" design to improve stiffness. To fulfil the highest NVH demands, a stiff "upper oil pan" solution was used. For the 2.2 l variant a mass balancer shaft unit which reduced the free mass forces by more than 80 % was used. The oil pump is integrated in the same housing, **Figure 1** left top.

The piston group consists of cracked con-rods and oil-cooled pistons with optimised bowls. All moving parts have been optimised regarding friction. The dimensioning of bearings and their lashes as well as piston ring pre-load considers the demands regarding peak pressure and oil consumption. The aluminium cylinder head embed the two assembled camshafts, which are coupled with an acoustically optimised helical gearing. The valves are actuated via friction-reduced roller finger followers with hydraulic lash adjusters, Figure 1 left bottom.

Timing drive was built by a maintenance-free two-step chain drive. The primary drive – activating the high pressure pump – as well as the secondary drive, is equipped with a 3/8'' bush chain. The layout was made with the help of Finite Element Method and Multi Body Simulation activities, and comprehensive functional tests routed to optimised tensioners in terms of spring pre-load and leakage gap. Reduced chain force helps to achieve friction reduction. Despite of the challenging performance data, which claim engine mechanic, the complete engine friction was reduced by about 20 % in comparison to the D-engine. The typical excitation with timing drive order was effectively damped by an excellent chain cover design. Even for the engine periphery parts, the criteria function, weight, and cost have always been in focus. This leads to a substitution of classic components by recyclable material, Figure 1 right. An additional aspect is the benefit to build subsystems with a high degree of integration. For material recycling and weight reduction, conventional materials of a cylinder head cover, the intake manifold with an electrically controlled swirl flap, and oil filter housing were replaced with plastic ones. Modern plastics allow the application even under severe boundary conditions. Comprehensive endurance tests on benches as well as in vehicle showed the lifetime durability of all components.

4 Combustion Concept

To cope with Euro 5 emission limits and reach high specific power simultaneously, the combustion concept of the new R-2.2 l engine was refined with the newest technology.

4.1 Combustion Chamber

A lower compression ratio of a combustion chamber and higher pressure fuel injection system are required to achieve high power density with minimised increase of in-cylinder pressure and compliance with stringent emission requirements. For these prerequisites, the diameter of the combustion bowl had to be widened but its depth was shallower, **Figure 2** left top.

A compression ratio of 16:0 of the combustion chamber was employed to obtain better NO_x emission potential and higher power density, but carbon monoxide (CO)/tetrahydrocannabinol (THC) emissions during the warm-up phase and cold startability at the extremely low temperature conditions had to be also considered. Application of a ceramic glow system that quickly transfers high energy into the combustion chamber was helpful for improving both cold startability and idle stability right after the engine start. The fine tuning between combustion chamber and intake swirl was done by various computational simulations and fundamental experiments to maximise air utilisation and to promote fuel-air mixing, Figure 2 right top, middle and bottom:

- air induction process into the combustion chamber through an intake manifold
- in-cylinder air motion
- interaction of in-cylinder air with the injected fuel
- discharging process.

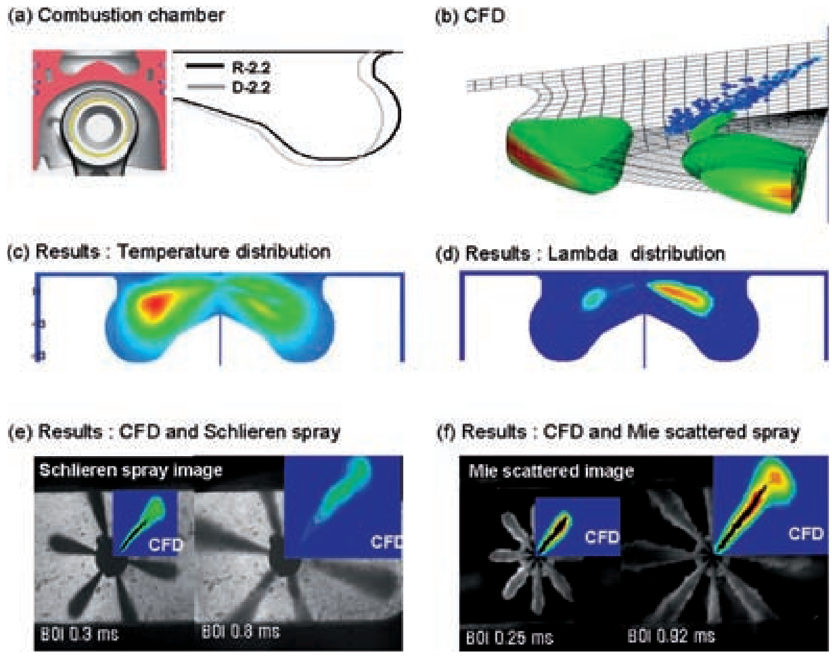


Figure 2: left top: combustion chamber; right top, middle, bottom: 3-D combustion simulation

4.2 Intake Port Concept

The development target for the new cylinder head concept was correlated on high demand on specific performance which requires excellent gas aspiration. Extensive gas exchange simulation required changing concept towards flow optimised ports realised by a parallel orientation of tangential and filling port. To keep high integral intake swirl level, the valve seats are equipped with optimised design of seat chamfering, which offered high air motion especially at low valve lift position, **Figure 3**. For fully variable handling of swirl in the whole engine emission range, an electrical actuated flap is controlled via an electronic control unit, Figure 1 left bottom.

4.3 Fuel Injection System

The third generation piezoelectric common rail system was adopted for significant benefits of reduced emissions and enhanced engine power. Higher injection pressure of 1800 bar led to shorter injection durations, thereafter enhancing engine power at the rated speed. The injector with an eight-hole nozzle and a spray hole diameter of 134 μm allowed low raw emission and secured high coking robustness for a wide range of fuel quality by adopting a short hole length of 0.73 mm. It also provided precise control of small

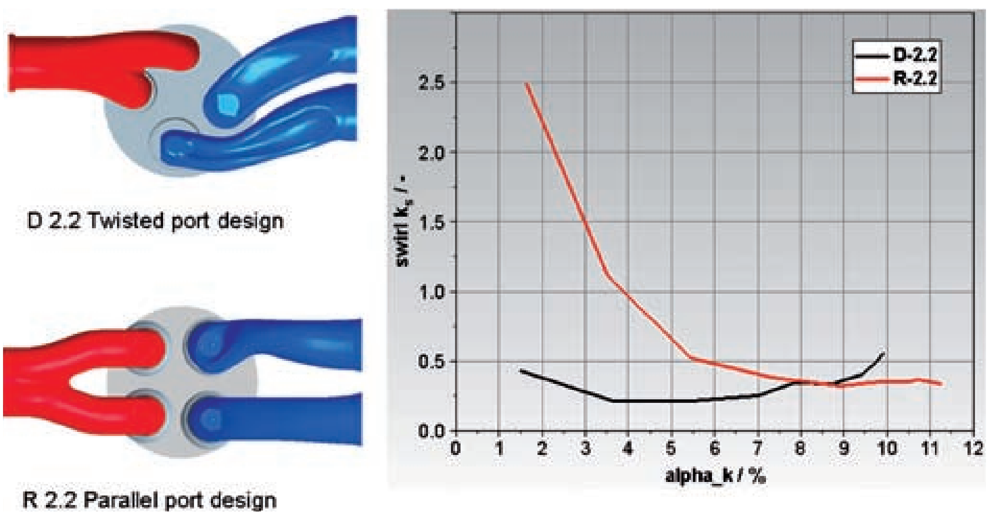


Figure 3: left: port concept; right: flow coefficient

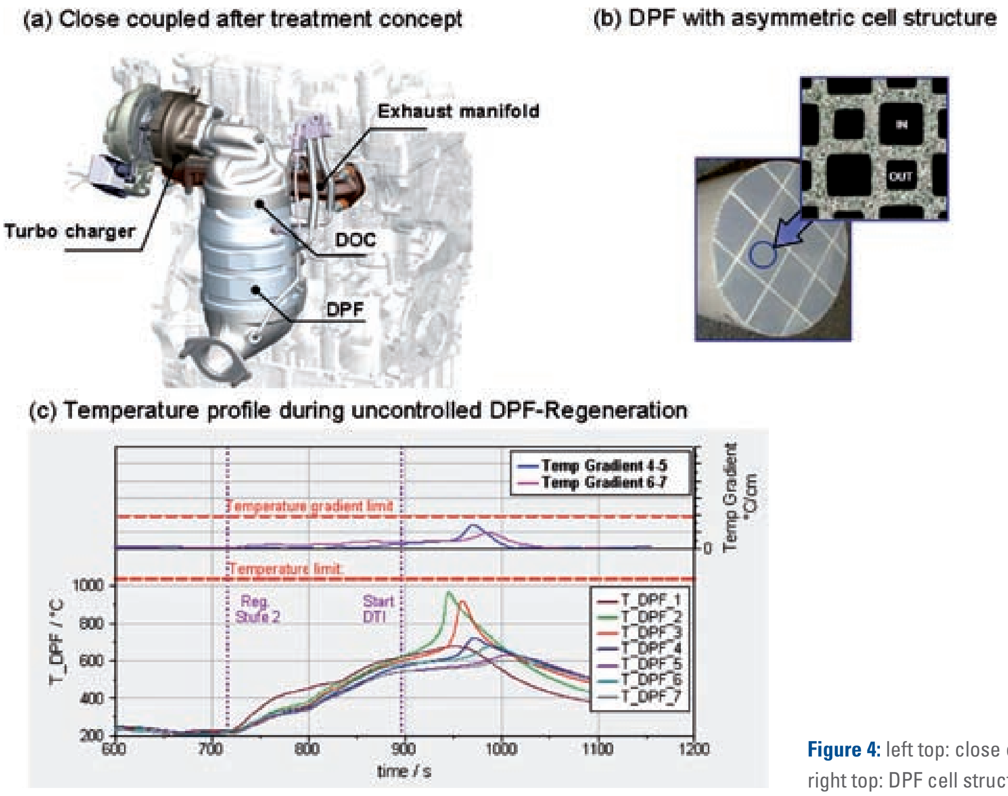


Figure 4: left top: close coupled DPF aftertreatment system; right top: DPF cell structure; bottom: temperature profile

quantity of fuel delivery and a shorter interval between different injection events compared to the conventional solenoid fuel injection systems. The best combination of the single and double pilot injections with elaborated calibration of other parameters enabled optimal compromise between smoke, fuel economy and acoustics within a system reliability limit.

4.4 Air Management System

To meet the strengthened regulation, especially NO_x-emission, even at high transient conditions the new R-family adopted a model-based open loop Exhaust Gas Recirculation (EGR) control method which enabled the actual EGR mass to precisely follow the desired mass converted from effective area of the EGR and air control valves. The novel air model required massive information reflecting physical behaviours of the air breathing system as well as the exhaust system, and detailed physical information for each key position of the system were mapped. A high performance EGR cooler with optimised pressure loss across the cooler (with a switchable cooler by-pass valve) was adopted. During engine warm-up, increasing temperature of the inlet and outlet of the combustion chamber was required to reduce the level of CO/THC emissions. One of the methods to avoid cooling down of the exhaust gas temperature was to bypass the EGR gas during the warm-up phase. To do so, the EGR gas travelled from the exhaust manifold passing was directly guided into the intake manifold by using the EGR cooler by-pass valve, thereby lowering CO/THC emissions. A further benefit of this modular multi layer EGR cooler might be easily realised by modifying the number of the layers without changing package and piping depending upon the level of emission tightness.

An electrically controlled variable geometry turbocharger provided faster response, more accurate control of desired boost pressures and minimised hysteresis characteristics. The centre housing of the turbocharger system was water cooled to prevent engine oil and its bearing from exposure to high temperatures.

5 Aftertreatment System

The close-coupled aftertreatment system integrated with a DOC and a DPF, **Figure 4** left top, assured faster heat up of the DOC thereafter minimising CO and THC emissions. The close-coupled layout was beneficial for the regeneration of PM accumulated inside the DPF because of relatively higher temperature, compared to the under-floor type.

Positioning the DPF inside the engine room, however, limited the soot and ash storage capacity. For enlargement of the soot and ash storage capacity, a novel geometrical design of the substrate was introduced and, as a result, ensured an ash maintenance-free DPF system; the inlet channel volume was larger than that of the outer inlet for improvement of ash storage capacity, Figure 4 right top.

One of the important factors for developing the DPF was estimation of the soot mass accumulated inside the DPF. Evaluation of the pressure drop over the DPF is a simple way to estimate the accumulated soot mass and ash but its accuracy is known to be limited to certain operating conditions. Therefore, a method to extend the reliability to a wider operating range was adopted; estimation of the accumulated soot mass was updated by applying correction factors depending upon the vehicle driving conditions. For reflecting the effect of ash accumulation on

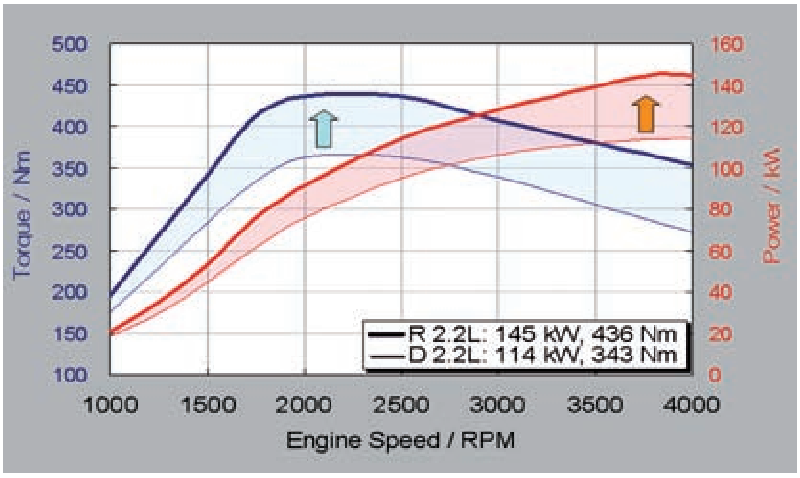


Figure 5: Engine power and torque at the full load conditions of the R-2.2 l in comparison to its predecessor

Table 2: Vehicle performance and fuel consumption of the R-2.2 l in comparison to its predecessor

Engine			R22 (new)	D22 (current)
Vehicle type			D-Segment SUV ~ 1800 kg	
V-max		km/h	200*	180
Acceleration	0 – 100 km/h	s	9.4	11.3
Elasticity	80 – 120 km/h		9.1	11.4
Fuel consumption		l/100 km	6.5	7.0
CO_2		g/km	171	185
DPF (maintenance free)			Close couple (standard)	Under floor (option)
Emission level			Euro 5	Euro 4

*depend on country related tyre specification

soot estimation, various kinds of the ash accumulated DPF samples were acquired from vehicles operating in a variety of driving modes, and intensive investigations were carried out with the samples.

Another key technology is the management of air and injection systems that control the regeneration temperature to burn out the soot accumulated inside the DPF. To secure DPF regeneration at all driving patterns Hyundai-Kia adopted a controlled temperature model for "controlled regeneration". It allows a continuous burning of soot within the temperature limits of DPF material.

A special challenge for the DPF system is the uncontrolled regeneration with high oxygen content and maximum soot loading during fuel cut phases. During several test campaigns this critical driving area was optimised by Drop To Idle tests to gain maximum possible soot loading and extended regeneration interval within all temperature limits, Figure 4 bottom.

6 Vehicle Performance and Eco Management

By adopting state-of-the-art technologies, engine power and torque were elevated: The 2.2 l engine delivers 145 kW of power and 436 Nm of torque, around 66 kW/l of power density and 200 Nm/l of maximum specific torque, **Figure 5**.

Thanks to the enhanced engine torque and power, acceleration performance from low to high speeds was improved by 15 % to 20 % compared to the predecessor engine currently available in the market.

For improving fuel economy from the vehicle point of view, additional functions such as a battery management system and a neutral control unit for a six-speed automatic transmission were implemented. With the implementation of such technologies, the fuel consumption became more competitive and the CO_2 level was reduced with a faster dynamic response of the vehicle compared to the current version of the engine.

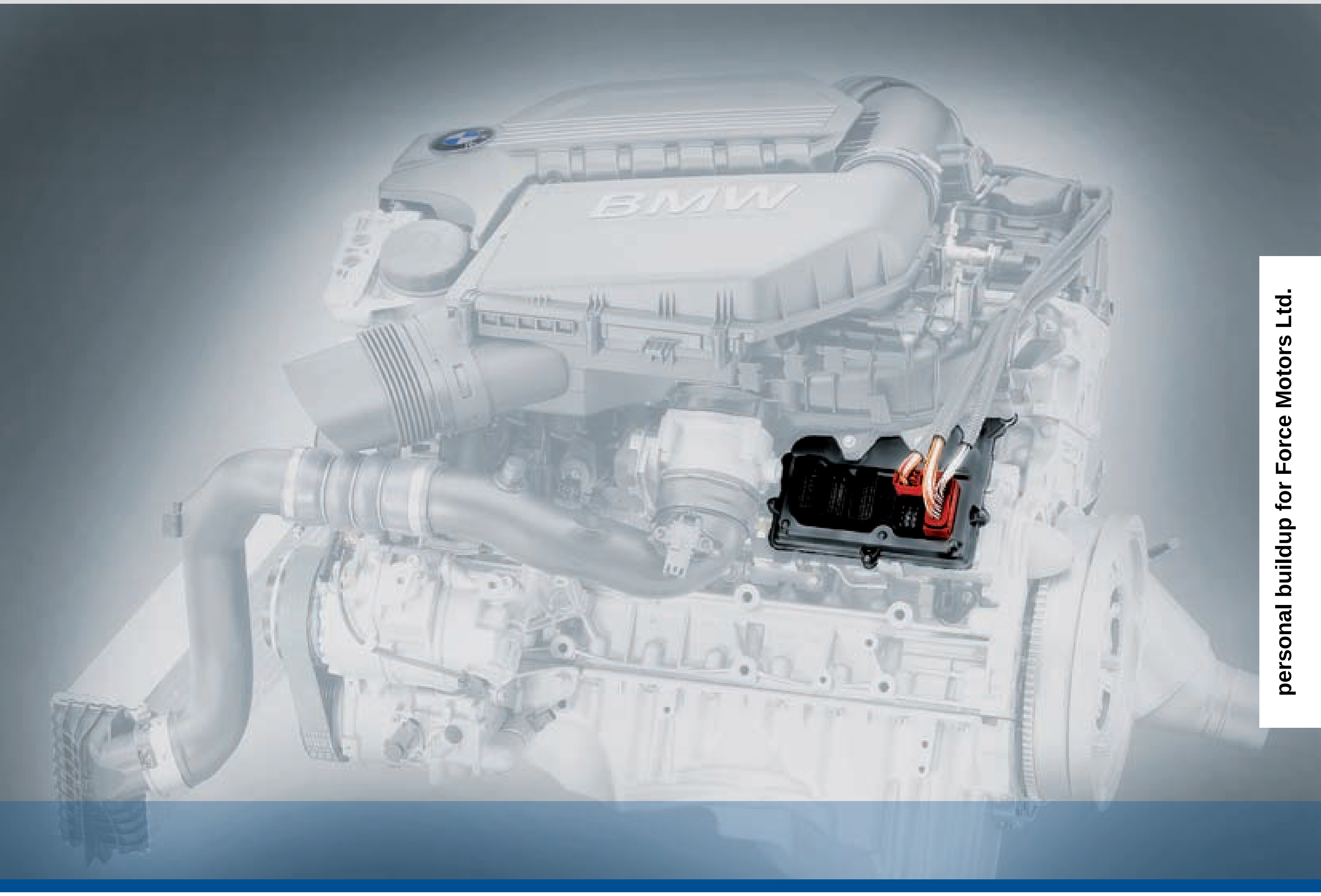
By consequently optimising all powertrain related components it was possible to reach beside the Euro 5 emission level with eco friendless and, thus for customer benefit 8 % lowered fuel consumption, **Table 2**.

7 Summary

Hyundai-Kia developed a new high-powered, eco-friendly diesel engine at the top of the 2.2 l segment to comply with the Euro 5 emission standard. Power and low-end torque were improved; around 66 kW/l of power density and 200 Nm/l of maximum specific torque. Secured emission characteristics and fuel economy were achieved thanks to the advanced air and fuel management systems with the well-designed combustion hardware, and additional vehicle functions.

Replacement of the conventional materials with plastic contributed to improved recyclability and fuel consumption. The close coupled aftertreatment system ensured minimisation of the CO and THC emissions, effective PM regeneration and a maintenance-free DPF system. Optimisation of the engine part geometry and auxiliary part positioning ascertained the reinforcement of engine stiffness followed by higher natural frequency and better acoustic comfort.

The new 2.2 l engine will continuously evolve into various versions, for instance, lower power engines with smaller displacement; the next variant R-2.0 l will complete with the introduction at the new Hyundai ix35 in autumn 2009 the new R-engine family. ■



ECU becomes an Integral Element of the Engine

BMW shows a concept for the integration of electronic components into the drivetrain which has been realized for the first time, in collaboration with Bosch, on the new six-cylinder TVDI SI engine (N55): Now the engine control is an integral element of the engine. The required installation space and the package have been optimized, for example by improved cooling. This created new crucial space under the bonnet that can be utilized for improved pedestrian protection.

1 Introduction

Modern vehicles are currently presenting tremendous challenges as far as the development of electronic components is concerned. Requirements relating to installation space and environmental impact, as well as statutory requirements concerning pedestrian protection, for example, pose particularly challenging problems for the integration of such complex electronic components as the engine control unit into the front end of the vehicle.Large numbers of electric sensors and actuators frequently give rise to control units with bulky enclosures, watertight multi-pole plug-and-socket connections and a high level of power dissipation with the need for appropriate cooling measures. A cost-effective, lightweight design is absolutely essential in the automotive sector and must be achieved in spite of high ambient temperatures, exceeding 100 °C in some cases, and violent vibration loads, while minimising the number of variants at the same time. In addition to this, new challenges for EMC (electromagnetic compatibility) are emerging as a result of highly critical signal wave shapes in the ignition and fuel injection systems and because of the usually long supply leads connecting the engine control unit to the other items of equipment. Electronic hardware and software specialists are needed for these spheres of activity and the BMW Group is always on the lookout for such expert personnel. The BMW Group is still recruiting development engineers in the fields of engine and powertrain control systems, computation and simulation, electrical energy storage technologies and electrical machines. In an effort to resolve the apparent conflict of objectives, BMW developed a concept for the integration of electronic circuitry into the power plant and implemented it for the first time in the new six-cylinder TVDI spark-ignition engine (N55) in collaboration with Bosch. The engine control unit has now become an integral element of the engine, **Figure 1**.

2 Turbo Valvetronic Direct Injection (TVDI)

One of the milestones of the holistic stratgegy "BMW EfficientDynamics" is high-pressure direct injection (GDI) with exhaust-gas turbocharging and BMW's fully variable valve timing system (Valvetronic/VVT), **Figure 2**. Referred to as Turbo Valvetronic Direct Injection (TVDI), this combination offers the driver greater power density, a considerable reduction in fuel consumption, better dynamic performance and smoother running. The load and rpm of an internal combustion engine with VVT is not controlled by throttling the intake air with a butterfly valve in the conventional manner, but can be achieved by means of a continuously variable amount of intake valve lift. Completely integrated into the cylinder head, an electronically commutated,

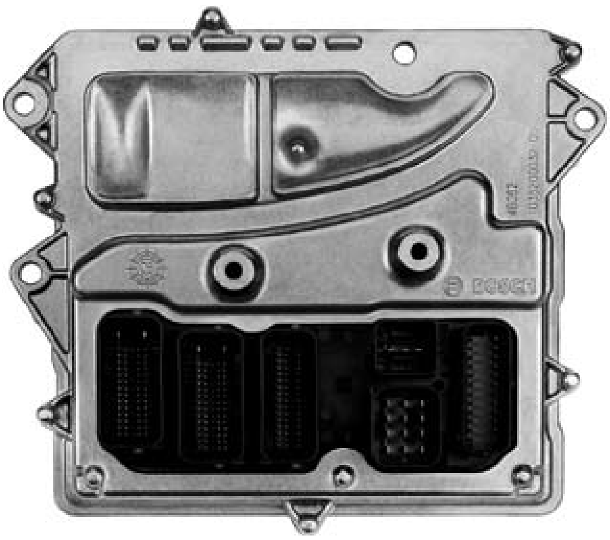


Figure 1: Engine control unit six-cylinder TVDI (N55)

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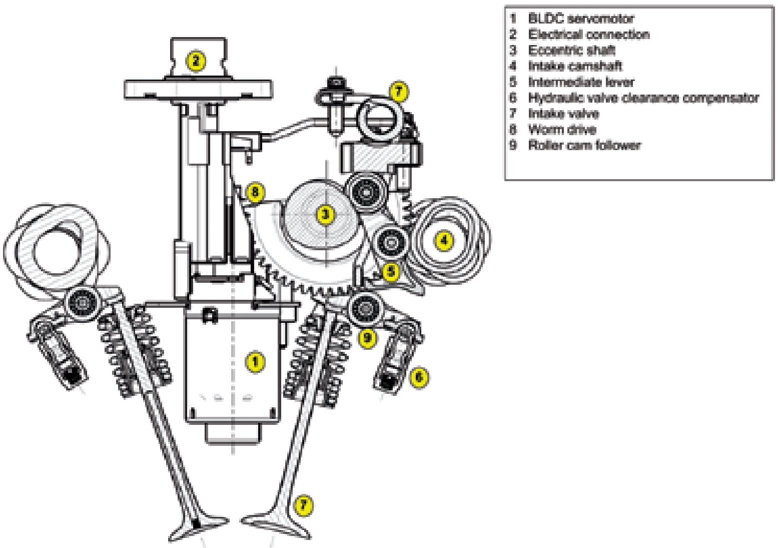


Figure 2: Third-generation VVT system

brushless electric (BLDC) motor with built-in sensors serves as the actuator in the third-generation VVT system. The power output stage with up to 60 A current carrying capacity used to generate the rotating electrical field and for sensor evaluation is included in the scope of the engine control unit.

The requirements to be met by the electronic circuitry were consistently taken into consideration as early as the concept phase and the implementation was optimised with regard to the prevailing boundary conditions. Optimum results were achieved in several areas by mechanically integrating the engine control unit into the intake module.

3 Installation Space

The engine control unit was successfully accommodated in this environment thanks to the very close cooperation established between the design engineers and installation space specialists from three companies (BMW, Bosch and Mahle, the manufacturer of the plastic intake manifold). As a result, the engineers were able to find a suitable place for the control unit on the underside of the intake module and make optimum use of the previously unoccupied space. The engine becomes even more compact as a result of these measures, offering essential advantages, particularly in the front end area. Compared with an ECU mounting position on the top surface of the engine, this solution increases the clearance to the nearest "hard" components and releases the extra space required to ensure optimum pedestrian protection. In the event of a collision with a pedestrian, the body panel collapses into the engine compartment (head impact zone) so that pedestrian injuries can be reduced to a minimum.

4 Assembly

Another major advantage of permanently attaching the ECU to the engine is the drastic reduction in variants when using an engine in different vehicles and carlines. If the engine control unit is permanently attached to the vehicle, the engine wiring harness has to be adapted according to the various models. The problem can be eliminated by mounting the ECU on the engine, not only offering advantages in terms of the time and effort involved in logistics and parts management, but also financial benefits.

The engine-mounted arrangement enables early automated 100 % testing of the engine, including all electrical components, with the target hardware as a complete module at the engine plant before the engine is fitted into the vehicle. The so-called "cold test" involves running the completely assembled engine with all of the pertinent electric components in towing mode. This test not only checks that all sensors and actuators are functioning properly, but also records specific characteristics, such as the current input curve. In this test, the components are controlled directly by means of the engine control unit rather than via an external control unit. There are no additional plugging or unplugging operations and a large proportion of the tooling up and stripping down work is unnecessary. This ensures that the test is carried out under conditions that are as near to normal customer operation as possible. The data acquired in this way can be used to immediately identify drifts relating to individual parameters and initiate targeted measures where necessary This not only leads to a signifi-

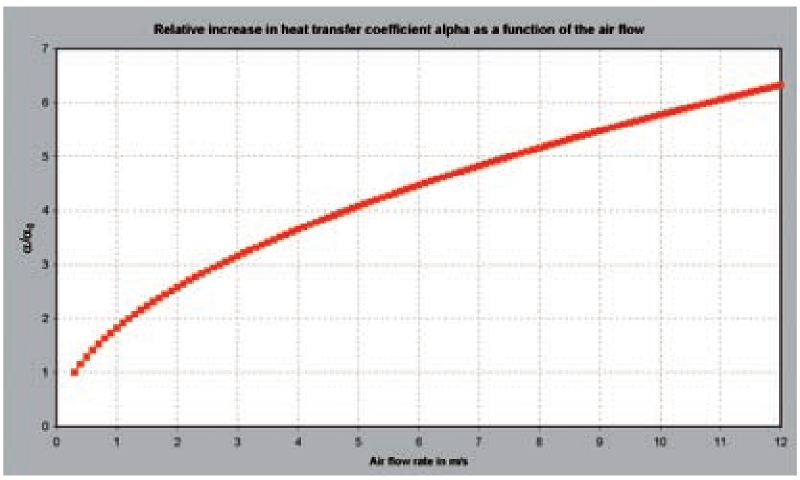


Figure 3: Qualitative characteristic of the heat transfer coefficient as a function of the air flow

cant improvement in the quality of deliveries from the engine plant to the vehicle plant, but also lowers the costs of any rectification work.

5 Thermal Constraints

Unavoidable power dissipation occurs in the control unit during operation. This may amount to anything up to 55 W according to the operating point of the engine. With the ECU fitted in the engine compartment and the resulting high ambient temperatures, which exceed 100 °C in some cases, measures must be taken to ensure that the resulting heat is dissipated. Targeted utilisation of convection cooling constitutes the approach adopted here, making use of the high air flow rates in the intake pipe.

5.1 Convection Cooling

The following equation can be used to describe the heat transported from a surface into a fluid by means of convection:

$$\dot{Q} = \alpha \cdot A \cdot (T_O - T_U) \qquad \text{Eq. (1)}$$

where
$\dot{Q}$ = transferred power $[W]$
α = heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$
A = surface area in the flow field $[m^2]$
T_O = object surface temperature
T_U = ambient temperature

The following equation applies to heat transfer coefficient α for laminar flow:

$$\alpha \approx \frac{\lambda \cdot \sqrt[3]{Pr}}{\sqrt{v}} \cdot \sqrt{w} \qquad \text{Eq. (2)}$$

where
λ = thermal conductivity of the fluid $\left[\frac{W}{m \cdot K}\right]$
Pr = Prandtl number of the fluid
v = kinematic viscosity $\left[\frac{m^2}{s}\right]$
w = fluid flow rate $\left[\frac{m}{s}\right]$

Alpha increases as the flow rate increases. The characteristic of this increase approximates that of a square root function over the flow rate range that is typical for air cooling. As long as the variables do not remain constant over the surface, they must be considered locally, **Figure 3**. Integration must take place across the surface in order to calculate the power and simulation programs are required for this.

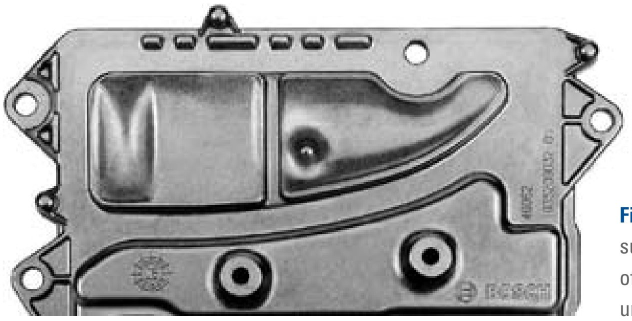


Figure 4: Cooling surfaces in the base of the engine control unit housing

Equation (1) indicates that the dissipatable heat loss increases linearly with the heat transfer coefficient. This, for its part, is determined by the flow rate via a square root function. The control unit cooling concept is based on the use of the high air flow rate in the intake pipe to regulate the temperature of the electronic system. In this respect, it is expedient if there is a sufficiently large difference between the temperature of the air in the intake pipe (up to 80 °C) and the temperature limits of the electronic circuitry. This presents a new challenge to be met by the design of the housing base, which performs a heat sink function, and the structure of the intake pipe. Although the heat sink should not disturb the flow inside the intake pipe, the cool intake air must flow across a sufficiently large surface area to ensure adequate heat dissipation at all of the engine's operating points, **Figure 4**.

The surface contour continues to pursue the intake pipe geometry and is adapted in such a way as to prevent turbulence in the intake tract, to the greatest extent possible, which would otherwise give rise to a loss of power in the internal combustion engine, **Figure 5**.

The cooling concept benefits from the fact that the air flow rate and ECU power dissipation are essentially determined by the engine speed and load: high power loss on the one side is accompanied by a high air flow rate and the associated heat dissipation on the other, and vice versa, **Figure 6**.

As far as an electronic system is concerned, a satisfactory transfer of heat from the electronic components to the housing is just as important as a satisfactory transfer of heat from the housing to the environment. This is the only way in which it is possible to generate high power dissipation density with the associated ability to concentrate extensive circuitry into a confined space. As far as power electronic components are concerned, this not only requires an assembly and connection technique that guarantees a consistent transport of heat right through to the housing by means of thermal conductivity, but also the use of materials and designs with optimised thermal conductivity proper-

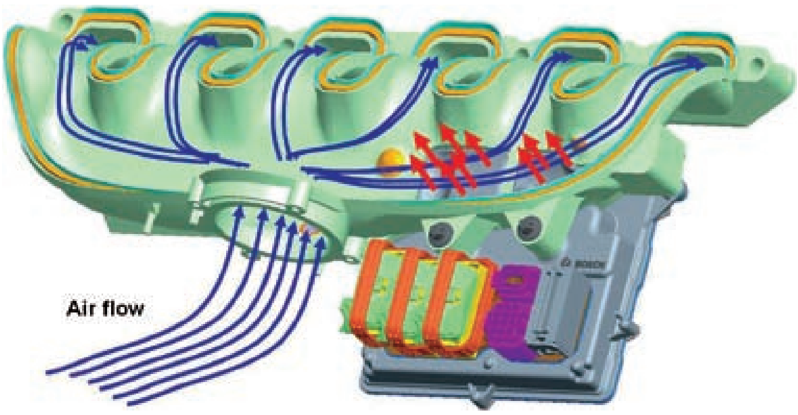


Figure 5 : Using the intake air for active cooling of the engine control unit

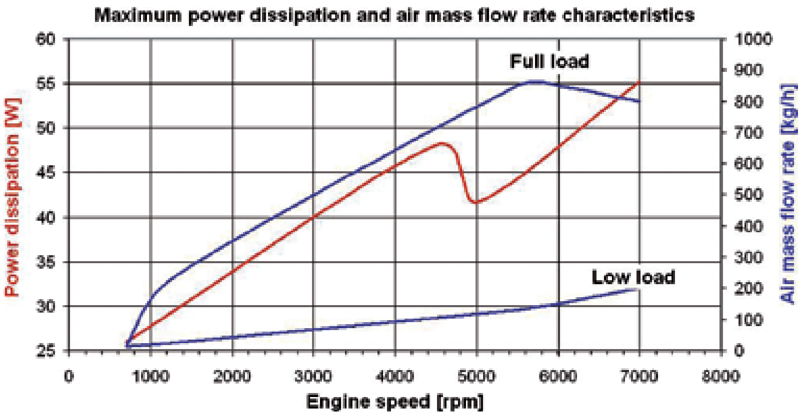


Figure 6: Relationship between air mass flow rate (load-dependent) and idealised power dissipation

ties, which restrict the heat conduction distances to a minimum. This poses paramount challenges for assembly and manufacturing processes in order to comply with the tight tolerance requirements within the framework of large-scale production.

5.2 Validating the Thermal Conditions

Extremely exact, detailed knowledge of the thermal histogram (temperatures, air speeds, engine loads) is required for the thermal rating of the control unit and the components used. Tests were carried out using a "thermo dummy" in order to acquire this knowledge. To this end, a control unit was prepared with switchable power resistors to enable simulation of the power dissipation in different operating states. Load histograms were then derived from the measured instantaneous state variables. Based on these histograms, it was already possible to validate the thermal characteristics of the control unit concept during the early concept phase.

Furthermore, these histograms were also used to devise the endurance tests, while allowing for the relevant aging mechanisms (e.g. Arrhenius, Coffin-Manson). The measurements were repeated on later sample states in the vehicle with a functional engine control unit in order to verify the validity of the assumptions and estimations.

6 Vibratory Load

With the control unit being fitted so close to the engine, special attention must be given to the considerable vibratory load. Unlike a body-mounted component, the excitation frequencies and amplitudes vary considerably from those of conventional systems in some respects.

With this concept, a directly engine-mounted ECU was realised using conventional PCB technology for the very first time in collaboration with Bosch. An implementation with anti-vibration mounts proved to be inexpedient because of the limited space available, with the result that the intake module (plastic) actually constitutes the damping element.

The actual vibratory load was determined in the course of several measurements and provided a point of reference for dimensioning the control unit and the individual components. The measured data enabled the engineers to improve the simulation model to such an extent that it was capable of supplying exact information concerning the actual conditions.

6.1 Optimising the Control Unit in Terms of Vibration Requirements

The compact design of the PCB, with components mounted on both sides, gives rise to diaphragm vibration in the excitation frequency range, which could couple with the components' natural oscillation. The vibration response of the control unit and the critical load withstand capability of the critical components must therefore be known in order to predict the control unit's vibrostability, **Figure 7**.

The modal forms were determined by means of experimental testing as early as the first sampling phase and the pertinent FEM models were synchronised in terms of dynamic rigidity and damping in order to obtain a fundamental understanding of the systemic vibration response. This offered a means of predicting critical loads in components, which could be avoided by modifying the design of the control unit, component or circuit at an early stage. The vibrostabili-

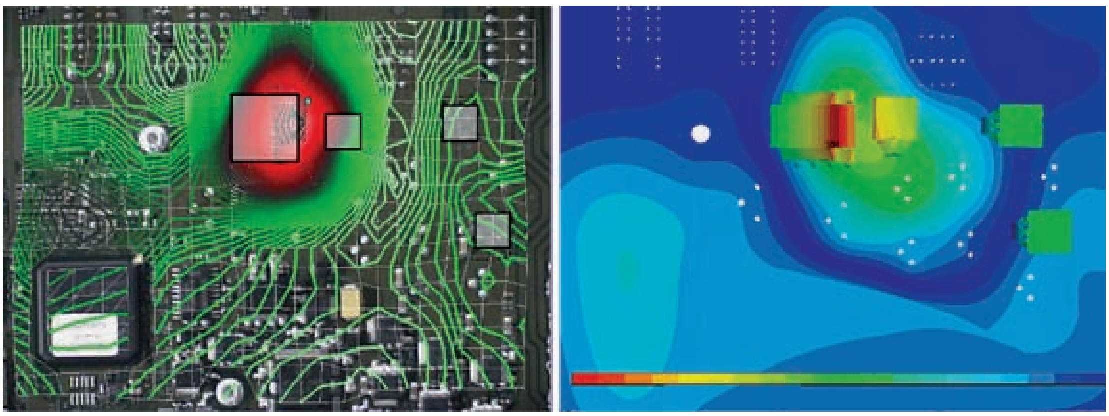


Figure 7: PCB deformation for a higher modal form – measured (left) and FEM calculation (right)

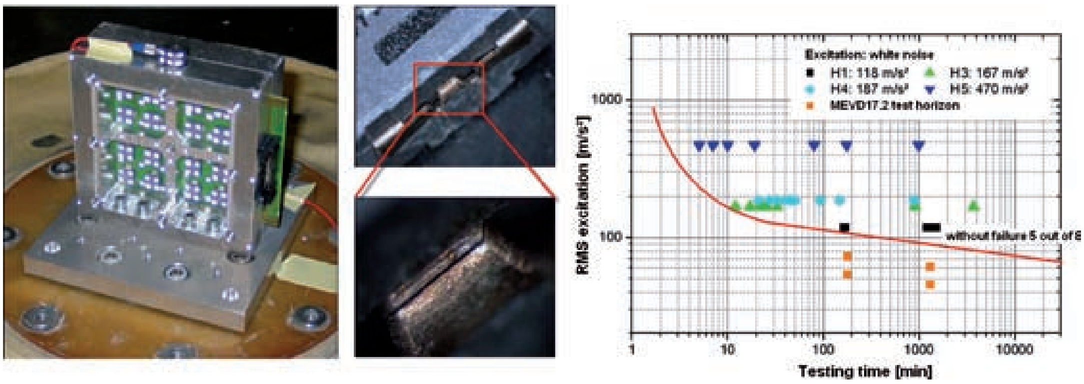


Figure 8: left: test structure for component testing; middle: 1. failure pattern (electrical monitoring); right: measured TTF characteristic with collective excitation and ECU test requirement

ty was particularly improved by selectively coupling components with the control unit housing.

6.2 Component Selection

The selected components must undergo a critical assessment, particularly with respect to their vibrostability. Component-specific tests (e.g. AECQ200) do not cover the stipulated vibration requirements as a rule, which means that the critical load withstand capability of the components must be determined during the early project phase. This initially involves a determination of the components' vibration performance on test structures. The time to failure (TTF) of a component subjected to vibratory load was established by means of horizon testing with collective excitation. Simultaneous visual and electrical monitoring permit specific correlation of the failure pattern. A knowledge of the component's vibration response and load withstand capability enables the definition of highly targeted measures for its improvement. It is then possible to verify the efficacy of these measures very quickly at component level, **Figure 8**.

6.3 Validating the Vibratory Load

The specific mounting conditions on the intake module are such that the use of a standard vibration profile did not present an expedient solution. BMW and Bosch therefore joined forces to establish differentiated load histograms within the framework of in-vehicle measurements and, allowing for the testing equipment, used these to derive the conditions for vibration testing of the control unit. In addition to this, the damage incurred under these conditions was examined by comparison with the damage incurred during field trials and endurance tests, allowing for the respective engine speed and torque histograms, **Figure 9**.

The engineers were then able to use this as the basis for implementation of lifetime-dependent vibration tests during the A, B and C sample phases. The overall verification procedure under real conditions was carried out within the framework of numerous durability tests performed on the engine test rig and vehicle endurance tests with typical customer driving behaviour and high load cycles that have been specially designed to examine component stress.

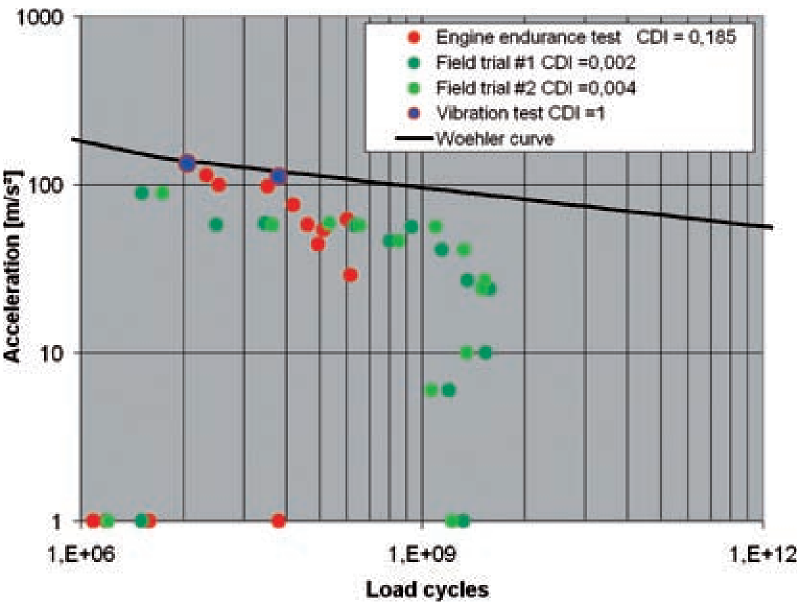


Figure 9: The relative damage incurred during vibration testing on the control unit is much greater than the damage incurred during endurance tests or field trials (assumptions: vibration fracture, linear accumulation of damage)

7 Electromagnetic Compatibility

Another advantage of the engine-mounted control unit concept is reflected in a drastic reduction in the lengths of the leads. Apart from saving raw materials, this also exerts a very positive influence on the electromagnetic compatibility of the entire powertrain. The main benefits are enjoyed by the ignition system, with very steep current gradients, the injectors for the gasoline direct injection (GDI) system, with voltages up to 65 V, and the actuator for the fully variable third-generation valve timing system (VVT3), with up to 60 A of switched current.

Attention was already given to maintaining a modular wiring system as early

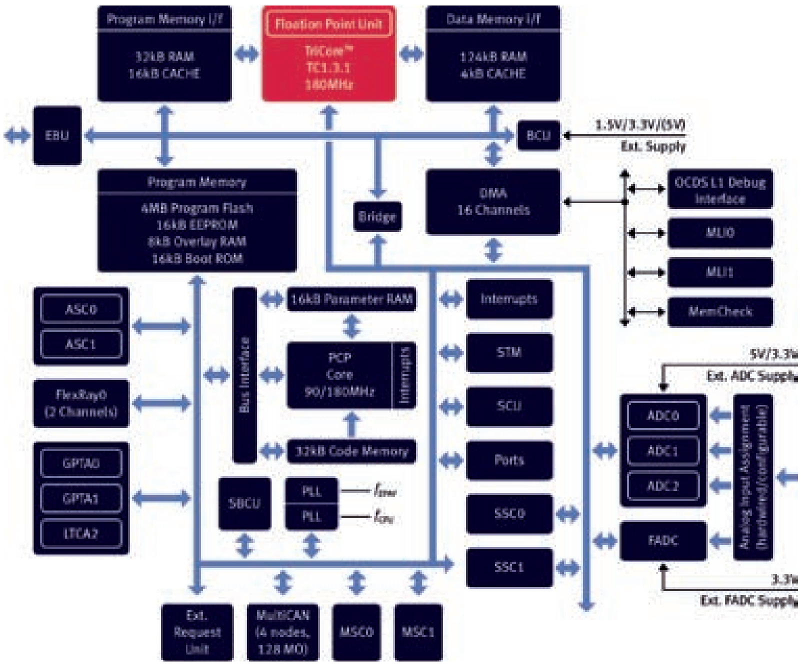


Figure 10: Architecture of the Infineon TriCore 1797

as the concept phase. This refers to consistent 1:1 cabling between the control unit and the various items of equipment without any additional electrical couplers in the wiring harness. In concrete terms, that means that the supply of power to all items of equipment is also routed through the control unit. This is the reason for the high number of 211 contact pins on the control unit and an appropriately large, watertight pinboard. The wiring harness has been modularised and divided up into six individual modules, however, with the result that it can be manufactured automatically, bringing about a substantial reduction in the system costs. Once the engine has been fitted into the front end of the vehicle, the electrical connections to all of the other systems in the vehicle is established by simply plugging in a single connector module. This minimises the time and effort required on the assembly line.

8 Modular Electronic Add-on Concept

The engine control unit for the N55 engine was developed according to a modular approach. The advantages of such an approach include the following:

- high level of carry-over for circuit modules
- high quality standard as the modules are developed by just a few experts
- should changes be necessary, these involve little effort or expense as the change is validated once within the circuit module, giving rise to very little expense for individual control unit projects
- standardised procedure for the development and documentation of circuit modules.

In order to achieve this, Bosch has designed the control unit architecture in such a way that every control unit is made up of predominantly standardised circuit modules. The internal power supply and injection output stage are just two examples of such circuit modules. Standardised interfaces are used to connect the circuit modules to one another within the control unit.

The circuit modules are adapted to the customer's requirements by means of application (adapting component values) and/or configuration (adapting the circuit structure). To this end, scope for application and configuration is defined and documented for each module as early as the development phase, ensuring that the modules can be adapted to meet the requirements of a specific control unit project within a predetermined framework.

Maximum integration density thanks to a new processor: The 32-bit Infineon TriCore1797 processor, **Figure 10**, is being used in the automotive sector for the very first time in BMW's new six-cylinder TVDI engine. This highly integrated processor was selected by virtue of the following characteristics:

- significantly improved performance compared with previously used processors, with 180 MHz clock frequency
- integrated peripheral control processor (PCP)
- integrated DSP
- 4 MB integrated flash memory
- 48 kB SRAM
- 2 FlexRay controllers
- 4 CAN controllers
- integrated 5 V analogue-to-digital converter
- full automotive qualification for temperatures between - 40 and + 125 °C
- high level of integration density with compact dimensions (BGA-416 enclosure).

The engineers were able to reduce the size of the control unit PCB even further by using this microcontroller. External components, such as the flash memory, the 5 V ADC and the FlexRay controllers, are now integrated into the processor directly and save space. Apart from anything else, this solution is much more cost-effective than a solution using individual components.

The development of this engine control unit constitutes a completely new phenomenon with respect to its complexity in terms of coordinating the activities of so many companies, suppliers and interface partners. The development process can only proceed smoothly and be completed within the specified period if production, service and development process partners are involved at an early stage and are given well thought-out time schedules. This will become even more important for future projects because of the growing scope of functions, the diminishing space available and the increasingly stringent ecological requirements. The BMW Group is looking forward to taking on these challenges in the future as well, joining forces with development partners to ensure that the company's customers continue to enjoy "sheer driving pleasure". ■

Special

50th Anniversary of Kistler

From Piezoelectric Sensor to Measuring System

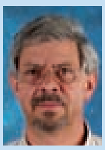
In 1959, Hans Conrad Sonderegger established Kistler Instrumente AG in Switzerland. In 1957, Walter P. Kistler and Hans Conrad Sonderegger had already founded Kistler Instrument Corp. in the USA and Hans Conrad Sonderegger had established Kistler Instruments in Switzerland. In 1958, Kistler launched the first universal miniature pressure sensor. In the years that followed Kistler set milestones in the field of sensor technology with its innovations and expanded its global presence. In 2009, its jubilee year, Kistler is adding the new KiBox, the mobile in-vehicle combustion analysis system, to its range of products.

The Beginnings

Piezoelectric effects were described for the first time by the brothers Pierre and Jacques Curie in 1880. However, these effects remained little more than a scientific curiosity for more than 30 years. The first publication on piezoelectric pressure measurement in internal combustion engines appeared in 1925, with the first publication on piezoelectric cutting force measurement being issued in Japan in 1927. In addition, forces and pressures were measured with piezoelectric sensors in Germany, France and the USA until the 1940s.

At the end of the 1940s the Schweizerische Lokomotiv- und Maschinenfabrik in Winterthur started developing and manufacturing piezoelectric pressure sensors on a larger scale. Together with the patenting of the charge amplifier by Walter P. Kistler in 1950, this revolutionized piezoelectric measurement technology and opened up undreamt-of opportunities for extremely precise dynamic measurement of mechanical variables. In 1957, Walter P. Kistler and Hans Conrad Sonderegger had established Kistler Instrument Corp. in the USA, and Kistler Instruments had been founded by Hans Conrad Sonderegger in Switzerland. Kistler launched the first miniature pressure sensor as early as 1958. It was universal in application and went on to set a new standard in pressure measurement. Over the next few years the company expanded successfully. In 1966, Kistler moved into its own new company building in Winterthur-Wülflingen. This building still houses the company's headquarters today.

The Author



Bernhard Bill
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Innovations Extend the Range of Products

The market success of the pressure sensor encouraged Kistler to develop high-quality measurement products for other areas of application as well. As a result, the company launched a number of innovations in close succession. In 1965, Kistler introduced the world's first quartz force sensor in the form of a load washer. The two-wire concept „Piezotron" for piezoelectric sensors with voltage output followed in 1968. From then on it was used, first and foremost, in accelerometers and – to a lesser extent – in pressure sensors. The following year Kistler launched piezoelectric three-component force sensors, a world first, and had them patented. Mounted in dynamometers they were used all over the world to measure cutting forces. The now legendary Type 5001 charge amplifier („measuring without math") was introduced the same year. The first ultra-sensitive quartz strain sensor, another world first, was launched in 1980. In 1983, the rotating quartz wheel-force dynamometer, which was yet another world first at the time, and was developed for and with VW and BMW, was introduced. In 1988, the first microprocessor-controlled charge amplifier was launched.

However, Kistler also continued to develop pressure measurement technology and, in 1973, introduced sensors using the piezoresistive measurement principle. The patented polystable quartz cut enabled the company to introduce quartz sensors for operating temperatures of up to more than 350 °C in 1974. They were the first uncooled engine pressure sensors. Another milestone was Kistler‘s uncooled high-temperature pressure sensor with a diameter of only 5 mm for use in engine measurement in 1989. In 1998, Kistler commissioned its first in-house crystal growing system. The resulting „PiezoStar“ crystals are particularly outstanding for their extremely stable temperature characteristics. 2002 saw the first M10 measuring spark plugs for use in Formula 1. In general, combustion analysis still plays an important role to this day; measuring spark plugs and glow plug adaptors enable measurement without an additional indicating bore. Thanks to new crystals, Kistler was able to increase the sensitivity of uncooled M5 engine pressure sensors to -45 pC/bar in 2005.

Kistler made the leap from sensor to measuring system manufacturer as long ago as the 1980s. The first step into process monitoring was made in 1987 with the introduction of the „ControlMonitor“ (CoMo). In 1992, Kistler‘s first rotating four-component cutting force dynamometer with integral electronics and telemetric signal transmission was launched. In the same year, the first control monitors with online monitoring functions and display (CoMo II) were introduced. In 2002, the company launched the Internet-compatible ControlMonitor „CoMo Net.“

In 1994, the first WIM station using Kistler Lineas sensors to determine the axle loading of moving vehicles was installed. In the same year, Kistler was accredited as a calibration center for pressure, force, acceleration and electrical charge. In 2004, Kistler built the first „SmartCrash“ barrier. These systems are now an everyday development tool and are used at Audi, BMW, Daimler, Fiat, Hyundai and PSA.

Internationalization

Kistler‘s corporate success is closely linked to the company‘s global orientation. Kistler‘s international expansion started shortly after the establishment of the companies in America and in Switzerland. Thus, in 1963, the Group company in Germany was established and, in 1966, the company in England was founded, followed in 1986 by the subsidiaries in Japan and in 1991 in France. Kistler expanded its presence in Asia with the establishment of Group companies in China and Singapore in 1996 and in Korea in 2000. The subsidiary in India followed in 2003. However, Kistler continued to expand in Europe as well: in 2000, a company was founded in Austria and in 2002 in the Netherlands. The firm set up Group companies in Sweden and Denmark the following year. In 2002, with the integration of IGeL Ingenieurgesellschaft für Leichtbau Kistler expanded the product portfolio of measuring wheels from the 1980s with lightweight measuring wheels. These are based on the strain gage principle and make it possible to measure static components. A strategically logical step was the takeover by Kistler of Velos Messysteme a year later in 2003. In 2006, Kistler acquired the long-established German company Dr. Staiger Mohilo, thereby extending its portfolio with the torque measurand. The Group companies in Australia and the Czech Republic were established in 2007, and the Group company in Spain a year later.

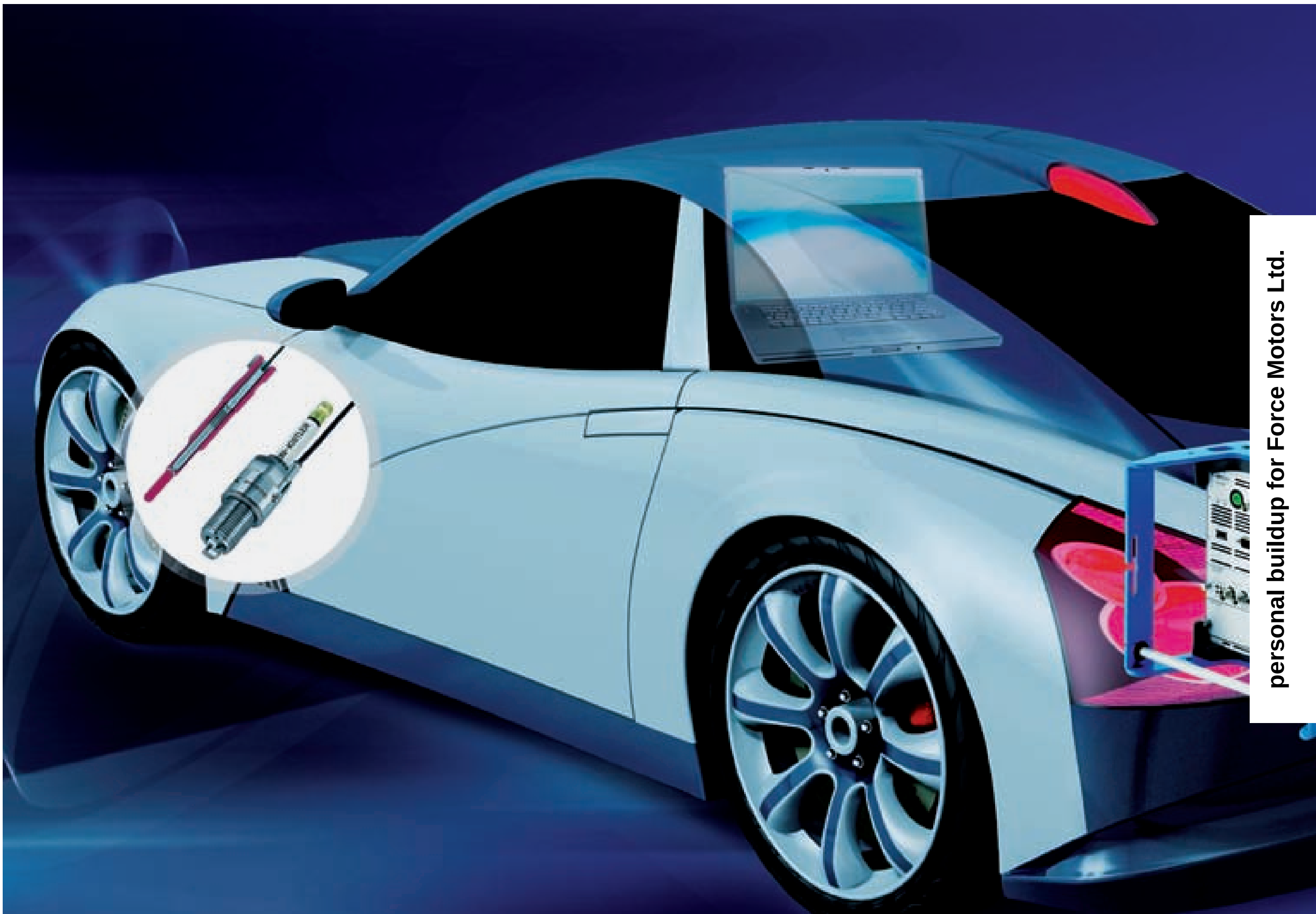
First micro-processor-controlled charge amplifier

2009 – A Jubilee Year Full of Innovations

In 2009, Kistler is celebrating its fifty-year jubilee. Kistler is marking this momentous occasion by the addition of the new KiBox, a mobile in-vehicle combustion analysis system, to its range of products. In addition, the new Type 5018 charge amplifier is being launched. On the product side, optical systems are also helping to round off Kistler‘s portfolio.

In 2009, Kistler also acquired MSC Automotive GmbH, thereby expanding the company‘s portfolio with dummy measurement technology for in-vehicle safety. Together with the SmartCrash barriers, Kistler is now able to offer comprehensive system solutions for safety as well. The acquisition of Corrsys-Datron Sensorsysteme GmbH enables Kistler to perfect its range of measuring systems for dynamic vehicle testing in automotive development. ■

Systems with SmartCrash barriers are now in use at Audi, BMW, Daimler, Fiat, Hyundai and PSA



personal buildup for Force Motors Ltd.

System Capability
A New Era in Dynamic Measurement

The Author

Heinz Jenny
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Over the last 50 years Kistler has developed from a pioneer of piezoelectric measurement to a technology leader and system provider. The sensors and charge amplifiers for measuring the mechanical quantities of pressure, force and acceleration have been perfected over this period. For approximately 20 years Kistler has been increasingly focusing on the development, manufacture, and sale of system solutions for the main application of engine and vehicle development as well as manufacturing process control. A great deal of importance is attached to both system capability and after-sales service.

Evolution of the Lab Charge Amplifier

Charge amplifiers convert the charge output by the piezoelectric sensors into a proportional voltage. To do this, the highest possible insulation values, the smallest possible input currents and a signal bandwidth from 0 to 200 kHz combined with minimum noise are required. The gap between the piezo sensor and the cathode-ray oscilloscope was closed with the invention of Kistler's Type 1 charge amplifier – which at that time was still built with tubes. This opened up the possibility of developing dynamic measurement technology with piezoelectric sensors. This was followed by the era of Types 5001 and 5007 with their integral „slide rule“. This made it possible to „measure without math” for the first time. The Type 5011 was the first charge amplifier with a microprocessor which could be remotely controlled via data communication interfaces. The Type 5018 will supersede Type 5011 with even better specifications and new features in 2009.

Universal Measuring Amplifier Platform

The market is increasingly demanding modular, multichannel amplifier systems, especially for combustion analysis of internal combustion engines on test stands. The cost-effective solution is the „Signal Conditioning Platform“ (SCP). It can accommodate up to 16 two- or four-channel measuring modules and includes five different rack variants. Measuring modules for piezoelectric and piezoresistive sensors and for strain gages and thermocouples are currently available. Manual configuration of parameters is tedious and prone to errors if there are a large number of measuring channels. Kistler was therefore involved from the outset in a working group in the USA set up to define the 1451.4 IEEE standard for the „Transducer Electronic Data Sheet“ (TEDS). The TEDS memory chip is integrated into the connector on the amplifier side and permanently linked to the sensor. The identifying features such as manufacturer, type and serial number as well as individual sensor characteristics and operating time are stored in the TEDS. When a TEDS sensor is connected to the measuring module, the amplifier immediately reads the sensor characteristics and automatically adjusts. This satisfied the desire of many measurement technicians for „plug and measure“. The SCP can be readily controlled, for example from the combustion analysis PC, using the graphical user interface.

The „Equipment Database“ web application makes it possible to efficiently manage the measuring equipment over its entire life cycle. It provides interfaces with the calibration system, other user applications, and the Kistler web server along with its calibration data. As of recently, customers have been able to call up their sensors' calibration data at any time and from anywhere in PDF and XML format.

Evolution of Kistler's lab charge amplifier

Mobile Combustion Analysis System for Over-the-road Engine Testing

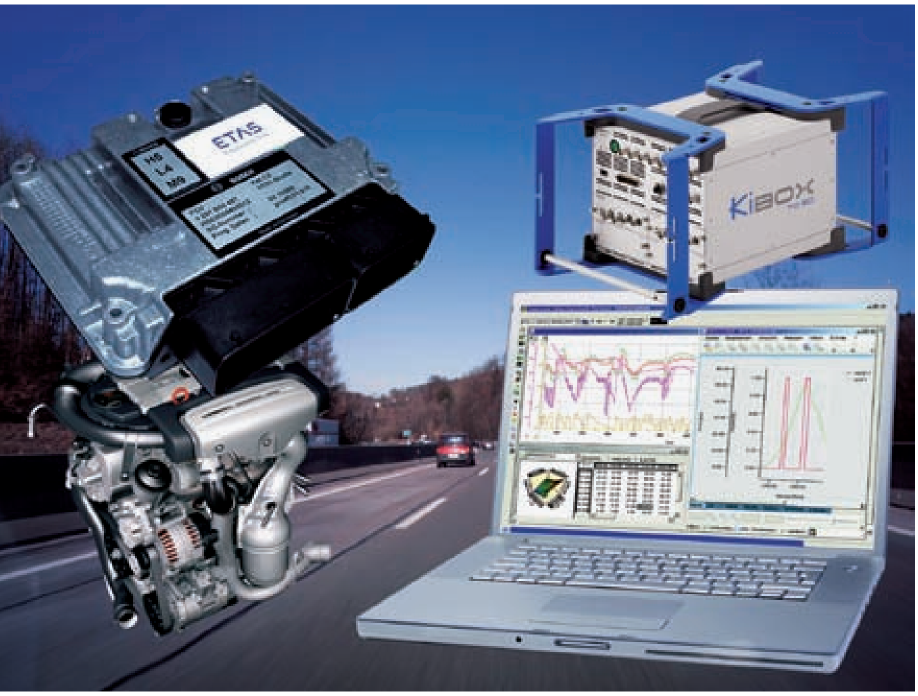
Over the last few years, the standards relating to exhaust emissions and energy efficiency have continually become more stringent. And there is no end to this process in sight. At the same time, the functionality and number of parameters in engine control units have drastically increased. Many of these parameters are directly governed by combustion. Combustion analysis parameters are very important for optimization of engine cold starts and driveability during over-the-road testing. They allow quick identification of the relevant setting parameters in the control unit and help to determine the amount and direction of the necessary adjustments.

During combustion analysis, piezoelectric sensors measure cylinder pressure directly in the combustion chamber under the most extreme operating conditions. If the combustion volume is determined at the same time, the combustion analysis parameters can be calculated. These allow experts to accurately judge the quality of energy conversion. With its „KiBox“ Kistler has developed a new data acquisition and processing system specifically designed for in-vehicle cylinder pressure analysis. In addition to an innovative data acquisition concept and simple integration into the „INCA“ application system, KiBox features a variety of new characteristics going beyond those of the state-of-the-art. The key combustion analysis parameters can therefore be determined very accurately in real-time under actual operating conditions. Integration into the “INCA” application system ensures that these parameters can be recorded and analyzed synchronously with the actuating data of the ECU. KiBox thus provides a mobile combustion analysis tool that ensures an extremely efficient approach to both: ECU calibration and engine troubleshooting.

Wheel Force Measurement on Test Stands and Over-the-road Testing

The forces and torques acting at the tire contact points must be known to design the components of the entire vehicle related to driving and to optimize driver assistance systems. „RoaDyn“ force measuring wheels record these forces and torques with a high level of precision and withstand the harsh operating conditions. They can be used across the full range of vehicles, from racing cars to commercial vehicles. The modularity of the RoaDyn System 2000 allows easy adaptation to suit the particular measurement task. Thanks to its high level of integrability and versatile interfaces, it can be combined with other measuring systems if necessary, for example with measuring instruments which record the vehicle‘s slip angle, longitudinal and lateral speed and log the vehicle‘s current position based on GPS.

Universal Signal Conditioning Platform (SCP) and „PiezoSmart“ (TEDS) sensor



Over-the-road engine testing and ECU calibration with the “KiBox” system

Quality Assurance Systems Integrated into Production Process

Joining processes – for example the pressing of bearings onto shafts – are very frequently used as permanent connection technique. As non-destructive mechanical testing of press-fits is virtually impossible, quality control integrated into the production process is almost mandatory. The „CoMo Net“ and „CoMo View“ monitors measure and evaluate the characteristic force-displacement curve for each pressing operation. These control monitors can be connected to the production network via Ethernet. The web technologies used significantly simplify integration into the system. They enable access to the CoMo units at any time from anywhere, for example, to monitor an ongoing process.

Kistler systematically expanded the range of products a few years ago to include electromechanical NC joining modules. The advantages of these compared with hy-

„Products Must Provide Concrete Benefits for the Customers“

In an interview, Rolf Sonderegger, CEO of the Kistler Group, spoke about the further development potential for testing equipment and sensors as well as the contribution of the Kistler Group towards the electrification of the powertrain.

Rolf Sonderegger, CEO of the Kistler Group

Question *In recent years Kistler has grown both internally and externally to become a global company with 1000 employees. What other growth targets have you set?*
Sonderegger *Growth is primarily a consequence of the right strategy; the products in your portfolio must find a market and provide concrete benefits for the customers. Growth per se cannot be the goal. Nevertheless, in order to be a partner to the automotive industry, a company needs to be a certain minimum size so that it can have a global presence and provide its customers with development processes locally. Expressed in figures, we believe that turnover of approximately CHF 500 million is required to attain this size. Over the next few years we expect to achieve our highest growth in Asia and in the USA.*

Question *Simulations are becoming more and more accurate. Soon it will be possible to carry out almost all aspects of engine, chassis and crash development work using virtual methods alone. Will this development make testing sensor technology superfluous?*
Sonderegger *That is a very good question. In theory, it is conceivable that virtual technology could supersede sensor technology. But in reality the opposite is true. Calculations and tests complement one another and are speeding up the development process enormously. Virtual test systems are very cost-effective and indicate a tendency. But in the end, when it comes to validating the virtual values it is always the real test that counts, particularly when one considers that quality and safety requirements are set to grow exponentially.*

Question *Combustion pressure sensor technology is discussed time and again as a method of precision-controlling engines, whether diesel or gasoline. What do you consider to be the technical possibilities from the perspective of the sensor manufacturer?*
Sonderegger *The technology already exists. A combustion pressure sensor which is suitable for series production is a reality, but unfortunately it does not come without a price tag. Combustion pressure monitoring is slowly becoming the standard for large engines. But when it comes to automobiles and commercial vehicles, it has not yet been demonstrated that the benefits outweigh the costs. In close collaboration with a major partner we have developed a product which was almost ready to go into mass production, but there was little interest from the market. If the market changes, we are ready to go.*

Question *What are the challenges in this field?*
Sonderegger *Combustion pressure monitoring is technically feasible and worthwhile, but only at very high volumes. But these volumes are simply not there at the moment. However, as Victor Hugo once said: „Nothing is as powerful as an idea whose time has come“. The combustion chamber pressure sensor's time has not come yet.*

Question *The electrification of the power train and electrical traction are key development trends for automobile manufacturers at the moment. What can Kistler contribute to this?*
Sonderegger *Although electrification is currently the number one mega-trend in drive technology, its economic relevance has been negligible to date. But if you believe the forecasts, the combustion engine – with varying hybridization but still as the primary unit – will always be the main power source. Kistler is focusing primarily on enhancing the internal combustion engine and its integration into hybrid power trains. Since 2006, Kistler has been involved in developing electric motor test stands; this area has seen a fair amount of growth and is also being promoted intensively at our plant in Lorch near Stuttgart. The acquisition of Staiger Mohilo has made Kistler a force to be reckoned with in torque sensor technology. Attractive niches are currently opening up in this area, which we intend to exploit to the full.*

Numerically controlled and force/displacement-monitored joining systems from Kistler

draulic systems are compactness, dynamics, controllability and energy efficiency. In line with market needs, joining modules, servocontrollers, force-displacement monitoring and process control have been further developed to form the flexible and very reliable NC joining system. The cost of integrating all these is reduced thanks to the smaller number of external interfaces.

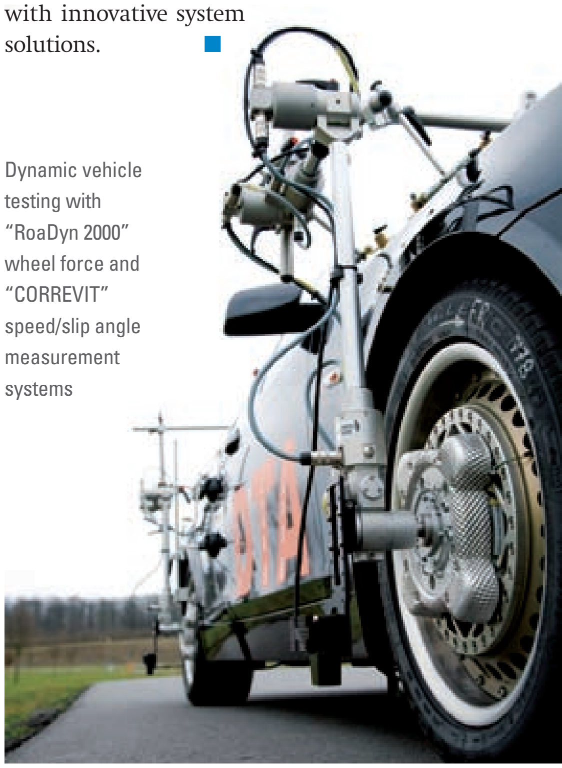
Given the high production volumes, evaluation of the quality of finished plastic parts is very cost-intensive. Since mold cavity pressure is directly correlated to the quality characteristics of the manufactured molded part, the injection molding process can be fully monitored in this way. Sensors reliably measure the filling pressure in each mold. The „CoMo Injection" units capture up to 24 channels simultaneously and evaluate the typical filling pressure curve for each molded part in real time. If the specified tolerances are not met, the machine separates out these parts immediately after the mold is opened. Quality assurance integrated into the process is the only way to guarantee cost-effective zero-defect production. Moreover, by allowing faster process initiation and optimization, for example during a mold change, the system offers additional benefits.

Process and quality information must be available globally at any stage of modern production, since only those who detect defects can eliminate them. The production information system „CoMo MIS" combines the latest web and database technology and features clearly arranged user interfaces. It provides effective information about the current production status of the individual machines and manufacturing sites. It also makes it possible to carry out extensive statistical analyses while documenting the process quality of the parts or batches.

Outlook

In particular, internal combustion engine development demands very high quality results under increasingly extreme operating conditions. In developing piezoelectric sensors and laboratory charge amplifiers we are therefore close to the limits of physics. Alternative technologies are still not sufficiently mature. Further optimization of the individual components in combustion analysis measuring chains scarcely allows any quantum leaps as far as essential measuring data are concerned. However, by focusing even more intensely on the particular task, and taking a more interdisciplinary approach to the mechanical engineering, electrical engineering and computer science aspects, it is possible to open up new opportunities. Just one example is the potential of microelectronics and software for dynamic measurement, which is far from exhausted. Innovation means creating something new by thinking in a different way. Having started to think outside the box quite some time ago, Kistler can be expected to continue to come up with innovative system solutions. ■

„CoMo Injection" systems guarantee zero-defect production and process transparency during injection molding



Dynamic vehicle testing with "RoaDyn 2000" wheel force and "CORREVIT" speed/slip angle measurement systems

Research and Innovation for the Future

The investigation of new piezoelectric crystals, materials, coatings, piezoresistive semiconductor structures and optical measurement principles underpins the sensors of the future at Kistler. The trend is towards enhanced functionality, system capability and miniaturization. The establishment of a global network of technological expertise is proving to be one of the successful formulas in order to meet future system requirements.

Introduction

As a pioneer of applied piezotechnology, Kistler began developing and manufacturing quartz crystal sensors for measuring engine cylinder pressures 50 years ago. A wealth of innovations made possible by a spirit of research, the ability to put ideas into practice and market proximity were to follow. One important prerequisite was Kistler's position as a technological leader, particularly in piezoelectrics. This know-how has been deepened and extended over the decades. The investigation of new piezoelectric crystals, materials, coatings, piezoresistive semiconductor structures and optical measurement principles now forms the basis of the sensors of the future. The impetus generated by ongoing development and greater user expectations demands efficient, cost-effective R&D solutions. Kistler therefore works closely with universities and research institutes to exploit cutting-edge results. This formation of a worldwide network of technical excellence is turning out to be a central factor in the company's success. Some very fruitful examples of this type of research collaboration include the development of „PiezoStar" crystals (and the associated know-how of in-house crystal growing), piezoresistive high-temperature pressure sensors and of an optical probe for detecting light emission in the combustion chamber of combustion engines.

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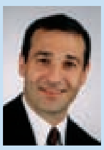
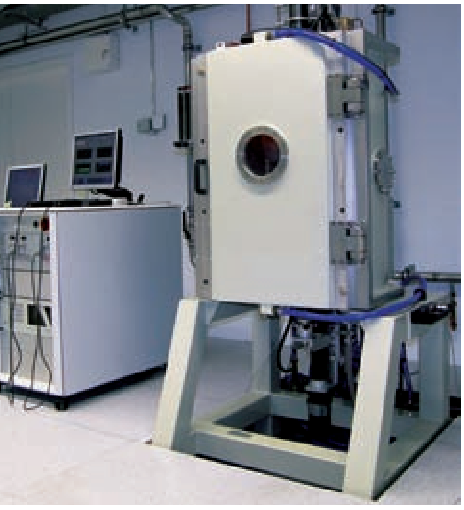


Dieter Karst
is Head of Sensor Basics in Research and Technology at Kistler Instrumente AG in Winterthur (Switzerland).

Innovative Crystal Technology

Based on the requirements for combustion chamber pressure sensors for engine combustion analysis, Kistler started an intensive search for new piezoelectric crystals about 20 years ago. The ever-increasing scarcity of space in engines necessitated miniaturized pressure sensors with improved sensitivity and high-temperature characteristics as well. As the potential of quartz was practically exhausted, Kistler focused on investigating new crystals. In collaboration with leading research institutes all over the world, new piezoelectric crystals were grown and characterized. This led to the development of the „PiezoStar" family of crystals with their excellent properties. The decision to transfer the crystal growing know-how to Kistler's own center of technology in Winterthur was in line with the existing corporate strategy.

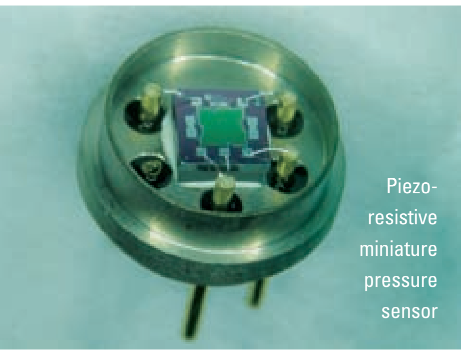
PiezoStar crystals are now used in numerous applications in highly sensitive sensors measuring pressure, force and acceleration in particularly harsh environments, for example in measuring spark plugs with integral miniature pressure sensors. Kistler is also continuing to explore new crystals for the sensors of the future with its research partners. In addition, use of the Czochralski method to grow its own crystals from the melt, is enabling the company to achieve very reliable industrial production within a short period of time.



Kistler's facility for growing „PiezoStar" crystals from the melt

Piezoresistive Pressure Sensors

Kistler was one of the first sensor manufacturers to look into using the piezoresistive effect of silicon for sensors for static measurement. These preliminary studies resulted in the first piezoresistive pressure sensors as long ago as 1973. Kistler mainly specialized in designing silicon sensor chips and devising construction and connection technology for stable pressure sensors. In addition to the standard technology of oil-filled pressure sensors, Kistler is increasingly focusing on high-temperature and high-pressure applications such as injection pressure in internal combustion engines or nozzle pressure in injection molding of plastics. Its research collaborations have therefore developed special high-temperature silicon sensors using silicon on insulator (SOI) technology. These sensors are able to withstand a constant temperature of up to 350 °C and a pressure of 4000 bar. Miniaturized low-pressure sensors, which can cope with particularly harsh ambient conditions, were developed for measuring the intake and exhaust pressure in engines. Achieving the required miniaturization while retaining a high degree of stability in all environments still represents the greatest challenge for piezoresistive technology in current research.



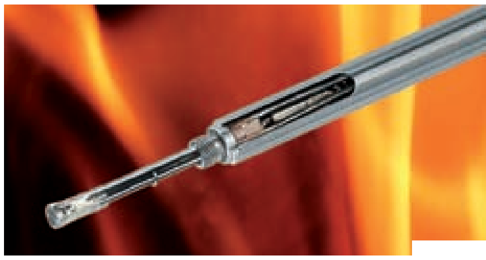
Piezo-resistive miniature pressure sensor

Optical Probe for Measurement of Soot in Combustion Chambers

In addition to further developing existing technologies, Kistler is dedicating resources to new technologies with objectives such as usefully extending the application of piezoelectric measurement technology to internal combustion engines. Pressure is not the only measurand of importance for the development of combustion processes. Other measurands of greater relevance to harmful emissions include the combustion temperature and the soot concentration. Optical systems represent an inexpensive way of recording the total emission of light, from which the combustion temperature and a measure of the soot concentration can be calculated using two-color pyrometry.

The optical measurement system developed by Kistler in cooperation with external partners is sufficiently compact to allow incorporation into pencil-type glow plugs or spark plugs. This technology can therefore be used without the need to modify the enginecylinder head. The system has already been successfully integrated into mass-produced spark plugs as well. This is of particular importance in the case of direct-injection gasoline engines, whose predefined spark plug types and bore locations cannot be changed under any circumstances.

Kistler has particularly focused on the fundamental problem of all optical systems, namely the contamination of their probe, which is coated with soot after a short time when used in diesel engines or direct-injection gasoline engines, making analysis impossible. Many possibilities were explored during the development phase, with thermal self-cleaning of the probe ultimately being favored. The clean burn temperature of at least 560 °C requires that the components of the probe must be extremely resistant to high temperatures.. The temperature-controlled self-cleaning system is now operating reliably, allowing optical analyses to be carried out at diesel engine operating points at which soot is formed, which was previously impossible. The system is ideally suited as a development tool on test stands, allowing conclusions to be drawn about NO_x and soot concentrations in the exhaust. This avoids the need for expensive exhaust systems on engine test stands.



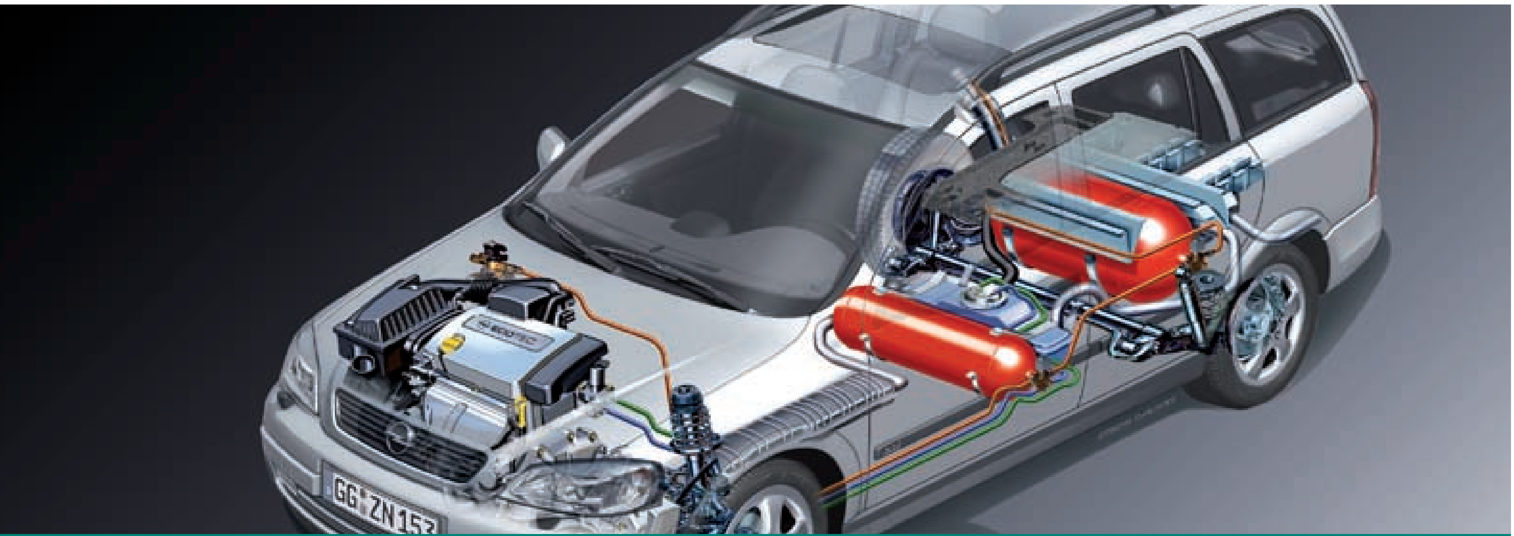
Optical probe for measurement of soot in combustion chambers

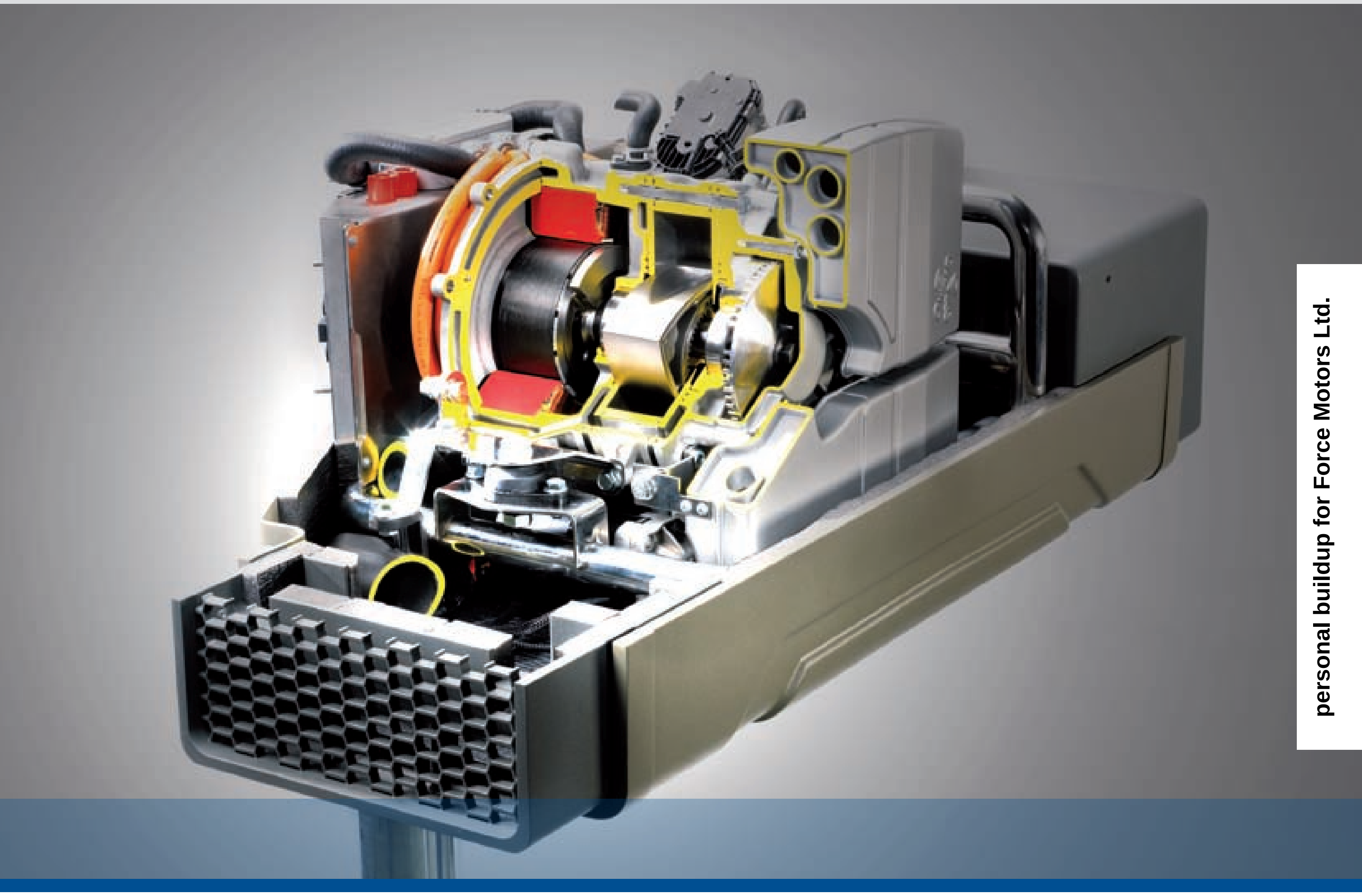
One future project is to combine the optical measuring system with the new Kistler „KiBox" combustion analysis system in order to enable determination of the soot formed in each cylinder and cycle, even during driving tests.

In developing an optical measuring system suitable for industry Kistler has set foot in a new technological and application sector. This technology exploiting existing access to the combustion chamber provides valuable information about local events and phenomena during combustion that complements the global information from pressure indication.

Future Prospects

These examples elucidate Kistler's broad technological basis, without which it would not be possible to offer a complete range of sensors for numerous applications. The trends in sensor technology are towards greater functionality, system capability and miniaturization. Collaborations with universities, research institutes and technology companies are therefore becoming an increasingly important means of converting new technologies into new products as quickly as possible. This requires an innovative spirit in close proximity to the market and global competence networking. ■





Range Extender Module
Enabler for Electric Mobility

The Range Extender as an auxiliary power supply for extended driving ranges is of significant importance in achieving a high level of customer acceptance for electric vehicles. The AVL concept is optimized for electric power generation in single-point operation and allows a compactly integrated, cost-efficient and weight-efficient module design. The internal combustion engine requirements of the Pure Range Extender from AVL permit not only the use of simplified four-stroke concepts but also the application of emission-optimized and fuel consumption-optimized two-stroke and rotary piston engines.

1 Introduction

Completely new vehicle configurations are necessary if the future demand to reduce the CO_2 emissions of passenger cars is to be fulfilled. The future powertrain cannot be an incremental optimization step but will be based on a high level of integration of mechatronic systems, such as the internal combustion engine (ICE), transmission, electric machine(s) and energy storage system (battery). The focus, however, is on their intelligent vehicle integration and the electronic control system that merges these elements for maximum customer benefit. This new combination of technologies offers the development engineer a new and fascinating degree of freedom for optimization on the basis of intensive interdisciplinary cooperation [1].

Today's electric vehicles are limited because of the costs and weight of the battery. The accumulated figure of the driving distances of all driving events illustrates that 70 % of all daily trips do not exceed 50 km, **Figure 1**. However, even for pure city vehicles, for which this percentage is shifted to even lower distances, the driver needs to be able to cover longer distances without exchanging vehicles. The AVL system approach focuses on these demands. The secure coverage of longer and less frequently required driving distances is made possible by the Range Extender, which represents a highly integrated auxiliary power source with a superior level of energy density and production costs compared to battery systems for an equivalent driving range.

The following analysis assumes a city vehicle with pure electric propulsion as the basis. **Figure 2** shows the consequence of the installed driving range on the system costs. The assumed range of battery costs of between 250 and 500 euros per kWh is based on a level of industrialization conforming to volume production. With an assumed energy requirement of 20 kWh per 100 km, the battery costs for a driving range of 160 km result in a margin of between 10,000 and 20,000 euros. With a reduction in the pure electric driving range to 50 km, which is sufficient for a city vehicle in the majority of cases, and the inclusion of a Range Extender, a cost reduction potential of between 5400 and 12,200 euros and a weight reduction potential of 275 kg (battery energy density of 80 Wh/kg) would be possible [2]. In addition, the total driving range of the vehicle would be significantly increased depending on the fuel supply of the Range Extender.

The functional requirements of the Range Extender allow two different approaches. Compared to a conventional hybrid vehicle, the electric driving range will be increased and therefore the battery will be enlarged in the first approach.

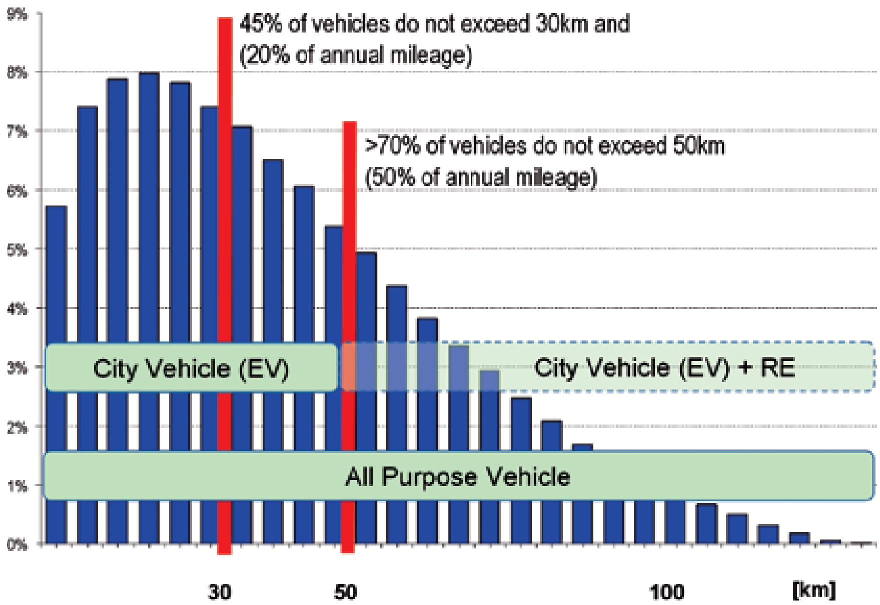


Figure 1: Statistics of all daily driving requirements in Germany

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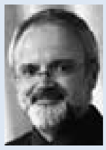

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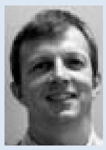

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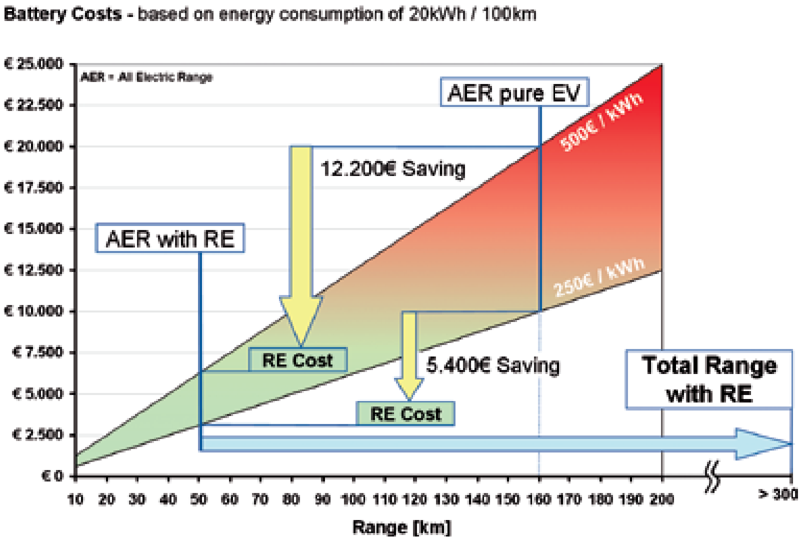


Figure 2: System cost comparison for the AVL Pure Range Extender

In return, the transmission complexity could be reduced to a mechanical direct drive system with only a single gear ratio. This approach supports the usage of existing ICE production facilities. The second approach involves a pure electric vehicle. A Range Extender without a mechanical direct drive allows an uncompromised design of the ICE for single or dual point operation. However, the dual energy conversion implies efficiency losses, which have to be compensated for by an increased electric driving range.

2 Requirement Development for Electric Mobility

Future electric vehicles will be different from those of today. The key to positioning fundamentally different propulsion configurations successfully on the market will increasingly be system optimization:
- maximization of the vehicle's energy efficiency
- application-specific optimization regarding power, driving range and production costs
- durability and dependability at least equivalent to today's propulsion systems
- high-voltage system safety
- drivability at least equivalent to today's propulsion systems.

Already existing examples for electric vehicles with Range Extender functionality are the GM Volt [3], with a serial configuration of the ICE, and the VW Twin Drive [4], which utilizes both serial and parallel hybrid functionality depending on the driving mode. Besides the topic of this article – the AVL Pure Range Extender as a serial hybrid solution – AVL is also progressing in the development of direct drive ICE configurations. These concepts consider a two-cylinder, four-stroke inline engine and especially focus on the maximum continuity of existing production facilities and processes. All approaches show that a serial hybrid can be designed completely differently based on the application requirements. Therefore, what are particularly interesting are questions regarding the optimum definition of the key powertrain components early on in the development process. The leading development methodology for propulsion systems for electric vehicles established at AVL emphasizes the following issues, **Figure 3**:
- requirements engineering
- concept development
- model-based system and component development
- use-profile-optimized system verification
- production and quality planning.

The AVL Pure Range Extender starts automatically when the battery's state-of-charge (SOC) drops below a predefined minimum battery energy reserve. The ICE operation is therefore decoupled from the silent driving experience of an electric vehicle and should not or only indirectly be noticeable by the customer. Acoustics, comfort and dependability are consequently the highest development priorities. The system should be installed in an electric vehicle and should save space, weight and especially costs. For that reason, those are the next important priorities. The priorities of the AVL Pure Range Extender development can be summarised as follows:
- lowest acoustic radiation and excitation
- dependable system availability even after a long standstill
- compact package and high power density

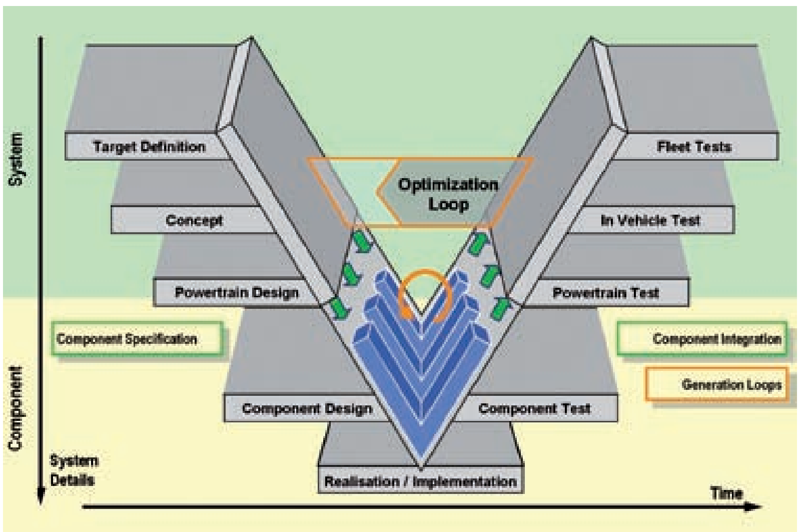


Figure 3: AVL development process

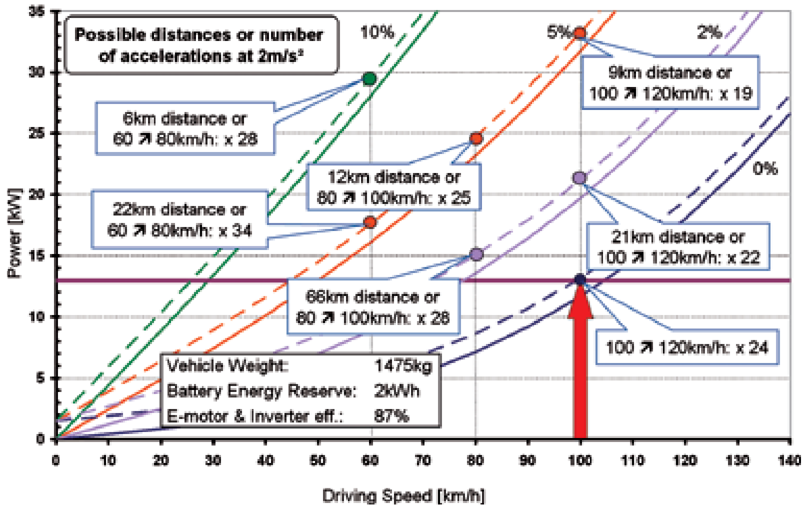


Figure 4: AVL Pure Range Extender – performance requirements/benefit of energy reserve

- low system costs, good vehicle integration properties and performance scalability
- high system efficiency.

Another design criterion for the Range Extender is its power output. This depends on several factors. The maximum power of the electric propulsion motor of the vehicle is set at a high level primarily for acceleration and for driving up gradients, and this is not necessarily required as continuous power. The Range Extender can have a smaller power output, and, during dynamic phases, the required power peaks will be covered by the addition of the battery's energy reserve. **Figure 4** shows a dimensioning diagram. The driving resistance curves for several gradients are plotted. The dotted lines represent the total power required, including the use of auxiliaries. The selected vehicle (1475 kg fully occupied) requires a propulsion power of 13 kW at a constant velocity of 100 km/h, correlating to a total electric power requirement of approximately 15 kW. With a battery reserve of 2 kWh, the total combined power allows a maximum driving distance of 21 km at a gradient of 2 % and a velocity of 100 km/h. It can also be determined what constant speeds are possible at certain gradients as well as how many accelerations can be performed at a given vehicle speed [2].

3 Range Extender as a Highly Integrated Performance Module

As a self-regulating auxiliary power supply unit for electric vehicles, the AVL Pure Range Extender can therefore be optimized for single point operation by a specific system design of the generator-starter (GS) and the ICE. Reduced development effort, reduced system complexity and optimized fuel efficiency at its defined operating point are key advantages. The complete functional, mechanical and control-specific integration of the ICE and the GS and minimum interfaces with the vehicles (electric power connections, control signals, fuel supply, cooling and mechanical mountings) allow various vehicle applications to be implemented with low development effort. An essential step in the further concept definition was the comprehensive comparison of alternative technologies for the system core functionalities. **Figure 5** shows an extract of the concept assessment for the ICE and the GS, from which the concept decision in favour of the rotary piston engine (RPE) and the synchronous permanent magnet machine has been derived, **Figure 6**. The **Table** summarizes the key specifications of the AVL Pure Range Extender.

	Combustion Engine				Generator - Starter System			
	Otto 2-cycle 1-cyl. Piston-ported balance shaft	Rotary Engine singel piston	Otto 4-cycle 2-cyl. inline balance shaft	Diesel 4-cycle 2-cyl. inline balance shaft	PM Axial Flux Disk Drmature	A-Synchronous Machine	PM Synchronous Machine	Switched Reluctance Machine
I NVH	o	++	o	–	o	+	+	–
II Package	o	++	o	o	+	+	++	o
III Weight	o	+	o	–	+	o	+	o
IV Product Cost	+	o	+	o	o	+	o	++
V Efficiency	o	–	o	++	++	+	++	o

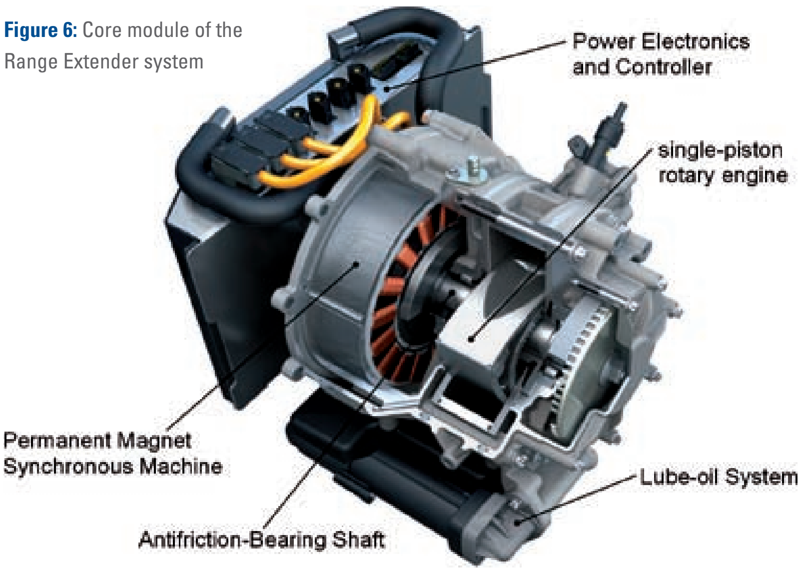
Figure 5: Technology comparison for the internal combustion engine and electric machine

3.1 Internal Combustion Engine

The RPE generally exhibits concept-specific advantages regarding power density, acoustic radiation and compactness. In addition, the known dominant concept-specific disadvantages, such as HC raw emissions, durability of the apex seals and elevated fuel consumption, can be avoided completely, or at least considerably, by the special Range Extender requirements. This presents the RPE as a concept alternative with exceptional potential compared to rather conventional approaches.

The thermodynamic engine layout was consequently carried out for the narrow specified target range of quasi-steady-state operation and a required electric output power of 15 kW. The defined engine speed of 5,000 rpm represents the optimum regarding efficiency and NVH. The specific displacement of 254 cc represents a compromise between the boundary conditions of low fuel consumption, low wear, beneficial airborne sound conditions and the required potential for a further increase in performance. Thermodynamic simulation using "AVL BOOST" has shown that different levels of performance in the range from 15 to 25 kW can be achieved with a unified geometry by increasing the mean effective pressure and engine speed. By extending the width of the rotary piston by 20 mm, the displacement increases to 357 cc and the potential electric output

Figure 6: Core module of the Range Extender system



to approximately 36 kW. Further performance categories are feasible with the multiple use of identical rotary pistons.

The centrally positioned common shaft of the RPE and the GS allows a compact design of the core unit. The high degree of shaft bending stiffness due to the short shaft length makes it possible to eliminate the GS-sided third roller bearing. The low-friction roller bearing design reduces the oil pump requirements to the needs of the rotary piston cooling. An integrated unbalance in the rotor carrier of the GS as well as a second balancing weight at the other shaft end completely eliminates the unbalance of the rotary piston, thus fulfilling the high acoustic demands. **Figure 7** shows an example of the FE simulation of shaft bending and the CFD optimization of the cooling jacket. The joint cooling circuit of the ICE and the GS is integrated into a tubeless common housing. Due to the low acceptable temperature level of the GS and the power electronics, the coolant temperature level is considerably lower (< 75 °C) than for typical conventional ICE configurations. This requires an appropriate design of the friction-relevant components. In the RPE segment of the housing, only the "hot" part of the trochoid that experiences the heat transfer from combustion is cooled. The temperature of the "cold" part is regulated by material heat conduction. The trochoid surface and the oil temperature are important for the wear and friction of the sealing components. The oil temperature is at a higher level compared to the cooling medium temperature since oil is used for piston cooling.

The engine-out exhaust emissions of the RPE, especially HC, depend on the operation (lambda, oil lubrication). Because of the integrated cooling of the Range Extender module and the electrical vehicle propulsion system, the engine will not be started with coolant temperatures lower than 30 °C. Due to the RPE-specific higher exhaust emission temperatures immediately after starting and the increased starting speeds, a shorter CAT-heating strategy becomes feasible. The first combustions can already occur in slightly over-stoichiometric conditions. This results in lower HC emissions, which, in combination with an oxygen surplus, already start secondary reactions. The emissions during a 30 min charging cycle (7.5 kWh energy charging with 15 kW power) will be lower than the emissions acceptable during a 20 min ECE driving cycle. The engine operation independent of the load or speed requirements of the driving cycle allows emission-optimized starting and catalytic converter heating procedures. The most stringent emission legislation requirements such as SULEV can be met.

3.2 Generator-starter

The GS used in the Range Extender has to fulfil requirements different from those of the electric propulsion motor of the vehicle. The functions required are basically limited to fast and low-vibration starting of the ICE and the generation of electric energy in a very limited operating range. This is possible with conventional technologies. However, the central demand of a very compact, efficient Range Extender module with minimum production costs that has been optimized for vehicle operation and achieves the re-

Table: Core specifications of the AVL Pure Range Extender

Core Specifications AVL Pure-Range-Extender	
Combustion Engine	Single-Piston Rotary Engine (RE)
Displacement	254 ccm
Engine Speed	5000 rpm
Specific Fuel Consumption	260 gr / kWh
Generator – Starter Machine	Permanent Magnet Synchronous Machine
Electric Output Performance	15 kW at 320 – 420 V (12 kW from 250 V)
Cooling System	Integrated Single-Loop Cooling System
Control System	Integrated AVL Rapid Prototyping ECU
Communication	CAN Bus
System Box Dimensions (l x h x w)	490 mm x 400 mm x 980 mm
Sound Emission	65 dBA (1m averaged Sound Pressure)
System Weight (ICE + GS Core Module)	65 kg (29 kg)
Performance Scalability (Single-Piston RE)	15 kW → 36 kW (240 %)
Interfaces Range Extender – Vehicle	HV and 12 V Connections, CAN Bus, Fuel Supply, Cooling, Acoustic Decoupled System Mounts

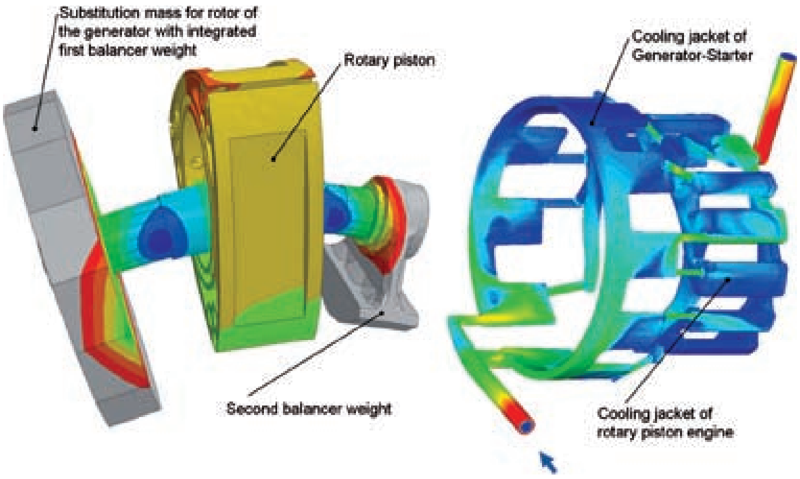


Figure 7: Simultaneous strength and CFD simulation

quired robustness called for intensive development work. Because of the package requirements and the efficiency and NVH benefits, the synchronous permanent magnet machine was selected as the base technology, Figure 5. The system optimization regarding the reduction of the overall width, weight and costs was accomplished by an suitable detail design and simulation. The GS is designed for an electric power output of 15 kW in a voltage range of between 320 and 420 V (12 kW at 250 V) and achieves a machine efficiency of up to 96 %. Further performance classes can be obtained by scaling and adaptation of the GS design. Special attention was paid to the additional thermal load caused by the ICE on the electric components. For optimum cooling conditions, the cold coolant first enters the power electronics module and the integrated GS cooling jacket and is then guided to the directly connected ICE housing.

The integrated module control of the AVL Pure Range Extender merges the functionality of the power electronics, the GS controller, the ECU and the hybrid logics in a common device, Figure 6. Expensive and sensitive sensors, such as an ICE position sensor, can be avoided by the fixed coupling of the ICE and the GS. **Figure 8** shows the control system layout of the AVL Pure Range Extender.

The complete integration of the Range Extender core module with the intake and exhaust system, the acoustic decoupled system mounts and the module ventilation system is accomplished by the module enclosure, **Figure 9**. The acoustic labyrinth damper for the incoming air and the outgoing mixture of air and exhaust emissions, as well as the damping elements of the module mounts and especially the intake and exhaust system volume and effective length are optimized to achieve an averaged 1 m sound pressure of 65 dBA provided by detailed acoustics simulations.

4 Common-part Concept for Production-optimized Application Variability

The production-oriented system layout is due in part to an optimized component design but also to the system flexibility to meet different target vehicle requirements with low additional effort. The interface design of the key system functionalities and the scalability of the RPE and the GS allow a compact adaptation of the system performance for diverse applications. **Figure 10** gives an overview of a possible Range Extender power range.

The displacement and the RPE-specific parameters (base-cycle radius, eccentricity and rotor width) were especially defined to allow a high number of performance variants of naturally aspirated single and dual rotor engines in an electric output range from 15 to 50 kW while maintaining a high degree of component commonality (side part, housing, trochoid, rotors and periphery parts). Even with an increased width of the rotor, production-similar bearing housings can be used. Due to identical key machining dimensions, components such as the trochoid housing and rotors can also be manufactured on common machining centres. The intake and exhaust system have to be adapted to higher performance classes, causing the required volume to increase approximately linearly with the system power.

The specific design of the AVL Pure Range Extender requires an end-of-line function check without the availability of a free shaft end. With its integrated generator and an external simulation device, the functional parameters of the ICE and the GS can be tested in the fully as-

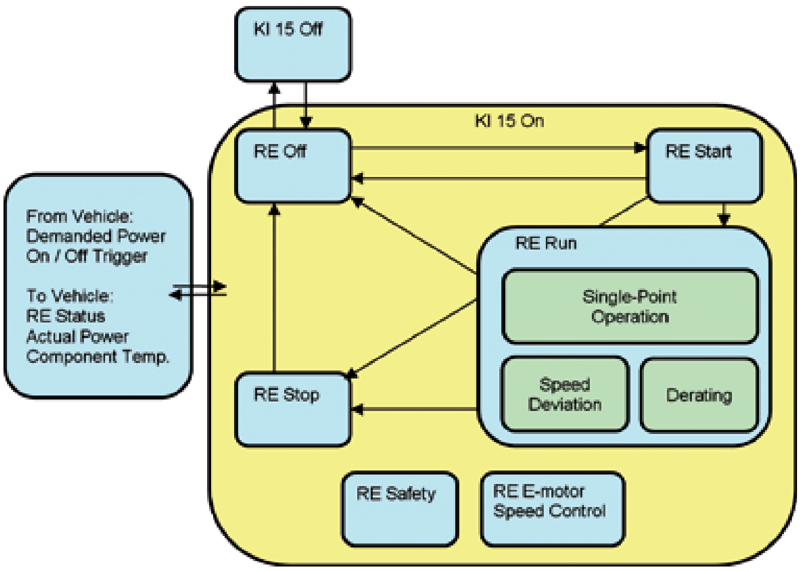


Figure 8: Concept of the system control structure

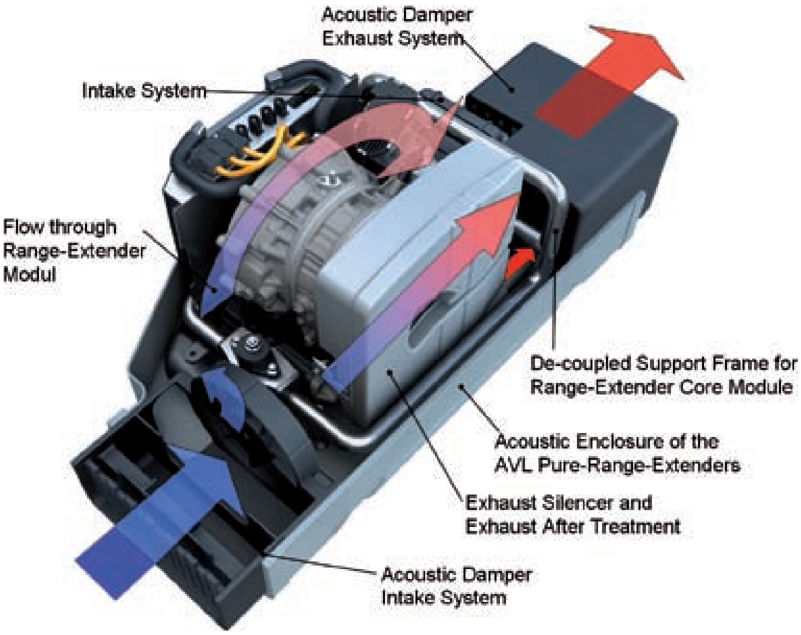


Figure 9: AVL Pure Range Extender

sembled state. The test is designed to avoid any additional modification effort.

5 Real-life Verification in an AVL Demonstrator Vehicle

The AVL Pure Range Extender system is integrated into an AVL demonstrator vehicle for the real-life validation of the AVL development processes and tools. This electric vehicle is designed as a city vehicle and equipped with a 10 kWh lithium-ion battery, which allows a pure electric driving range of at least 30 km of city driving with the auxiliaries engaged. This covers the required zero-emission driving range typically for the city. The AVL Pure Range Extender module with a power output of 15 kW guarantees independency because of its additional driving range of at least 200 km. Propelled by a synchronous permanent magnet motor with 75 kW of peak power, the vehicle accelerates from 0 to 100 km/h in about 12 s and achieves a continuous maximum speed of 100 km/h with a peak vehicle speed in excess of 130 km/h.

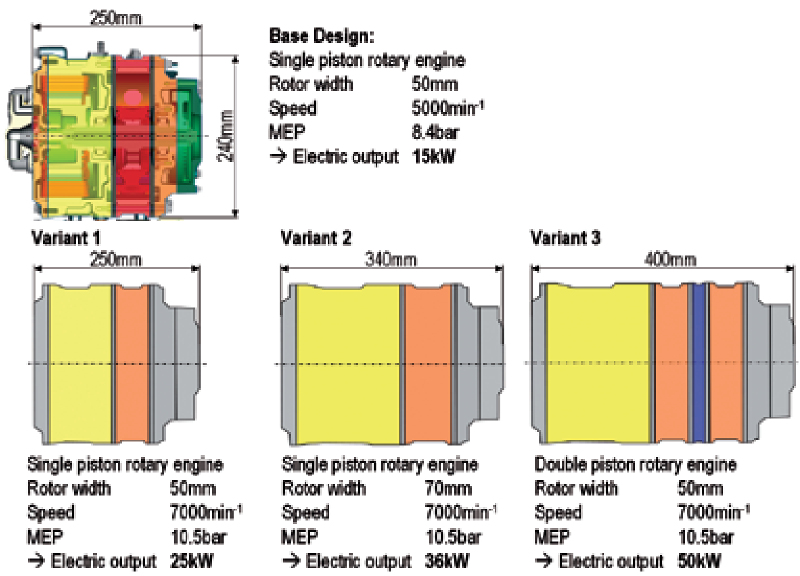


Figure 10: Performance scalability of the Range Extender core module

6 Summary and Conclusion

The AVL Pure Range Extender is a fully integrated and compact unit consisting of an ICE, GS, power electronics and controls, which provides a reassuring driving range reserve comparable to conventional vehicles when the pure electric range has been exceeded. The AVL Pure Range Extender sets new standards regarding acoustics, costs, weight and the required package volume and is therefore an essential enabler for the high acceptance and market success of electric vehicles. This system can be put into production in the short term due to its well-established technologies.

AVL concentrates on achieving an optimum balance between innovation, customer benefit and costs during the development. The AVL approach focuses on the requirement-specific optimization of the system approach, the battery as a new key technology and intelligent control concepts and system integration. Because of the continuous development tool chain in design, simulation and verification as well as the wide competence range of AVL from prototype to production, AVL's overall strength lies in a broad overview and consistent and early optimization of the electric vehicle's core functionalities.

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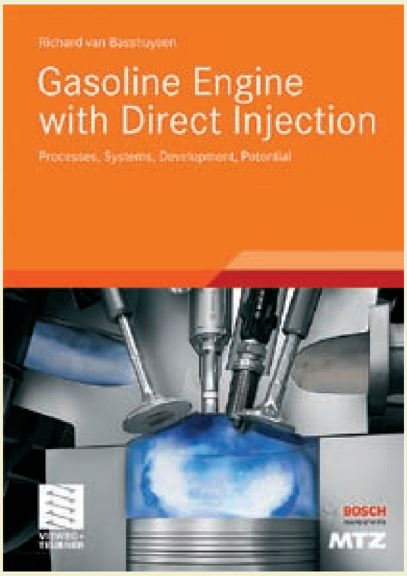

Richard van Basshuysen

Gasoline Engine with Direct Injection

Processes, Systems, Development, Potential

2009. xviii, 437 pp. With 399 Fig. Hardc. EUR 49,00
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Direct injection spark-ignition engines are becoming increasingly important, and their potential is still to be fully exploited. Increased power and torque coupled with further reductions in fuel consumption and emissions will be the clear trend for future developments. From today's perspective, the key technologies driving this development will be new fuel injection and combustion processes. The book presents the latest developments, illustrates and evaluates engine concepts such as downsizing and describes the requirements that have to be met by materials and operating fluids. The outlook at the end of the book discusses whether future spark-ignition engines will achieve the same level as diesel engines.

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Comprehensive 3D Evaluation of Honed Surfaces

The demands made of honed cylinder liners continue to rise, while the process by which their surfaces are evaluated has stagnated. By using state-of-the-art, optical 3D surface scanning techniques, a solid basis for making comprehensive, objective, and function-oriented evaluations has now been established. Developed by Daimler AG, this method has been defined in an internal company standard and facilitates the honing process providing for a consistently high level of quality by ensuring that predefined tolerance requirements are met.

1 Introduction

Honed cylinder liners, which come in a wide variety of configurations, serve as the starting point for the tribological processes that occur as the piston rings and pistons move up and down inside the lubricated engine during operation. To guarantee an optimal surface structure, functional requirements and component design are factored into the process of designing a uniform honing pattern and precisely dimensioned contact areas to yield as few drawbacks as possible. Successful implementation of these requirements is key to ensuring that the engine runs in properly and continues to operate as intended. This, in turn, reduces internal friction, oil consumption, and emissions and minimizes liner and ring wear.

Until recently, engineers had to plan, design, and finalize cylinder liner surface structures in accordance with known requirements using imprecise characterization, definition, and implementation tools. This imbalance has been corrected by instating the new honed structure evaluation method, which was developed with two main goals in mind: to realize more analytically-based design steps and ensure comprehensive quality control during series production.

2 Designing the Surface and Cylinder Liner

Previously, the Rk parameters (Rk = peak-to-valley height of the core) associated with the contact profile method [1] were generally used to establish the basic layout of the honed structure and consider the surface from an integral standpoint. The problem with this approach is that the magnitude of the defining characteristics of the surface in question remain undetected. **Figure 1** and **Figure 2** show two surfaces, with a gradual level hone, whose state of defect greatly differs. When the contact profile method is applied, however, the parameters that result lead to very similar evaluations.

In the past, elaborate analyses had to be carried out in order to distinguish all the surface characteristics of a honed structure. During these analyses, it was

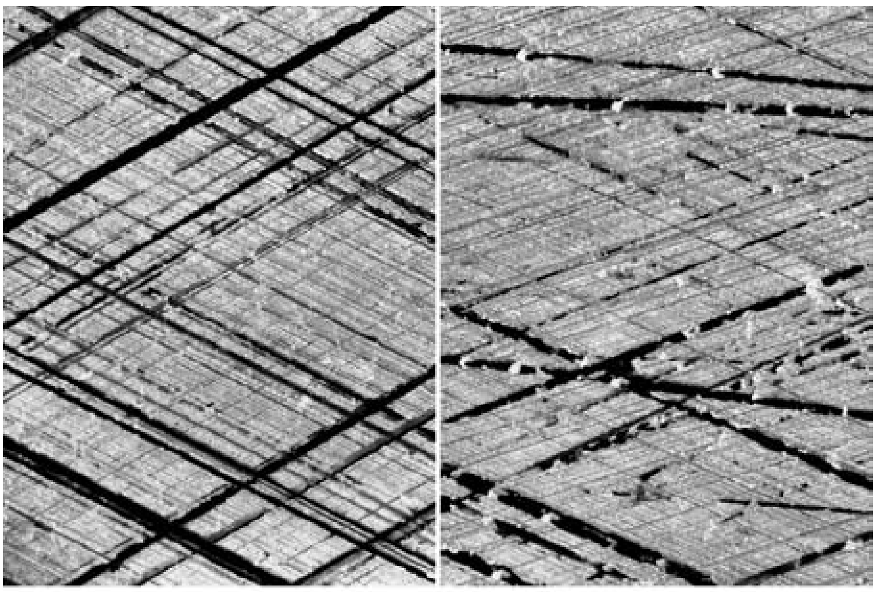

Figure 1: 3D view of honed surfaces with identical scaling; on the left: structure 1 with minimal state of defect; on the right: structure 2 with a high state of defect

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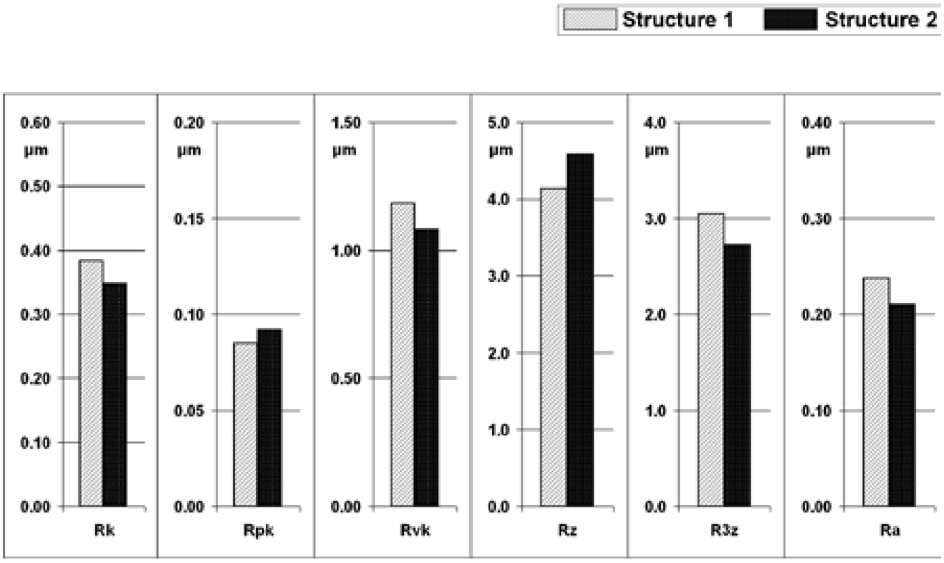

Figure 2: Contact profile parameters, determined from the profiles in Figure 1

not uncommon for the test object to become damaged. This made it next to impossible to obtain accurate repeat test results. Fax film, microscopes, X-rays and subjective interpretation in particular were used to reach a conclusion. The outcome did not accurately reflect the unique surface structure and the correlation between liner surface, component variants, and functional values was only partially understood. This made it necessary to carry out extensive, costly testing on the engine itself to ensure an optimal setup. This is where the new honing structure evaluation method comes into play, which incorporates optical 3D surface scanning technology that replaces subjective interpretations with objective evaluations based on three-dimensional parameters.

Now it is possible to analyze in detail how honed structure characteristics affect functional behavior, choose reference samples, and adapt contact areas from a standardized basis. Developing the best possible surface in line with functional requirements thus becomes considerably easier. The optimized and tested surface can also be "frozen" and assigned tolerance limits, thereby serving as a foothold for integrating the honing process into series production. It is only in this way that the liner surface will, without a doubt, match the tested and verified surface once the components fabricated for trial testing are refined to the point where they can be used in a production application without further modification.

3 Series Production of the Surface and Liner

The position tolerance of the honed structure parameters distinguishes the relevant characteristics quickly and objectively, enabling series process parameters to be defined and frozen much faster. Honing machines can, therefore, be approved and the series honing process implemented on the basis of an objective evaluation. Even after the series honing process has been implemented in line with development requirements, the function-relevant surface characteristics may only fluctuate within the tolerances set to safeguard a consistently high level of quality. To this end, monitoring the honed surface at the level of detail defined not only maintains these tolerances, but provides for detailed information about the honing process as it is affected by influencing factors such as working materials, tooling, cutting materials, and parameters. Tool changeovers and corrections to parameters can then be carried out accordingly based on the surface created.

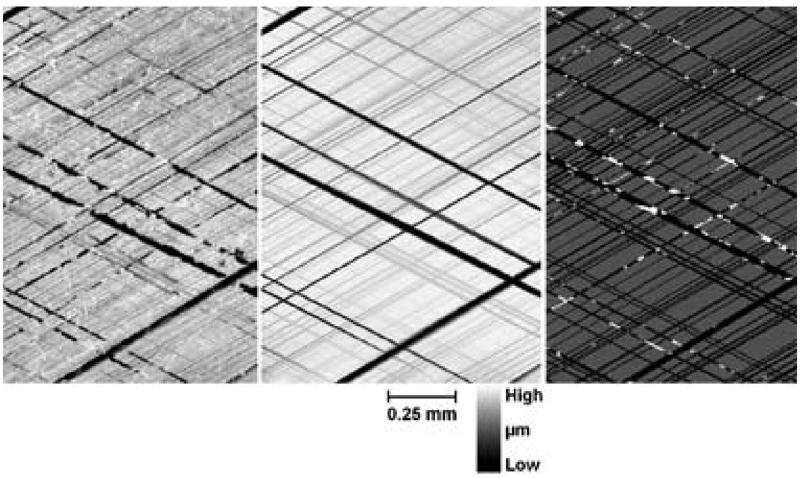

Figure 3: Sample structural separation; left: surface image excluding cylinder; center: grooving image after separation; right: relevant grooving, contact area, and sheet jacket images (binarized and superimposed)

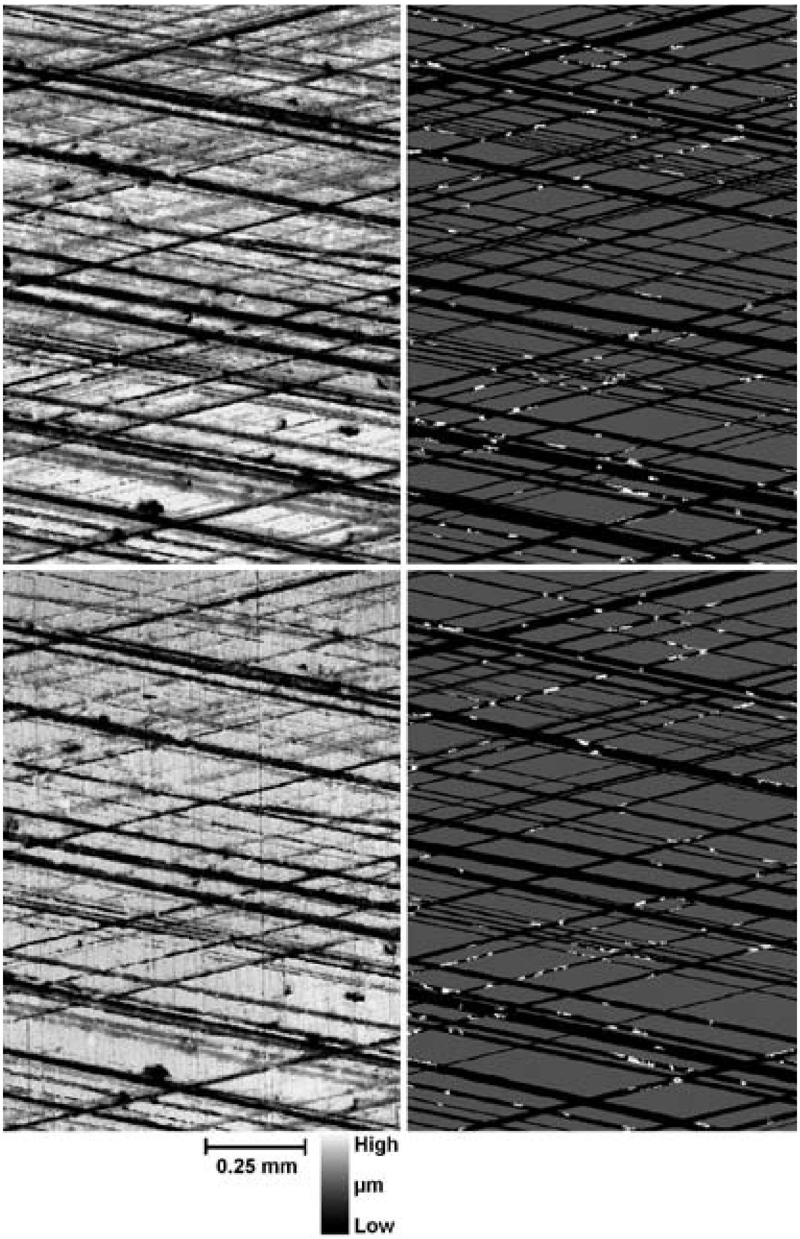

Figure 4: 3D View of a honed surface in factory condition (top) and after running in (bottom), at the identical position of the grooving, contact area, and sheet jacket image

4 Three-dimensional Surface Scanning of Cylinder Liners

An accurate and detailed 3D surface contour map must be created to apply the new honed structure evaluation method. For this purpose, scanning equipment takes surface measurements to gather a mass of information quickly. Optical 3D scanning is nothing new to Daimler AG, which has many years of hands-on experience in this area. As a result and after comprehensive test data had been collected using different methods, a decision was made to use white light interferometry as the standard means for measuring the honed structures in the cylinder bore without causing physical damage. Honed liner surfaces have fine structural characteristics that place very high demands on measuring equipment, whereby both lateral and depth resolution may need to be adapted to the structure (depending on the honing pattern) and the measuring areas to be included in the scan optimized in terms of number and size in order to make a factually correct statement. Measuring and evaluation parameters are specified in the Daimler internal standard to ensure comparability. All measurements are thus carried out using predefined, identical configurations company-wide.

5 Basics of Structural Separation

The first step toward structure-optimized parameters is identifying patterns characteristic of honed surfaces. These include grooving, contact surfaces surrounded by grooving, and remnant structures. Structural separation involves separating arranged structures as depicted in the global plotted image (original image) using adaptive image processing algorithms developed by the Department of Measurement and Control (MRT) at the University of Karlsruhe [2, 3, 4].

The algorithms were jointly adapted to the three-dimensional data sets of current honed structures as part of a project. Structural separation forms the basis of all parameters and aims to facilitate the evaluation of target, actual, and deficient structures independently of each other. The first step is to “slice” the global plotted image into grooving and contact area images and a remnant image. The result is individual images for each characteristic or a characteristic group. Examples include the overall grooving image or grooving images for particular areas such as the contact surface, sheet jacket, or surface pores, created according to specific criteria (e.g. coarse, fine, ascending, transverse). Each image can be binarized and superimposed, as **Figure 3** illustrates.

6 New Functional Parameters

The functionality and quality of a cylinder liner are determined based on the liner’s key characteristics. The parameters listed below quantify the magnitude of these characteristics. Structural separation provides a systematic approach to this end by subdividing image data into grooving, contact area, and defect structure parameters.

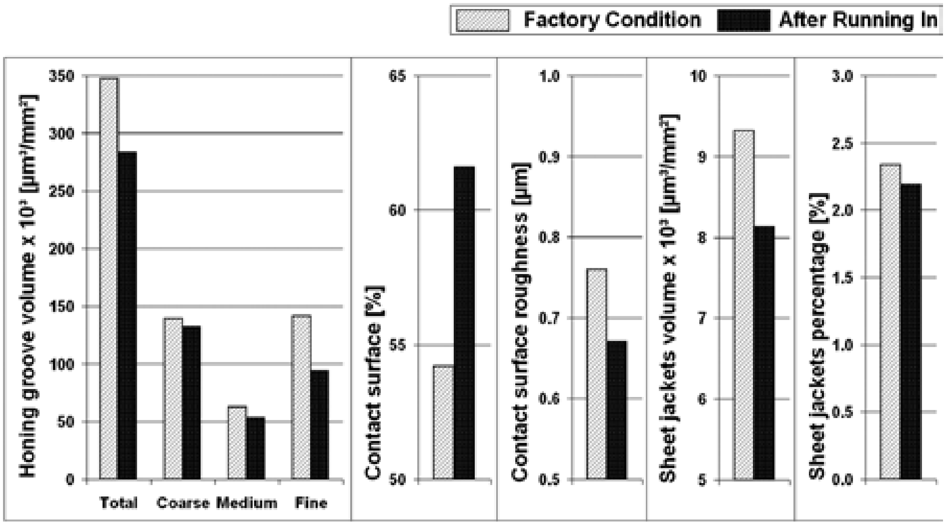

Figure 5: Comparison of new honing structure parameters of the surfaces, shown in Figure 4

Grooving parameters are defined differently, depending on the situation, with reference to volume, depth, width, density, honing angle, and uniformity. Grooving parameters are distinguished by position (e.g. inside or outside the honing angle tolerances) and type of honing groove (e.g. coarse, medium, fine).

Contact surface parameters describe the contact surface in terms of roughness and as a percentage.

Defect structure parameters are defined as surface and volume parameters with variable sensitivity for sheet jackets, marbling, and microscopic pores.

Defined parameters allow the large amount of information collected via 3D scanning to be condensed, contained, put into objective, quantifiable terms, and correlated with functional (performance) characteristics.

7 Practical Examples

Figure 4 shows the same section of a cylinder liner when new (factory condition) and after the engine has been run-in (used). In comparing the images, it becomes apparent to what extent the finely honed surface structure at the contact points has been smoothed, while the medium and coarse honed grooves remain all but unchanged. **Figure 5** shows the magnitude of several additional parameters that have been factored into the honing structure evaluation as carried out in both states. The differences in magnitude are quite clear, allowing for an objective evaluation to be made.

8 Summary

The honing structure evaluation method introduced here is already being applied at several Daimler AG locations and provides for comprehensive, objective analysis in the development and series phases. Elaborate subjective evaluation methods are thus no longer required. The defined surface parameters can be correlated with functional results, provided that additional influencing variables are held constant. Developing this method in conjunction with state-of-the-art optical 3D surface scanning technology has given rise to a new approach that greatly facilitates the process by which honed liners are designed with respect to current functional requirements and safeguards final quality in the series phase.

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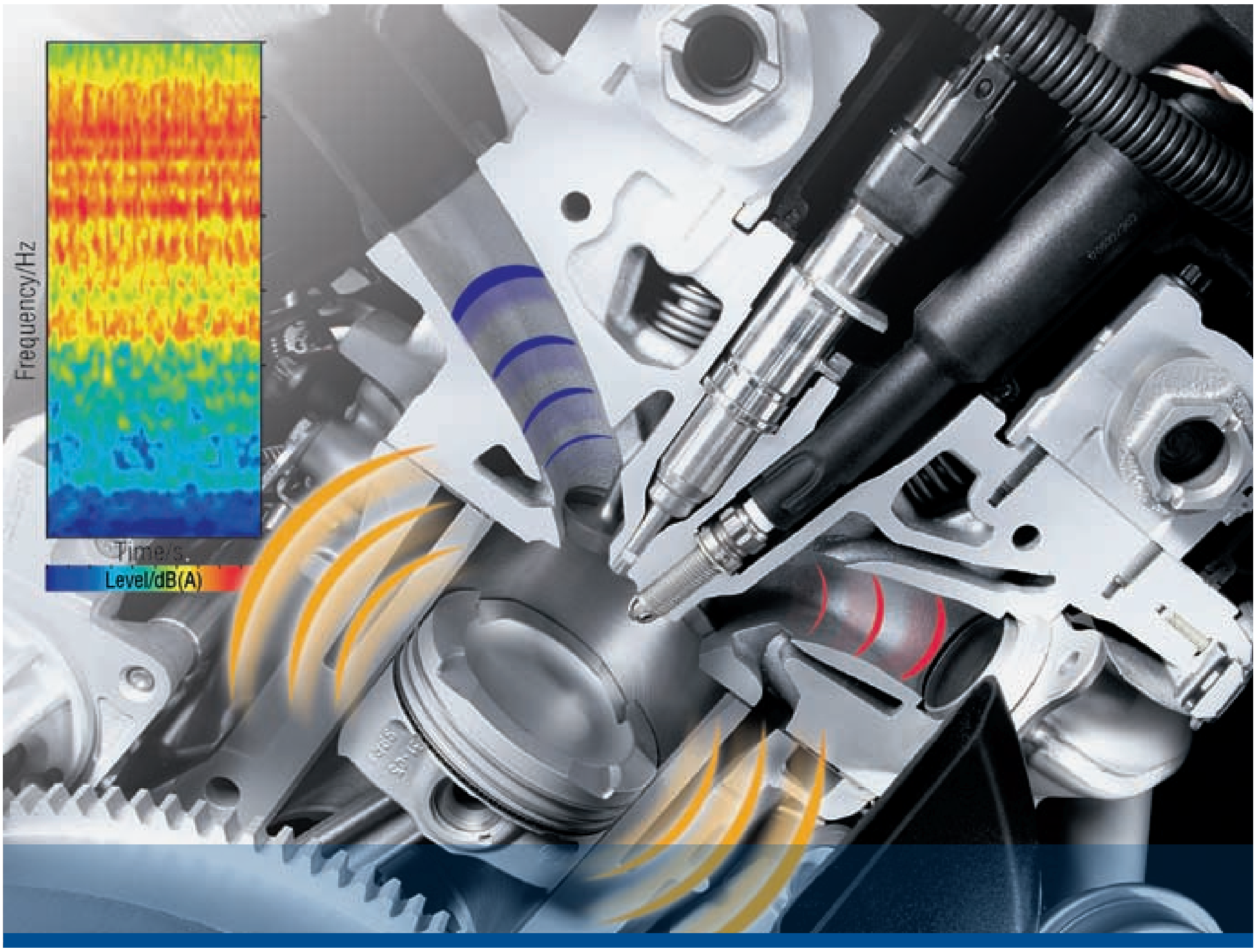


Acoustic Behavior of New Gasoline Engine Combustion Processes

The reduction of carbon dioxide emissions takes highest priority in engine development. Due to high fuel prices and an increasing ecological awareness, many customers today prefer fuel-efficient vehicles. The carbon dioxide target values of the European Union reinforce this trend. As a consequence, new part-load concepts are being developed for gasoline engines and a further downsizing is required. The acoustic behavior of these new combustion processes is in part considerably different from previous conventional gasoline engine technology. The research study No. 914 of Forschungsvereinigung Verbrennungskraftmaschinen (FVV) carried out at the Institute of Internal Combustion Engines (VKA) of RWTH Aachen University analyzed the cause-and-effect-relationship between these new charge cycle and combustion concepts and engine acoustics respectively.

1 Introduction

To achieve a further reduction of fuel consumption and of carbon dioxide emissions, new gasoline engine combustion processes have increasingly moved into the focus of engine development as they are – compared to the conventional naturally aspirated gasoline engine – more efficient in terms of thermodynamics [1, 2, 3, 4]. Two major trends can be discerned: First, engine downsizing via displacement reduction which is increasingly applied or a reduction of the number of cylinders. And second, the use of part load consumption concepts, for instance throttle-free load control by fully variable valvetrains, or lean combustion processes such as stratified charge or controlled auto-ignition. These processes are in part considerably different from conventional gasoline engine technology regarding their acoustic behavior. Yet the noise and vibration behavior has to remain acceptable to the customer.

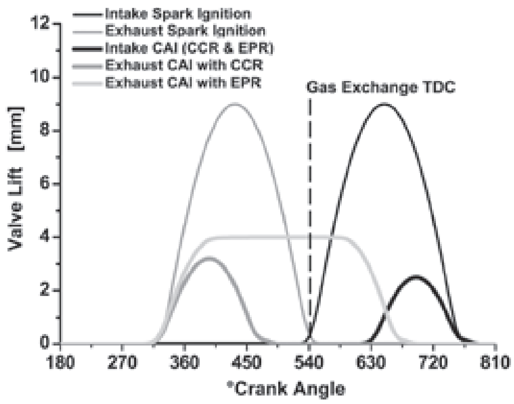
Previous studies have shown that the differences in the intake-side charge cycle noise that emerge with a throttle-free load control process result primarily from – compared with the conventional gasoline engine – considerably reduced throtteling [5]. Supercharging attenuates the pressure waves at the valve [6]. However, the supercharging device itself causes an additional pressure wave excitation which in turn depends on the applied supercharging method. In case of direct injection, other combustion focal points and higher pressure gradients can lead to a louder combustion. Gasoline engine operation with controlled auto-ignition implicates a significantly higher combustion noise excitation due to the fast fuel conversion and the involved high pressure gradients. The high supercharging rate combined with an rpm reduction (shifted load condition in the map) used in downsizing concepts [7] leads to different acoustic conditions compared with a conventional gasoline engine with the same required power output since load and speed are considerably different.

Due to these effects a combustion engine with an unmodified design of the intake air ducting and of the exhaust system can possibly become too loud. This research study investigated the cause-and-effect-relationship between the charge cycle and the acoustics as well as the combustion noise as a component of the total engine noise and the thermodynamic properties of the aforementioned new gasoline combustion processes.

2 Approach

Figure 1 gives an overview of the gasoline engine concepts investigated in the study

- PFI, λ = 1
- DI, λ = 1
- DI, boosted, λ = 1
- DI, stratified, λ > 1
- DI, CAI, CCR, λ > 1
- DI, CAI, EPR, λ > 1



Abbreviations:
PFI = Port Fuel Injection
DI = Direct Injection
CAI = Controlled Auto Ignition
CCR = Combustion Chamber Recirculation of the Residual Gas
EPR = Exhaust Port Recirculation of the Residual Gas

Figure 1: Investigated gasoline engine concepts

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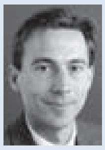

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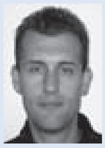

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as well as the applied valve timing. All investigations were conducted on a single-cylinder engine. For each investigated process, the engine was equipped with the specific compression ratios, piston shapes as well as the appropriate carburation device and timing. The test engine was equipped with a low-reflection intake and exhaust system in order to evaluate the pressure waves excited at the valve with as little as interference as possible. The supercharging occurred via an external supercharging unit as well as a throttle blade on the exhaust side to simulate the exhaust gas counterpressure of a supercharging device. The measurements on the single-cylinder engine were transferred for one combustion process (serving as an example) to a full engine (1.8 l displacement, direct injection, $\lambda = 1$ and turbocharging). The investigations on both test engines were accompanied by one-dimensional flow simulation calculations carried out by means of GT-Power software.

On the one hand this work investigated the influence of supercharging onto the gas exchange noise excitation at the engine valves and on the other how the charger influences the pressure waves that propagate from the valves towards the orifice. Investigations of the pressure pulsations that were induced onto the air stream by the charger itself are not implicated in this work. So the turbocharger like the throttle blade has been considered as a passive element. Influences on wave propagation from the valves towards the orifice regarding a turbocharger have later been investigated at the four-cylinder test engine.

For the internal exhaust gas recirculation that is necessary with controlled auto-ignition, two strategies were realized: combustion chamber recirculation and exhaust port recirculation. With combustion chamber recirculation, the exhaust valve is closed considerably before charge cycle top dead center (TDC) during the exhaust cycle. Thus a certain amount of residual gas remains in the combustion chamber and is compressed. During the subsequent intake cycle, the intake valve is opened considerably after TDC and the fresh charge is aspirated (negative valve overlapping). With exhaust port recirculation, the exhaust valve remains open long after charge cycle TDC which leads to the exhaust gas being aspirated from the exhaust system back into the combustion chamber. The intake valve is opened long after TDC and fresh charge is aspirated (positive valve overlapping).

3 Results

Regarding the multiple results of this work, the topics noise, fuel consumption and exhaust emissions, sound quality, switching between combustion processes, influence of supercharging but also downsizing aspects shall be described more in detail here.

3.1 Noise, Fuel Consumption and Exhaust Emissions

Figure 2 shows an overall view of noise, fuel consumption and exhaust emissions for the cycle-relevant part load operation point 2000 rpm and imep = 3 bar. The values are compared to those of a conventional gasoline engine with port fuel injection; the y-axis shows the difference regarding noise in ΔdB and regarding the exhaust emissions it depicts the percental deviation. The results are plotted against the percental reduction of the specific indicated fuel consumption. The engine noise is calculated from measured cylinder pressure data; the charge cycle excitation at the valve is based on ideal reflection-free calculations with GT-Power. Based on the geometries and test parameters, a GT-Power model for each of the two test engines was created and equipped with reflection-free intake and outlet ports at the cylinder head. From the reflection-free pressure curves resulting from the GT-Power calculations, pressure levels were calculated by means of an acoustic analysis software tool.

With direct injection and homogenous operation with $\lambda = 1$, fuel consump-

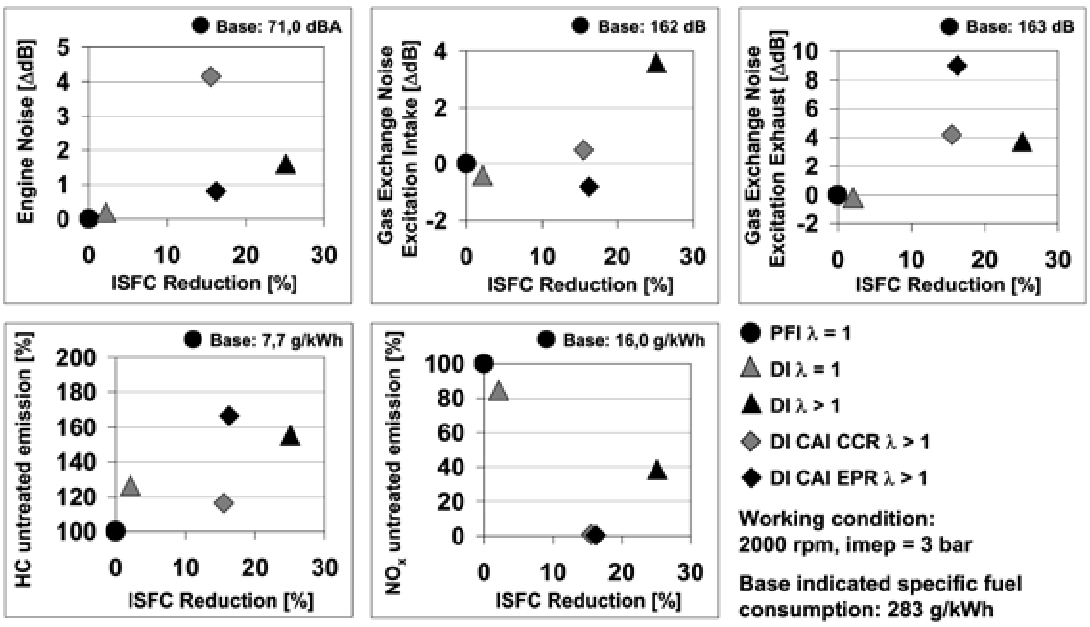

Figure 2: Noise, fuel consumption and exhaust emissions for different combustion processes at part load

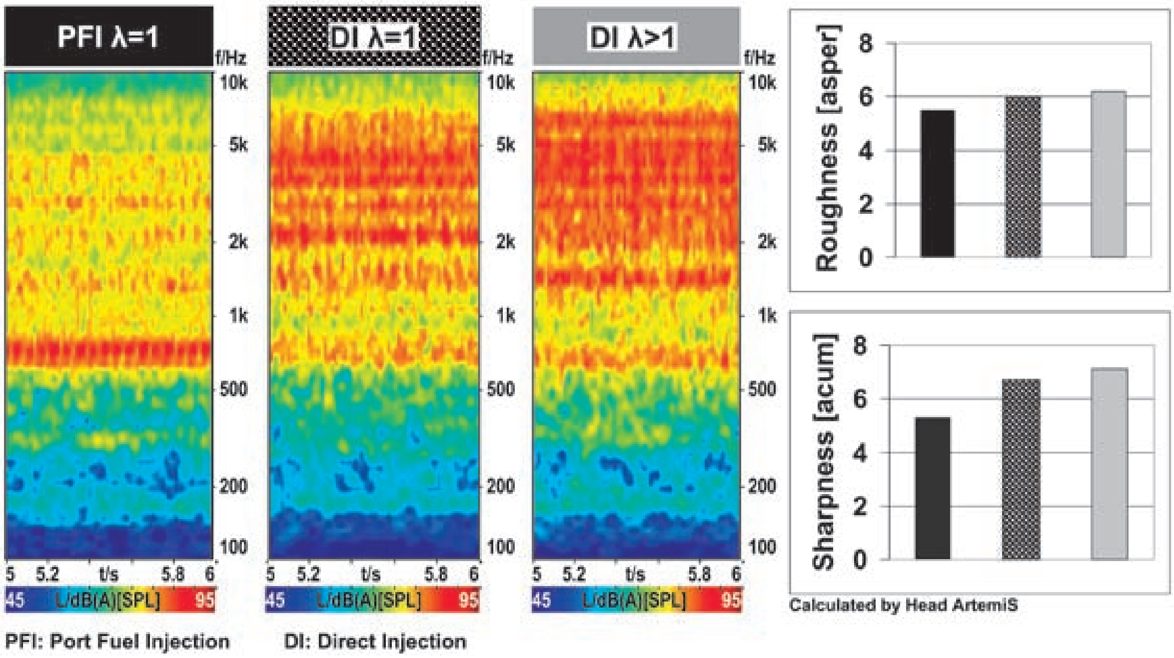

Figure 3: Wavelet analysis, PFI vs. DI at part load (2000 rpm, imep = 3 bar)

tion is slightly reduced by about 2 % due to a higher compression ratio while the noise remains nearly unchanged. With higher engine loads, the engine noise is increased by up to 1.5 dB compared to port fuel injection, since the combustion noise is increased by the faster conversion of the fuel – due the higher compression ratio. This leads to higher cylinder pressure gradients and thus higher engine noise levels.

In stratified operation with λ > 1, fuel consumption can be reduced by 25 % for this operating point resulting from the diminished throttling losses and improved medium values. The engine noise is increased in this part load point by approximately 1.5 dB which results from the early and initially faster conversion of the fuel. In addition the higher cylinder fill leads to a higher pressure level and higher gradients in the cylinder due to the dethrottling. In stratified operation, the charge cycle excitation at the valve is increased by approximately 4 dB compared with a conventional gasoline engine, since the moving mass flow rate through the valves is increased compared to the λ=1 process. Regarding fuel consumption, it must be noted that the necessary regeneration of the NO_x adsorption catalyst that is required for this process was not considered here. Due to the short-term operation at λ < 1 that is inevitable for regeneration, real fuel consumption is higher at part load.

With a 15 % fuel consumption reduction rate, controlled auto-ignition takes a middle place compared to the base, between the λ=1 process and the direct injection process in stratified operation. With combustion chamber recirculation, the engine noise level is comparatively high. It exceeds the engine noise of a conventional gasoline engine by 4 dB. This is due to the fact that the fuel is converted in a very short amount of time which leads to comparatively high pressure gradients. This constitutes a major difference to conventional gasoline engine combustion. The process with exhaust port recirculation shows a comparatively low engine noise in the examined operating point, since the engine is operated at the lower operating limit. However, with higher engine loads up to the upper operating limit, the engine noise is also considerably increased (approximately +3 dB compared to a conventional gasoline engine at imep = 6 bar).

The charge cycle excitation on the intake side with controlled auto-ignition (CAI) is on the same level as that of a conventional gasoline engine and thus below the level of the stratified engine with spark ignition which is operated – like controlled auto-ignition – with throttle-free load control. This is caused by the adapted valve timing in case of CAI compared to the full-lift timing of the spark ignition engine in stratified mode. As a consequence, the valve opening speeds and the mass flow rates are reduced which has a positive effect on the charge cycle noise.

All processes with throttle-free load control are marked by the fact that the noise radiation at the intake orifice is significantly higher compared to the λ=1 process. Due to a wide-opened throttle blade even in mid to lower part-load condition, the pressure waves propagated from the valves in the direction of the intake orifice are reflected to a considerably lesser degree than at the nearly fully closed throttle blade of a λ=1 driven engine in the same load condition. This reflection at the throttle blade is – depending on the opening angle – responsible for a significant level reduction. With throttle-free load control, the level at the orifice is up to 25 dB higher than with λ=1 (full stroke of the valves, lowest part load). By a slight throttling in the magnitude of 50 mbar [5] combined with supercharging – which has a dampening effect on the charge cycle excitation – or through a variation of the valve timing, this effect can be counteracted in case of throttle-free load control.

With CAI and exhaust port recirculation, the charge cycle excitation on the

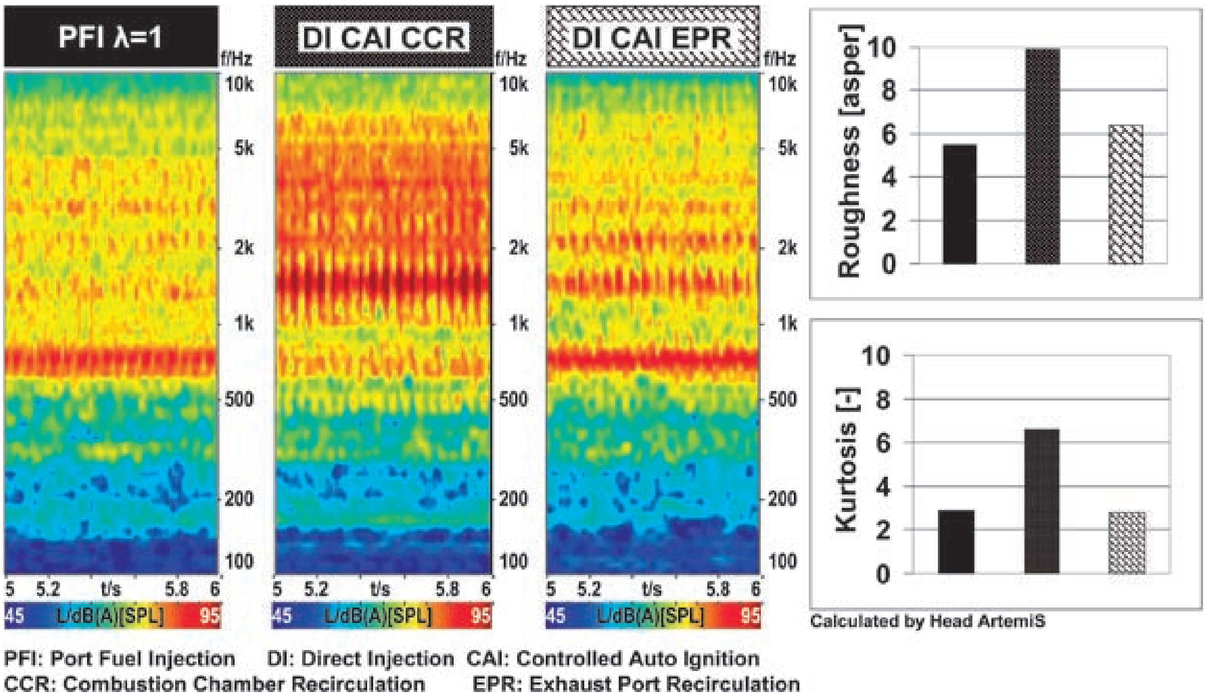

Figure 4: Wavelet Analysis, PFI vs. DI CAI at Part Load (2000 rpm, imep = 3 bar)

outlet side is conspicuously high. It exceeds the conventional gasoline engine with port fuel injection by 9 dB and thus it is considerably higher than CAI with combustion chamber recirculation and spark ignition in stratified operation with λ > 1. This is due to the re-aspiration of the exhaust gas from the exhaust system which causes a vacuum pressure wave to occur there.

Due to the process, nitrogen raw emissions are extremely low with controlled auto-ignition. Thus with such an engine and depending on the vehicle class, the Euro 6 limit values can be met – despite of a combustion air ratio greater than 1 – without any additional exhaust gas aftertreatment systems for nitrogen reduction. Such aftertreatment systems are required for spark ignition combined with stratified operation and λ > 1, even if stratified operation has a considerably lower nitrogen raw emission than a conventional gasoline engine due to exhaust gas recirculation. With all processes, an increase of hydrocarbon emissions could be observed compared to the base.

3.2 Sound Quality

Not only the noise level changes when new gasoline engine combustion processes are applied, but also the character of the engine noise is changed. The noise of a direct injection engine with spark ignition becomes sharper and rougher compared with a conventional gasoline engine, since the faster running combustion process is more high-frequent and more impulsive. This applies especially for stratified operation with λ > 1. **Figure 3** shows this effect in a time-frequency range analysis (wavelet) of airborne noise measured in the near field of the single-cylinder test engine. On the x-axis the time domain course of the sonic signal and on the y-axis the frequency content is shown. The colour intensity represents the sound pressure level. This kind of analysis facilitates an evaluation of the noise characteristics which exceeds a pure level assessment.

Due to the modified combustion process, the CAI leads to an increase of combustion noise, since very high pressure gradients occur in the combustion chamber. This is especially true near the upper operating limits. Due to the fuel being converted in a very short amount of time, the noise character is more impul-

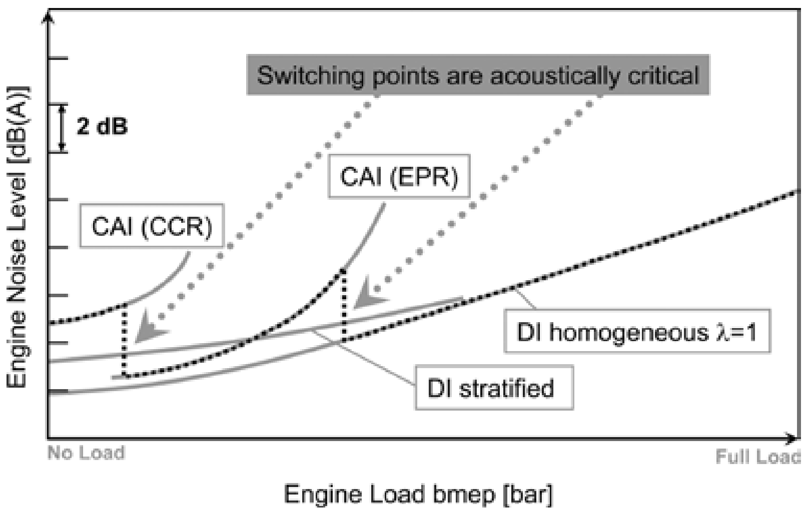

Figure 5: Process shifting problems with controlled auto-ignition (CAI)

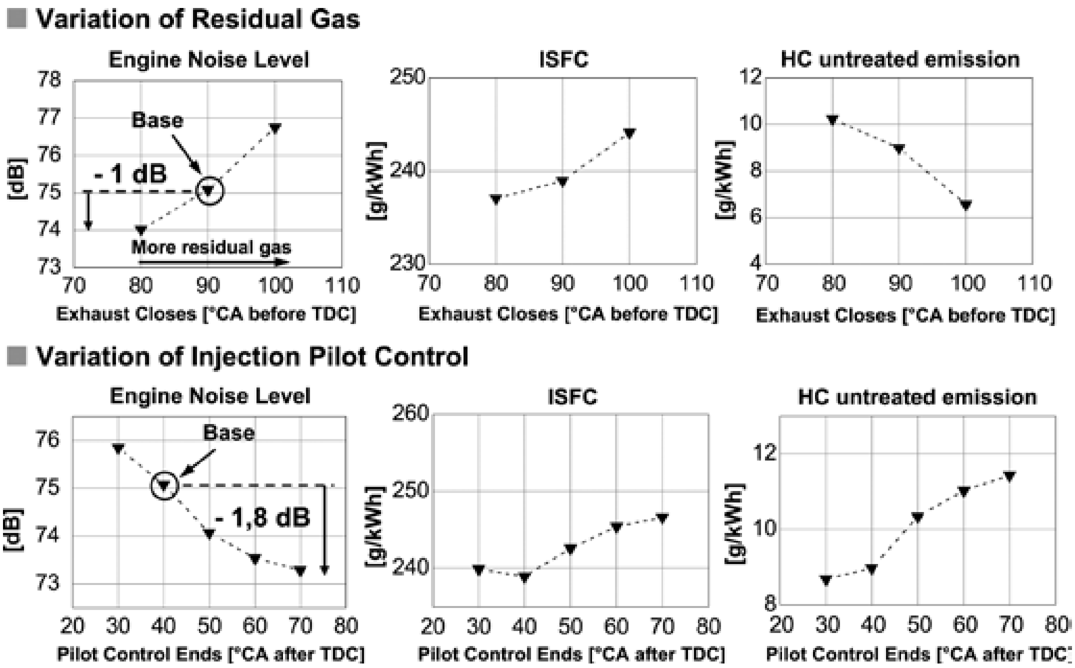

Figure 6: Parameter variation with controlled auto-ignition (2000 rpm, imep = 3 bar)

sive, rougher and louder compared to a conventional gasoline engine, **Figure 4**. Near the operating limits it resembles the noise of a diesel engine. The impulsiveness, which is expressed by the kurtosis parameter, can be clearly recognized especially in case of combustion chamber recirculation. A distinct structure can be observed in the time range for the 1 to 3 kHz frequency range. The more intense red coloring reflects the considerably higher noise level resulting from this process.

3.3 Switching Between Combustion Processes

The process "direct injection, $\lambda > 1$, stratified operation" as well as both processes with CAI are part load concepts, that means they are limited to a certain map area. With increasing load, operation must be switched to homogenous λ=1 mode. A quality analysis of the engine noise level compared to engine load for different processes is depicted in **Figure 5**. With spark ignition operation and $\lambda > 1$, the engine noise resembles with increasing load more and more an engine operated at $\lambda = 1$. Since the upper operating limit of modern stratified combustion processes is situated in a comparatively high load range (up to approximately 6 bar bmep in case of a naturally aspirated engine and approximately 10 bar bmep in case of a supercharged engine), switching to λ=1 operation is unproblematic with regard to acoustics, since the levels in the switching operating range are quite similar.

As near the operating limits the combustion noise with controlled auto-ignition is greatly increased and the noise character is very different from conventional gasoline engines, switching to a different combustion process is very problematic in terms of acoustics if the thermodynamic potential is to be exploited. The engine noise decreases suddenly at the switch points despite increasing load which occurs contrary to the driver's expectation. Moreover the noise character is changed. However, with controlled auto-ignition, the engine noise level can be lowered by 1 – 2 dB through a variation of residual gas content and injection pilot control. Only a slight increase in exhaust gas emissions and to some extent in fuel consumption can be observed, **Figure 6**. The nitrogen oxide raw emissions remain on an extremely low level due to the process.

3.4 Influence of Supercharging

Supercharging increases the engine noise at full load by approximately 1.5 dB

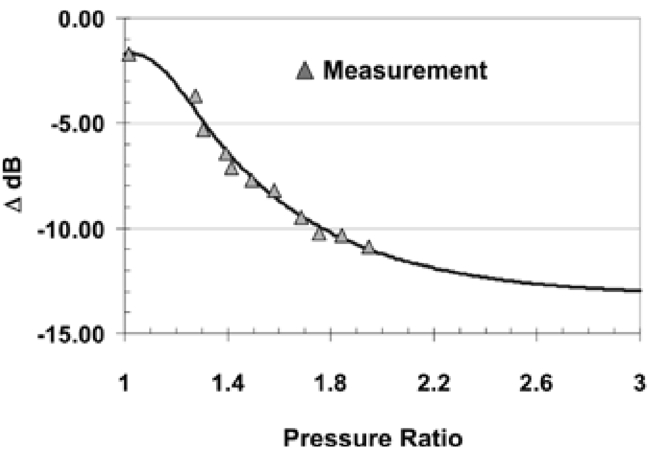

Figure 7: Attenuation behavior of a turbocharger on the intake side (load variation at 2000 rpm)

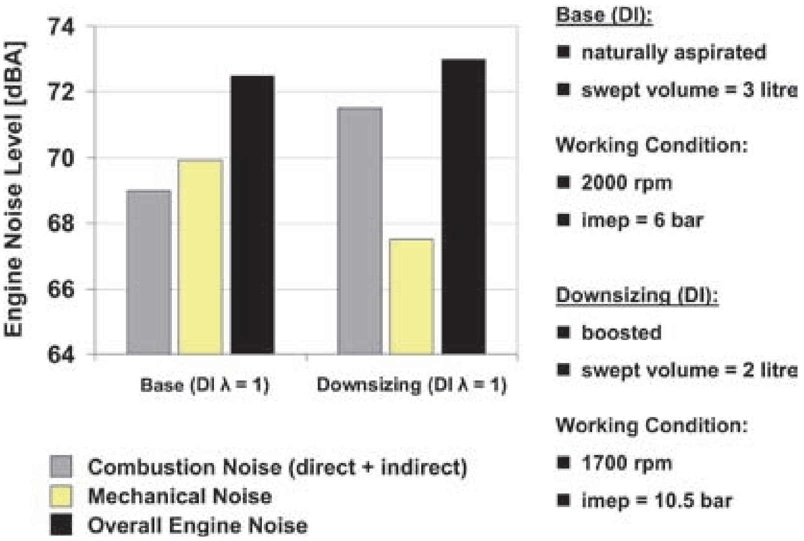

Figure 8: Noise behavior with downsizing and rpm reduction

and the charge cycle excitation is increased by 4 – 5 dB (turbocharged engine imep = 20 bar, naturally aspirated engine imep = 12 bar). The increased cylinder fill leads to a higher pressure level and steeper pressure gradients. Regarding the charge cycle noise the higher mass flow rate has a negative effect.

In case of a turbocharged engine, the charger system leads to an attenuation of the charge cycle excitation toward the orifice. The level reduction on the intake side ranges – depending on engine load and frequency – in an order of magnitude of 2 to 13 dB. **Figure 7** shows the damping which was determined at a in-line four-cylinder gasoline engine with 1.8 l displacement and turbocharger for a load variation at 2000 rpm. With a pressure ratio of nearly 1, only the restriction at the ring gab between the wheel and the spirale spring has an attenuating effect. With increasing load pressure, the increased pressure ratio, the higher mass flow rate and the higher speed of the turbocharger lead to an growing damping of the charge cycle excitation.

With regard to noise excitation at the intake orifice, dethrottled operation combined with $\lambda > 1$ and supercharging can to some extent compensate the higher excitation resulting from $\lambda > 1$ operation due to the turbocharger. Because of the damping property of the turbine on the charge cycle noise in the exhaust system, the exhaust system volume can be smaller with the appropriate design. The damping effect of the turbine on the charge cycle noise amounts in the ignition order to up to 20 dB.

3.5 Downsizing Aspects

With a downsizing concept where the naturally aspirated engine is substituted by a displacement-reduced supercharged engine with a longer transmission ratio, the engine noise can be kept constant or even reduced depending on the operating point despite the supercharging. This is due to the fact that the combustion noise is increased through the higher cylinder fill, but the mechanical noise is reduced as a result of the rpm reduction. **Figure 8** shows an example of this in which a conventional naturally aspirated engine with 3 l displacement is substituted by a supercharged engine with 2 l displacement and a transmission ratio increase by 15 %. In the following this will be referred to as the downsizing engine.

At part-load, the conventional engine is operated with bmep = 6 bar at 2000 rpm. With the same required power output, the downsizing-engine has to be operated with bmep ≈ 10.5 bar at 1700 rpm. The calculated combustion noise is increased by 1.5 dB. The mechanical noise is lowered by 2.5 dB due to rpm reduction. Since in case of the downsizing engine the combustion noise becomes level-dominant, it is louder but the level increase by only 0.5 dB for the total engine noise is negligible. If a downsizing concept is combined with rpm reduction, the engine noise can be kept constant or even reduced, since the higher combustion noise is counterbalanced by the lower mechanical noise.

4 Summary

The carbon dioxide target values of the European Union, the increased ecological awareness of customers and high fuel prices have prompted the development of new gasoline engine concepts with improved thermodynamic efficiency. Downsizing of engines or the applications of part load processes, such as stratified charge or controlled auto-ignition, offer the possibility of reduced fuel consumption. Gasoline direct injection and supercharging are already more often found on the market. These concepts differ in part considerably from conventional gasoline engines regarding their acoustic behavior.

The insights gained by this research study enable the engineer to estimate the acoustic behavior of a new combustion process and the identification of

FVV

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possible problem areas regarding noise and vibration already in an early stage of engine development. The investigations were carried out at the Institute of Internal Combustion Engines (VKA) of RWTH Aachen University during a research project of Forschungsvereinigung Verbrennungskraftmaschinen (FVV).

While gasoline direct injection combined with λ=1 operation can be realized without any drawbacks regarding acoustics, the intake orifice noise with quality control process (λ > 1) as well as the combustion noise with controlled auto-ignition near the operating limits and the thus involved switch effects have to be classified as problematic. The acoustic drawbacks however can be partly compensated by appropriate countermeasures: a combination of λ > 1 operation and supercharging as well as a variation of the valve timing can diminish the otherwise high orifice noise; a variation of residual gas content and/or injection pilot control can counteract the high combustion noise in case of controlled auto-ignition. A downsizing concept combined with an rpm reduction can keep the engine noise constant or even reduce it, since the higher combustion noise is counterbalanced by the lower mechanical noise.

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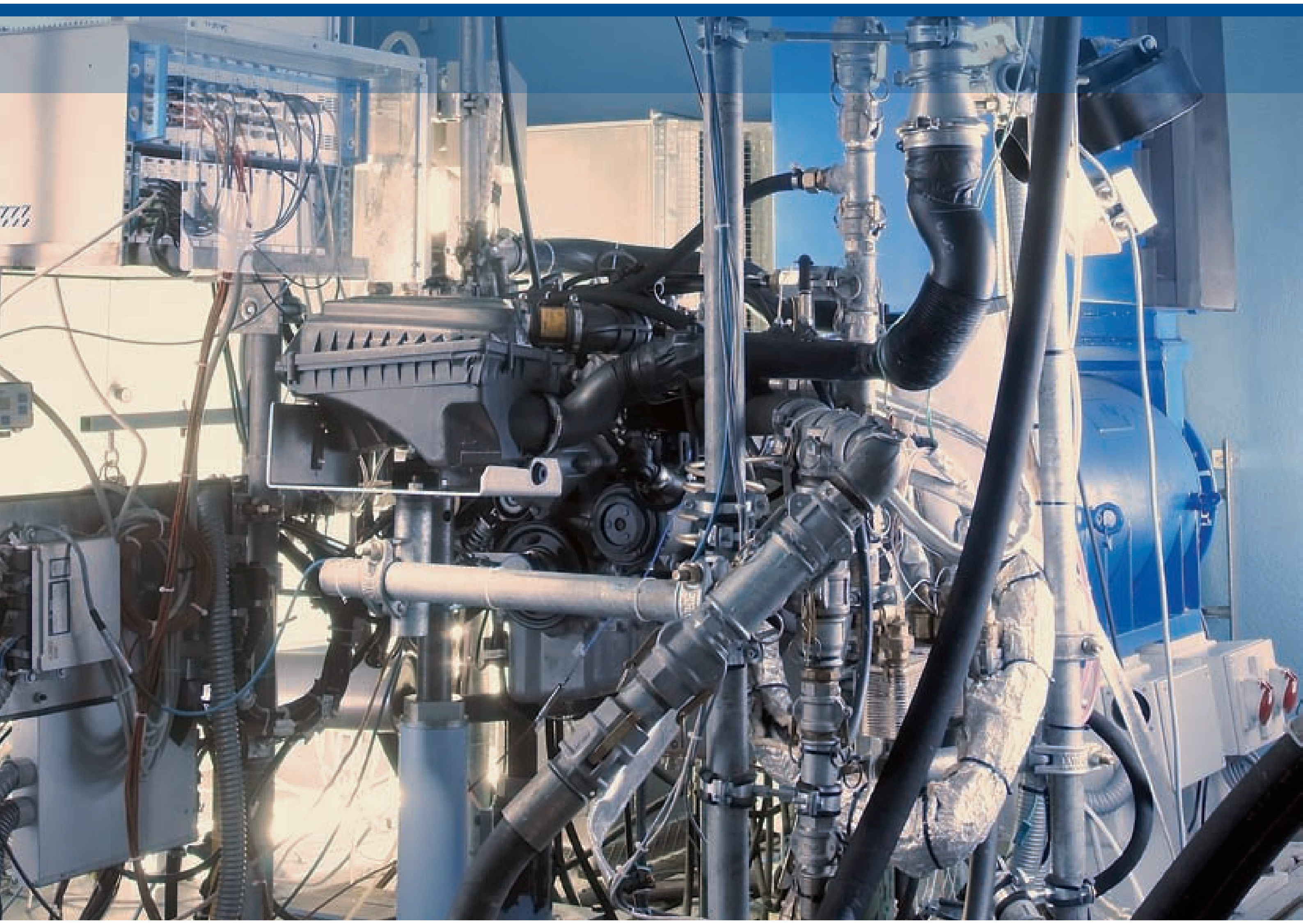
The Cylinder Module
New Simulation not only for Combustion Processes

Without doubt, the simulation of processes inside the combustion engine plays a decisive role for the optimization of efficiency level and emissions of the total vehicle. In the process, the demands on the simulation are constantly increasing, with respect to accuracy as well as due to new combustion processes and the use of alternative fuels. For this purpose, combustion and combustion chamber may no longer be viewed isolated from the total system. The seamless integration of the simulation of the "cylinder" in the gas exchange simulation and finally the simulation of the entire vehicle are of decisive important, particularly for the optimization of instationary processes. For the FVV research project No. 869, the IVK at the University of Stuttgart developed a simulation tool for the total process analysis.



1 Introduction

To implement further advances in emissions and consumption, it is necessary to be able to make statements about the behavior of the total powertrain and the vehicle at an early stage of the development. Until now, the internal combustion engine has generally been represented via characteristic maps within the simulation of the total powertrain. While this procedure ensures sufficiently short simulation times of the total model, it necessarily neglects quick changes of the boundary conditions (for example the gas exchange) like those occurring in instationary operation. It is precisely this point which presents a future focus of the total process analysis since improvements of the emission and consumption behavior of internal combustion engines are increasingly achieved by using electronic controls and controllers. For this reason, knowledge of the instationary behavior of the total system at an early development stage is desirable.

This type of module can be represented in form of a zero-dimensional or quasi-dimensional real working-process calculation. While such process calculation programs are now state of the art, they generally lack modularity. The current state of engine development shows that different combustion and charge cycle procedures must be investigated with respect to their fitness for a further reduction of the emissions and efficiency increase. To represent these different procedures within a working-process calculation, a significant development effort is generally required for the existing programs, if the structure of the software allows the necessary extensions after all (for example for six or eight-stroke procedure). For this reason, a new, fully modular, "component-style" approach for the process calculation is necessary to be able to easily integrate submodels that describe future combustion and gas exchange procedures. This was implemented with the "FVV cylinder module".

At the same time, a large number of submodels from previous FVV projects was integrated in this new cylinder module process calculation software (combustion, knocking, emissions etc.). The **Table** provides an overview of the models already contained in the cylinder module. Until now, these submodels have been independently executable at best, but could not be combined; however, they were frequently available as non-independent executable source code which, at first, had to be adopted into a (in-house) process calculation. Until now, this has been a problem when using FVV findings in the field.

The cylinder module with all its submodels from previous FVV projects offers

Table: Overview of the models already contained in the FVV cylinder module

"Zylindermodul" solver for · any number of thermodynamic systems · any number of thermodynamic zones	
new caloric approach for any fuels (burned and unburned) conventional approachs for calorics (Justi, de Jaegher, Zacharias, …)	
Combustion: · Wiebe · import from file · Barba burn rate · empirical Barba model (CI) · entrainment model (hom. SI) · Witt approach (hom. SI) · quasidim. Auer approach (CNG, with / without prechamber) · Hoppe approach (stratified SI)	**Initial values according to Zapf FVV approach for internal residual gas return** Heat transfer: · Woschni / Woschni-Huber · Hohenberg · Bargende · interface "FVV-Wandtemperaturmodell"
Other: · fuel injection (SI / CI) · fuel evaporation · knock: Franzke · knock: Worret · turbulence	Emissions models: · Zeldovich · Kožuch (NO, CI) · Heider (NO, CI) · Hohlbaum (NO, CI)
modules for gas exchange calculation (fill and empty method)	

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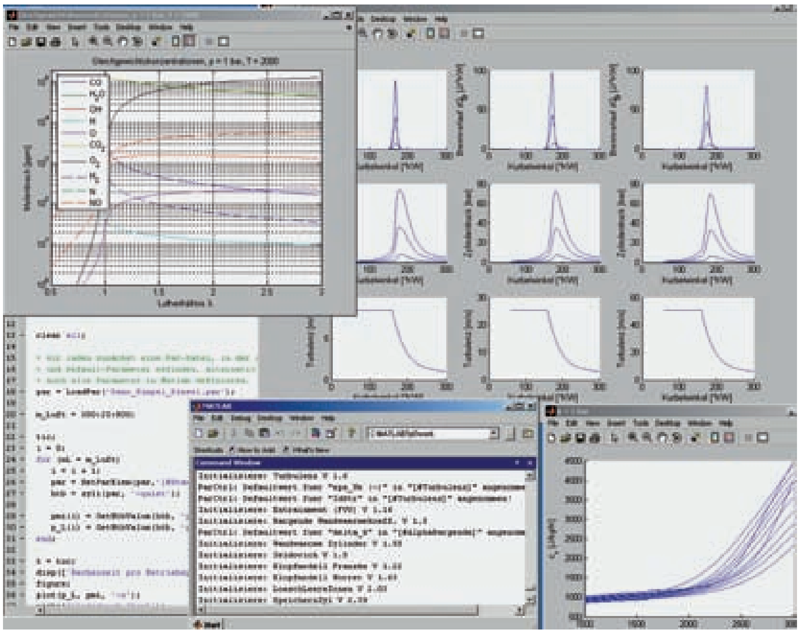

Figure 1: The FVV cylinder module in use under Matlab

the advantage that it is available as open source text as well as complete executable program (for Windows, Linux and Matlab): The cylinder module can be started immediately and used for simulations! A tutorial with more than 200 pages facilitates the introduction to the application by means of numerous examples.

2 Overview

The FVV cylinder module can be used in the following variants:

- As independent simulation software with a gas exchange simulation based on the “fill and empty” method.
- As independent simulation software that limits itself to the simulation of the high-pressure part of the working process. This is an important procedure particularly for investigating the combustion. In this case, the boundary conditions at inlet valve close must be set.
- As Matlab extension (“DLL” or “mex32”), optionally with or without charge-exchange calculation, **Figure 1**. Applications: for example the cylinder module as precise „heat source“ of the engine in a thermal management model of the total vehicle (Simulink). Or generally for automated calculations and optimizations.
- As cylinder module in the “GPA” software. This FVV-owned program can also be used to perform total system views. Until now, the cylinder or combustion could only be set there as characteristic map. Now, the cylinder module can be used which responds to changes of the boundary conditions, thereby allowing meaningful instationary simulations, **Figure 2**. Of interest: In the GPA software, the cylinder module can also be combined with the wall temperature model of the FVV (for example cold start).

The central requirement of the draft of a “future-quality process calculation” leads to the selection of an object-oriented basic structure for the simulation source code, among other things. In this object-oriented basic structure, submodels can be replaced and added at random. It is possible to compute using any number of “thermodynamic systems”, the submodels can be combined with any type of system and can also communicate among each other or couple with each other.

Previous process calculation codes supported either only a single or two-zone calculation or even a multi-zone calculation, which would then have to be solved iteratively. In the framework of the FVV cylinder module project, an analytical solution of this problem was developed that can compute as “n-zone” with any number of zones. By selecting “n = 1” or “n = 2”, the code can also work as single or two zone. Based on the analytical formulation, the n-zone solver does not feature any disadvantage with respect to speed compared to an explicit single or two-zone solver. But at the same time, it offers the flexibility, particularly in model development, to be able to activate additional zones at any time. Compared to an iterative solution of a multi-zone prob-

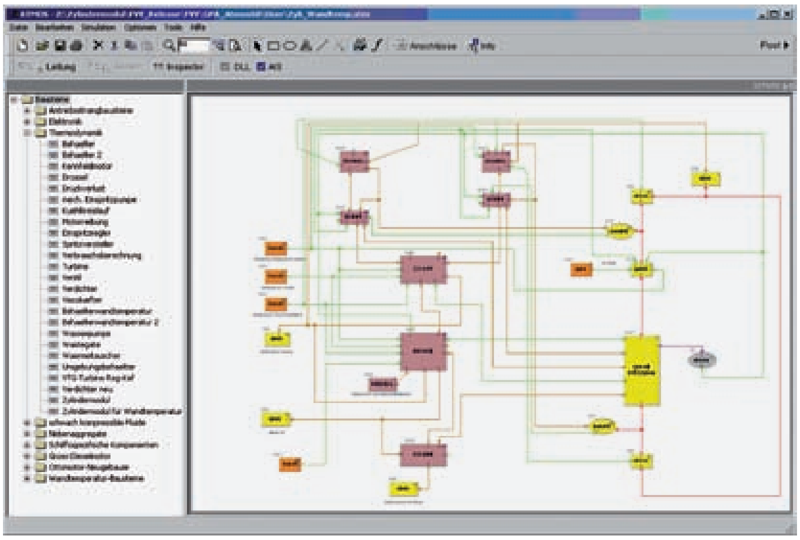

Figure 2: The cylinder module integrated in GPA. It is connected with “containers” for gas-exchange simulation and with elements for simulating the wall temperatures of cylinder liner, cylinder head, piston and valves

lem that has been customary until now, the analytical solver offers enormous advantages with respect to speed.

In current process computing programs, the known models from Justi, Zacharias and de Jaegher are generally to represent the properties of the working gas. They represent the required caloric variables, such as the individual gas constant, the specific inner energy and its partial derivatives. These models were each developed for a certain fuel composition and can be applied to new, alternative fuels, such as E85, natural gas or hydrogen, only to a delimited extent – or not at all. For this reason, a caloric approach for freely definable fuels was developed in the framework of the cylinder module project.

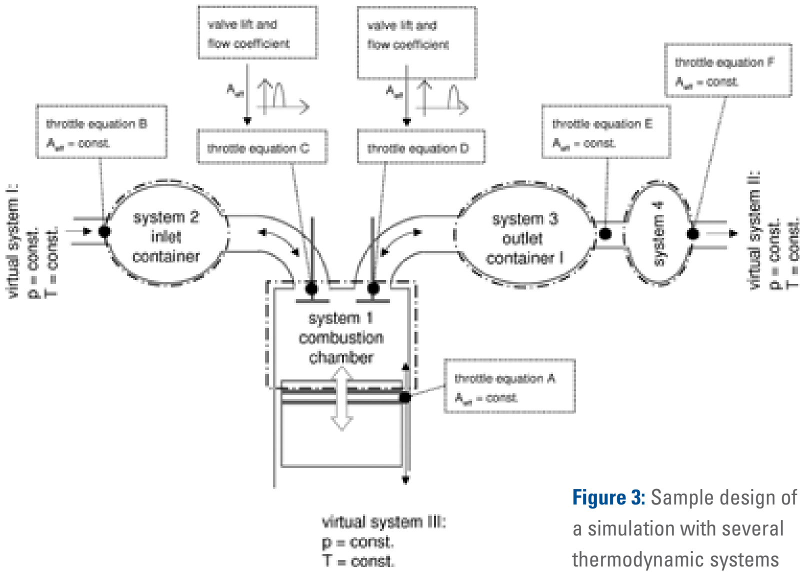

Figure 3: Sample design of a simulation with several thermodynamic systems

3 Object-oriented Process Calculation

Figure 3 shows an example for a simulation with gas exchange according to the fill and empty method with four thermodynamic systems. “System 1” is the combustion chamber with variable volume (piston movement) and it is modeled as two-zone. “System 2” represents the intake system. This can be modeled as single-zone or two-zone; for a two-zone representation, residual gas flowing back from the combustion chamber is stored in a separated zone. The two outlet containers are calculated as single zone systems 3 and 4.

“Simulation modules” can now be integrated into every system. A Wiebe combustion, for example, is a “simulation module”. The Wiebe combustion is typically linked with the “combustion chamber” system. However, it is irrelevant to the cylinder module solver – any “simulation module” can be linked with any system. This makes the cylinder module very flexible. Just a short time ago, it would have been difficult to image that a combustion could take place in an outlet container. Now, such a configuration in the context of exhaust gas aftertreatment is justified. Or: For a prechamber engine, the combustion can also act in the independent “prechamber” system. And: At the same time, the “Wiebe combustion” simulation module can also be “integrated” three times: Once for the actual combustion chamber, once for the outlet container and once for a prechamber. This simulation module is then activated in three “instances”, each instance calculates independently and is parameterized differently for the corresponding specific application.

But back to Figure 3 showing the charge-exchange calculation as an example. This Figure 3 depicts six instances of the “throttle equation” simulation module. The leakage (blow-by) flows via “throttle equation A” past the piston rings into the crankcase, which is represented as a “virtual system” with constant pressure and constant temperature. Intake and exhaust valve respond via “throttle equation C” and “throttle equation D” whose flow cross-section A_{eff} is controlled on a time variable basis by valve modules. This “valve” simulation modules are coupled internally with the corresponding “throttle equation” simulation module and provide the time-variable flow cross-section A_{eff} depending on time, valve stroke and flow coefficients. If A_{eff} equals zero, the valve is closed. Intake and outlet containers are also connected with the environment (“virtual system”) or among each other (between “system 3” and “system 4”) via “throttle equations”.

In summary: The cylinder module solver can solve the thermodynamic basic equations for any number of systems and zones. The cylinder module consists of a large number of “simulation modules”. The user decides which simulation modules should be “activated”, and on which systems and zones they should act or with which other simulation modules they should “communicate”. It is also possible to integrate or “activate” simulation modules multiple times, that means in several instances.

4 Calorics for any Fuel

Process calculation uses two central equations of thermodynamics: The instantaneous energy balance (first law of thermodynamics) and the thermal state equation of the working gas. These two equations are required in differential form for process calculation:
First law of thermodynamics:

$$\frac{dQ}{d\varphi}+\frac{dH}{d\varphi}-p\cdot\frac{dV}{d\varphi}=u\cdot\frac{dm}{d\varphi}+m\cdot\left(\frac{\partial u}{\partial T}\cdot\frac{\partial T}{d\varphi}+\frac{\partial u}{\partial p}\cdot\frac{dp}{d\varphi}+\frac{\partial u}{\partial\lambda}\frac{d\lambda}{d\varphi}\right) \qquad \text{Eq. (1)}$$

Thermal state equation of the working gas:

$$p\cdot\frac{dV}{d\varphi}+V\cdot\frac{dp}{d\varphi}=m\cdot R\cdot\frac{dT}{d\varphi}+\frac{dm}{d\varphi}\cdot R\cdot T+m\cdot T\cdot\left(\frac{\partial R}{\partial T}\cdot\frac{dT}{d\varphi}+\frac{\partial R}{\partial p}\cdot\frac{dp}{d\varphi}+\frac{\partial R}{\partial\lambda}\cdot\frac{d\lambda}{d\varphi}\right) \qquad \text{Eq. (2)}$$

The caloric material properties of the working gas refer in the following to the specific internal energy, the specific enthalpy and the individual gas constant, as well as the partial derivatives of these three variables. These caloric properties are shaded gray-blue in Eq. (1) and Eq. (2).

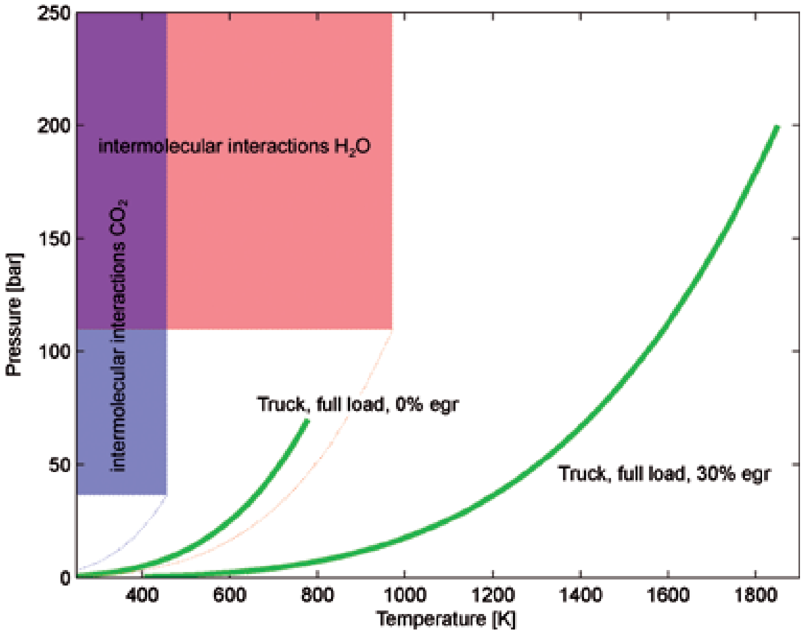

Figure 4: Temperature ranges in which intermolecular interactions in the calorics must be taken into account

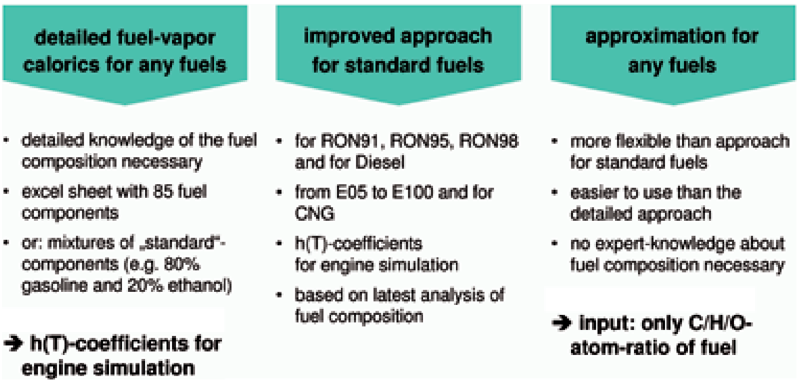

Figure 5: Approaches for calculating the fuel vapor calorics in the cylinder module

The number of marked variables informally leads to this: Without knowledge of these caloric properties, no meaningful process calculation is possible.

So far, these variables were generally calculated using the approaches of Justi, Zacharias or de Jaegher. Each of these models were, however, developed for a specific fuel composition and can be applied to new, alternative fuels only to a limited extent – or not at all. Since the importance of alternative fuels will undoubtedly increase, a new calorics approach was also developed in the framework of the FVV cylinder module project.

Creating a truly universal calorics for any type of fuel was a great scientific challenge. Since the calculation foundations have already been published several times [3, 1, 2], the focus below will be on the application of the new approach. In calorics, a distinction must be made between the burned gas calorics, which is responsible for burned gas (exhaust gas and returned residual gas) and air, and the calorics for unburned fuel vapor.

4.1 Burned Gas Calorics

The new burned gas calorics were developed for freely definable fuels. The fuel is defined via its C/H/O/N atomic ratio. A equilibrium calculation is performed for the respective fuel, the current temperature, pressure and air ratio. It provides the concentrations of the most important chemical species in the combustion chamber. The dissociation, that means the breakdown of molecules into radicals at high temperatures and, therefore, the real gas behavior, are also represented. The calorics of the gas mixture are then calculated via a "component approach" from the concentrations and properties of the individual species.

The intermolecular interactions were not taken into account. Such effects must be considered only if the temperature is lower than 1.5 times the "critical temperature" and the pressure reaches at least 0.5 times the "critical pressure". These "critical" areas, including the listed safety

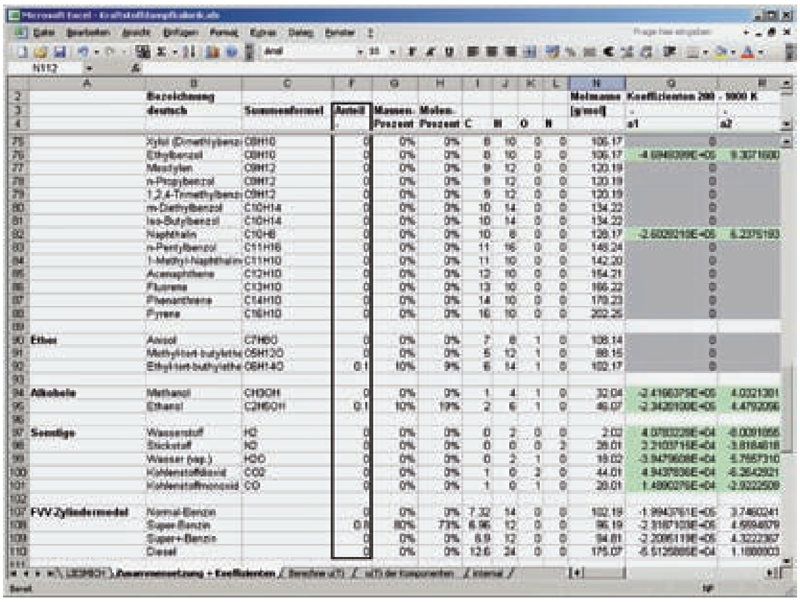

Figure 6: Input window of the detailed fuel vapor calorics

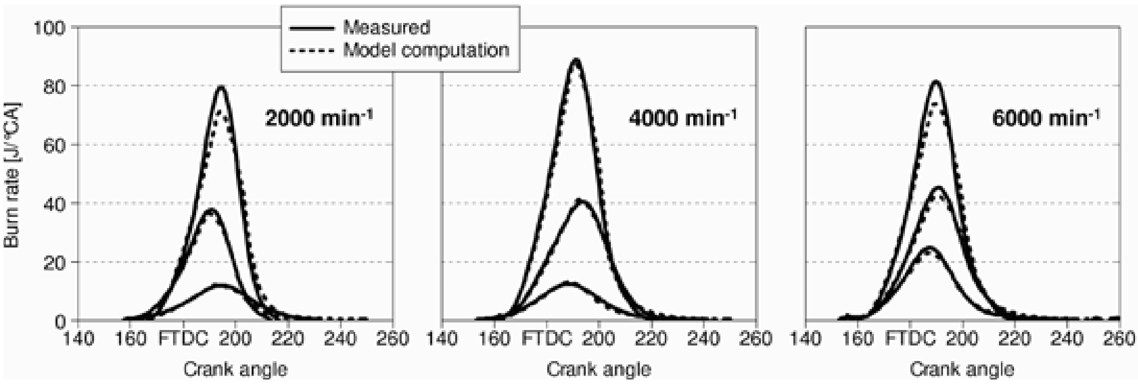

Figure 7: Burn rates simulated with the cylinder module (quasi-dimensional entrainment model) compared to measuring data (2000, 4000, 6000 rpm of part load to full load, passenger vehicle spark-ignition engine)

factors for CO_2 and H_2O, have been included in **Figure 4**, all other components are negligible. The "critical" combination of very low temperatures and high pressures can practically not be achieved in the combustion chamber. The closest approximation occurs at high supercharging with external exhaust-gas recirculation and strong charge-air cooling. A present-day commercial vehicle engine, which is operated at high EGR rates even under full load, serves as an example in the following. Figure 4 shows the compression graph of a commercial vehicle full load point with 30 % EGR that runs at a clear distance to the areas in which intermolecular interactions must be considered. The figure also shows a compression graph with 0 % EGR. By increasing the compression ratio, the „critical area" could be reached, but it would once again be unproblematic since there would be no significant H_2O concentration in the combustion chamber during the compression without EGR.

The new calorics approach is first integrated into the cylinder module process calculation. For purposes of comparison or backward compatibility, it is also possible to select the approaches according to Justi, Zacharias or de Jaegher. If the cylinder module calorics are to be integrated into another simulation software, it can also be done without any problems. The source text is available with detailed documented interfaces as Fortran code. An integration into C/C++ is also possible via the corresponding and included interfaces.

In addition, a Matlab interface of the cylinder module calorics is available. It allows the caloric properties or equilibrium concentrations to be calculated quickly and conveniently from within Matlab.

4.2 Fuel Vapor Calorics

The cylinder module contains three approaches for calculating the fuel vapor calorics, **Figure 5**.

All three approaches are integrated in the cylinder module process calculation, but they are also available as Fortran and Matlab source text for adoption into own projects. The core of the detailed approach (1) is an Excel table that is part of the cylinder module download. It contains the caloric data of approximately 80 of the most important fuel components. The composition of the desired fuel must be entered in the "Anteil" column, **Figure 6**; afterwards, calorics coefficients for the process calculation are output at the bottom of the table. In this calorics table, it is also possible to mix "complete" standard fuels with additional components. For example, a "biofuel" with 80 % super gasoline, 10 % ethanol and 10 % ETBE can be calculated.

5 Application

Figure 7 shows the simulation of a spark-ignition engine with a quasi-dimensional

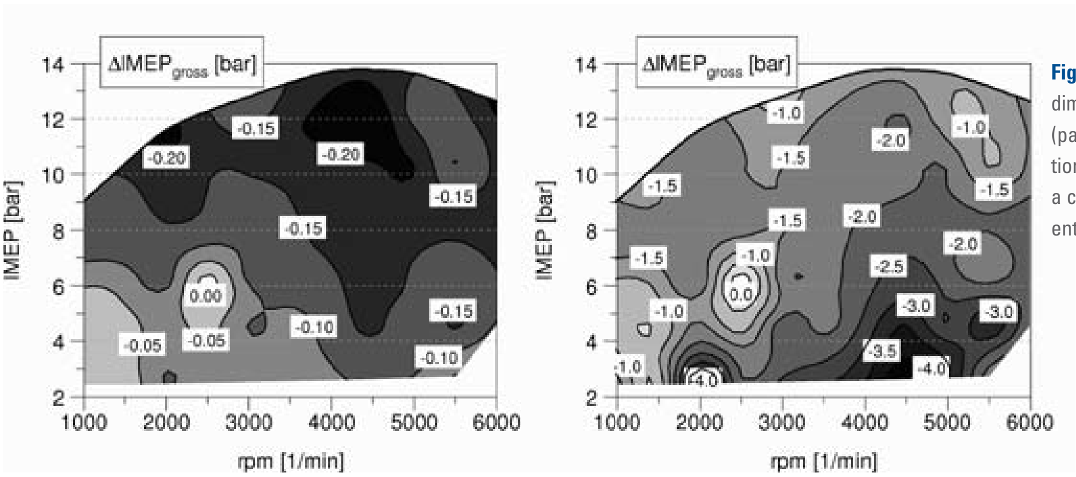

Figure 8: Accuracy of quasi-dimensional combustion models (passenger vehicle spark-ignition engine) for calculation with a constant parameter set in the entire engine map

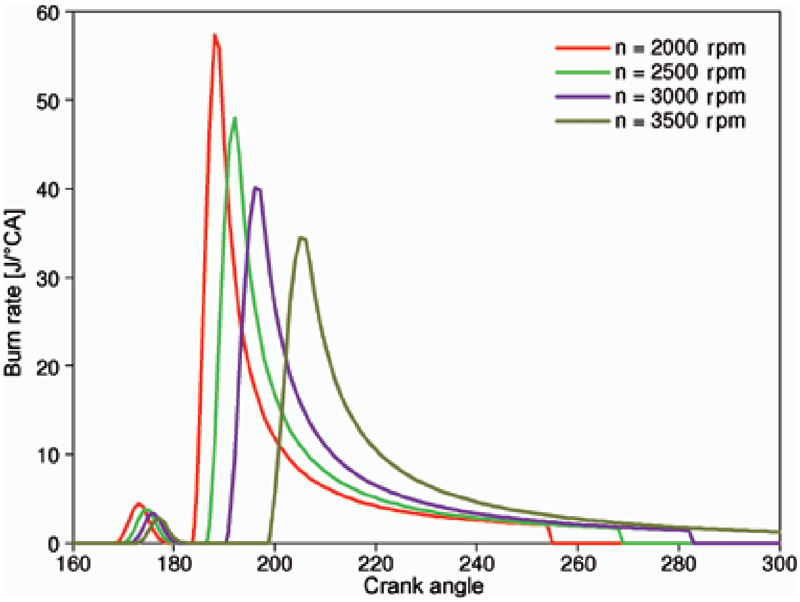

Figure 9: Engine speed variation with constant injection timing simulated with the Barba model (passenger car diesel engine)

entrainment model as an example for the application of the cylinder module. This combustion model must be calibrated at one operating point and can subsequently predict the change of combustion with a change of the operating point (engine speed, load, residual gas content) or the boundary conditions (charging pressure, intake temperature, turbulence).

It can be seen in **Figure 8** that the model can forecast the changes of the burn rate in reality very well. **Figure 9** shows the empirical Barba combustion model for a passenger car diesel engine using speed variation (with constant injection) as an example.

The cylinder module software can be downloaded from the ProMeta server of FVV as a compressed file. This download packet contains an extensive, three-volume documentation: The tutorial and reference manual as first volume (220 pages) is intended to provide a quick, simple and comprehensible introduction into the application of the FVV cylinder module by means of examples. At the same time, it serves as a reference for the parameterization of the individual submodels. The examples of the tutorial are contained in the packet and completely parameterized so that they can be "executed" immediately. They come from a variety of areas (gasoline and diesel engine, predictable models, emission and knock modeling, gas-exchange calculation, alternative fuels, Matlab integration etc.), so that a specific setting of a task can quickly be tackled by using a similar example.

The final report (240 pages) as the second volume of the documentation describes the scientific problem and the solutions established in the framework of the project. This applies to the creation of the new calorics approach, the setup of the object-oriented process calculation, the development of the multizone solver, but also sensitivity analyses concerning the influence of various assumptions and model parameters in the process calculation.

The programming manual (50 pages) as the third volume of the documentation is intended for those who want to insert their own models into the cylinder module. Such an expansion of the cylinder module, for example, has already taken place in the FVV project "combustion models of lean-mixture concept spark-ignition engines", which was processed at the LVK in the Munich University [6]. The models developed in this project are already integrated in the current version 1.1 of the FVV cylinder module. This has already shown how model developments of other research facilities can be integrated into the cylinder module without any problems and are then also available to the user in an immediately usable program in addition to the open source text.

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