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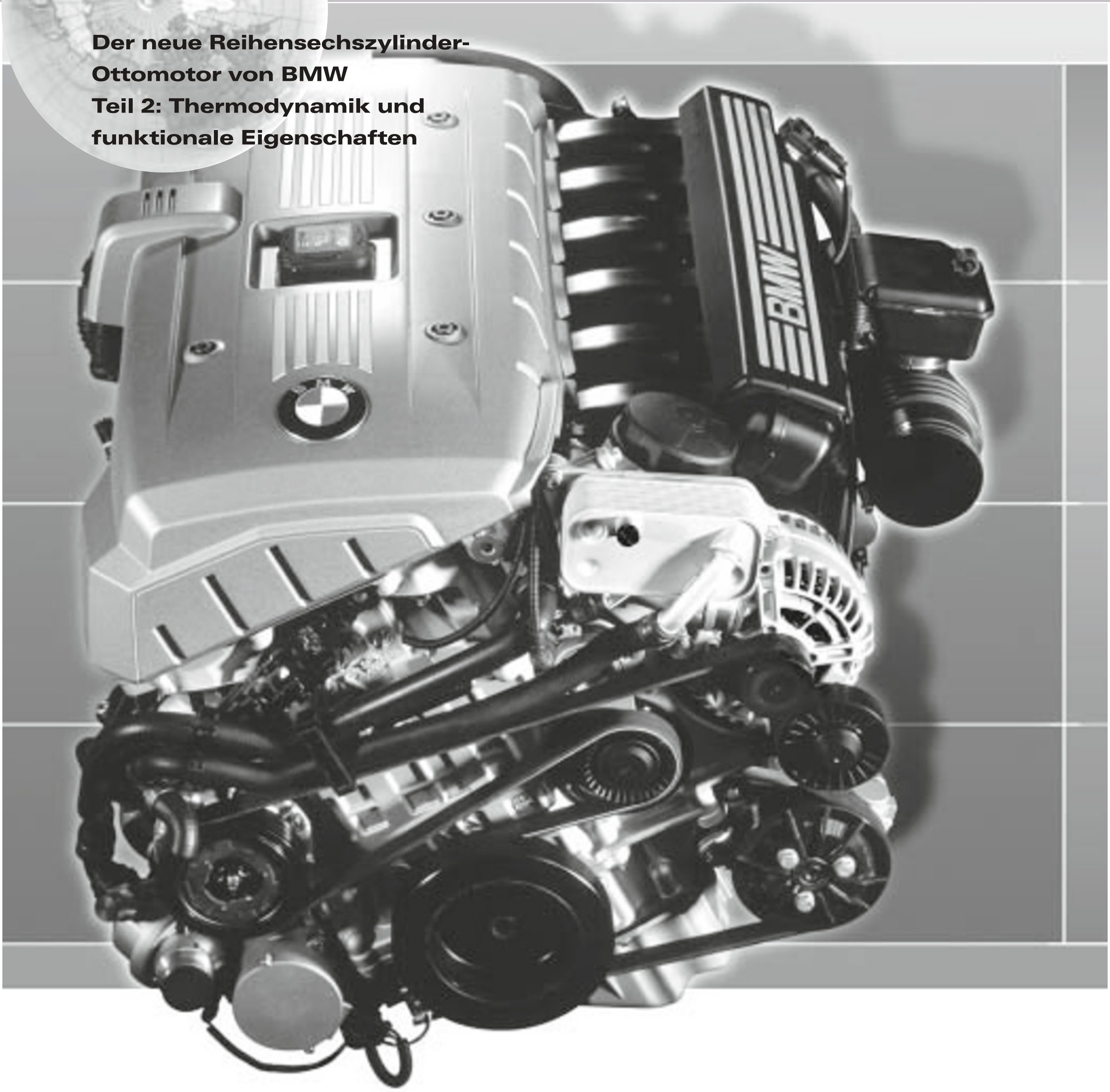
Der neue Reihensechszylinder-Ottomotor von BMW
Teil 2: Thermodynamik und funktionale Eigenschaften



The New BMW Inline Six-Cylinder Spark Ignition Engine

Part 2: Thermodynamics and Functional Properties

By Wolf Kiefer, Norbert Klauer, Michael Krauss, Werner Mährle and Erik Schünemann

BMW is currently launching its new inline six-cylinder engine with Valvetronic on worldwide markets, starting with the 630i Coupé und Convertible. Following the description of its weight-saving construction concept and design features in the first part of this article [1], the second part examines the thermodynamics and functional properties of the completely re-developed engine.

1 Introduction

The significance of the inline six-cylinder engine in BMW's range of power units, as well as the outstanding position achieved by the previous model equipped with double-Vanos variable valve timing and a turbulence system [2, 3], which helped it to win the "Engine of the Year" Award in its class on several occasions, resulted in demanding functional targets being set, **Figure 1**.

BMW's Valvetronic technology, which has been successfully introduced on the company's 4-, 8- and 12-cylinder engines around the world, was developed further. This article describes the measures taken to achieve the improvements with regard to full load and dynamics on the one hand and the efficiency and emissions targets on the other. Finally, the engine control functions developed by BMW are described. These make an important contribution to achieving the above-mentioned features and to the pleasure, so typical of BMW, of driving cars powered by the new inline six-cylinder engine.

2 Dynamics

One of the important challenges in the development of the new engine was to reduce part-load fuel consumption and emissions by using the Valvetronic system. At the same time, the specific power output was to be increased from 57 to more than 60 kW/litre, while still maintaining the extremely broad range of torque available from the previous engine. The full-load requirements were achieved by the following optimisation steps:

Induction side:
- 3-stage resonant intake air system
- de-throttling the intake airflow
- fully-machined, charge-optimised inlet ports.

Valvetronic system:
- maximum engine speed increased to 7000 rpm
- maximum inlet valve acceleration increased to up to 80 mm/rad^2
- maximum inlet valve lift increased to 9.9 mm.

Combustion chamber:
- larger inlet valves
- more compact combustion chamber with central spark point and quench area on the inlet side
- compression ratio increased by 0.5 of a unit

Exhaust side:
- exhaust manifold of flow-optimised separate-tube design
- exhaust system with low back-pressure
- entire exhaust system up to centre silencer acts as a resonance system.

Friction:
- optimisation of base engine, valve train and auxiliaries [1].

Figure 2 shows the torque and power output of the 3.0-litre engine in comparison to its predecessor. As the well spread-out torque curves show, at least 90 % of maximum torque is available from 1500-6700 rpm as a basis for good performance and welcome pulling power at various engine speeds.

The usable range of engine speeds has been extended by 500 rpm compared with the previous engine. To generate balanced torque across the entire engine speed range, the existing two-stage resonant intake air system had to be developed further. The basis for the specific influence of intake air system dynamics is achieved elegantly in the inline six-cylinder engine by the switchable separation of the main air collector into two groups of three, which draw air alternately during the 1-5-3-6-2-4 ignition sequence. The sub-collectors are connected together by pipe elbows, the dimensions of which have been chosen to create the desired resonance frequency and consequently the effective range of engine speeds. New to this engine is the linking pipe, which has an electrically activated flap controlled by engine mapping for mid-range engine speeds. If we consider the full-load engine speed range, the charge-increasing effects of the exhaust dynamics and the resonance pipe for lower speeds, the cross-pipe for mid-range speeds and the ram-air pipe layout for high engine speeds interact together almost seamlessly.

The function of the intake air system is shown schematically in **Figure 3**. At lower engine speeds, both flaps are closed and the low-frequency resonance pipe system works as two groups of three (blue). At medium engine speeds, the flap in the cross-pipe is opened. Both halves of the collector, together with the cross-pipe, now form an oscillating system that creates a charging effect (red). Above about 4500 rpm, both flaps are open ("power position", green). The dominant effect here is the recharging of the six individual oscillating pipes, which are designed for high nominal speeds, by means of reflections from the intake-side waves at the transition to the collector, allowing high air intake rates to be achieved at up to 7000 rpm.

However, the dynamics typical of BMW power units are not only achieved by stationary full-load values, but also determined to a large extent by properties such as response and the ability to run up to high engine speeds, which are characteristic of the engine's transient behaviour. As the Valvetronic engine controls cylinder charging when idling and at part-load by varying inlet valve lift, only a small vacuum of about 50 mbar is generated in the collector, and is required among other things for fuel tank venting and crankcase breathing. As engine load increases, the intake-system charging process no longer takes place, so that, for example, the time required to build up torque for the jump in load from wi = 0.2 kJ/litre to wi = 0.6 kJ/litre at n = 1500 rpm is almost halved compared to the predecessor, **Figure 4**.

3 Valvetronic Combustion System

In the Valvetronic combustion system, a further reduction in pumping work at part load together with good residual gas tolerance and increased combustion stability are pre-conditions for further reductions in fuel consumption as well as for robust, efficient and cost-saving emissions treatment with lean-mixture heating of the catalytic converter. In order to achieve these goals, the following measures have been taken:

Valvetronic system:
- reducing valve opening time at part-lift (reduction in pumping work)
- phasing (increasing charge motion at part-lift).

Combustion chamber:
- masking (increasing charge motion at part-lift)
- quench area on the inlet side
- increased compression ratio.

Vanos:
- extension of the Vanos inlet setting range (reduction in pumping work).

The shorter opening period at part-lift results in further de-throttling of the charge cycle, as the same load point is now run at greater maximum inlet valve lift and shorter inlet valve timing. Compared to the Valvetronic engines currently in production, this allows pumping work at the part-load operation point n = 2000 rpm; wi = 0.27 kJ/litre to be reduced by a further 7 %, **Figure 5**, bringing ideal throttle-free load control a step closer.

Significantly increased combustion stability is achieved by generating charge motion, specifically targeted at part-load and catalyst heating. A combination of "phasing", i.e. different inlet valve lift curves at part-lift, and "masking", which aligns the flow into the cylinder, satisfies the demand without requiring additional components as is described in the following.

Starting from minimal inlet valve lift, at which the valve lift curves of both inlet valves of a cylinder are congruent, an increase in load causes the lift and valve timing of inlet valve 1 to increase, whereas inlet valve 2 continues initially to operate at minimal lift, which only starts to increase when the load is increased further. A maximum lift difference of about 1.8 mm, **Figure 6**, is created. A subsequent increase in the valve lift, and therefore an increase in load, reduces the lift difference until both valve lifting curves again operate equally at about 6 mm. Asymmetric distribution of the mixture flow is therefore achieved at both inlet valves at lower part-lift.

The mixture flowing through inlet valve 1 is aligned at part-lift by means of masking in the area of the valve seat, **Figure 7**, resulting in the desired charge motion (tumble, swirl). The masking parameters were optimised using 3D CFD and experiments with regard to the required charge motion at part-lift and minimal charge impairment at full throttle. In design terms, this was achieved by creating a combustion chamber that combines masking with a quench area on the inlet side, allowing the compression ratio to be increased by 0.5 of a unit.

The results of tumble and swirl measurements on a flow testbed, as shown in **Figure 8**, reveal that without taking the necessary measures over the entire valve lift almost no global charge motion takes place, as the inlet ports are uncompromisingly designed as charging ports. Phasing creates a slight increase in the tumble and swirl values; the combination of phasing and masking supplies an intentionally high level of tumble and swirl at lower part-lift.

The 3D flow calculation for n = 2000 rpm; wi = 0.27 kJ/litre, **Figure 9**, shows the conversion of the macroscopic charge motion generated during the intake stroke into increased turbulent kinetic energy during compression. The combustion delay of the engine with phasing and masking in this operating range is therefore reduced by about 10 °CA. The resultant improvement in combustion stability permits further dethrottling of the charge cycle at part-load by increasing valve overlap over a Vanos inlet valve adjusting range that has been extended by 10 °CA, which has corresponding fuel consumption advantages, **Figure 10**.

Together, these measures deliver an improvement of up to 8 % in the specific indicated fuel consumption at n = 2000 rpm compared with the previous engine, which was already equipped with double-Vanos and turbulence system, **Figure 11**. The increased valve overlaps that favour consumption were implemented in the vehicle application. The lean burn ability also improved significantly.

4 Efficiency

The fuel consumption map of the engine at regular operating temperature as shown in **Figure 12** reveals significant improvements at part-load and during idling.

Additional reductions in consumption are achieved by means of consistent heat management using an electric coolant pump, a thermostat with mapped control and an electric fan. Engine warm-up takes place with the electric coolant pump standing still, in order to achieve quicker heating up of the components and the engine oil.

A differentiated control strategy when the engine is warm makes targeted use of friction potentials when idling and at part-load through high coolant and oil temperatures as well as charging and combustion advantages at full throttle by reducing the coolant temperatures, **Figure 13**. Very high cooling capacity can be made available at high loads and low engine speeds by decoupling the quantity of coolant supplied from the engine speed, without having to accept increased coolant pump power consumption at higher engine speeds.

The resulting fuel consumption potential of the new inline six-cylinder engine in the NEDC is as high as 12 % in the same vehicle compared with the previous engine with double-Vanos and turbulence system. Of this, 8.5 % is achieved by the improved Valvetronic combustion process, optimised application and lean warm-up without a secondary air system. Reduced friction in the basic engine and the cylinder head yields a 2 % consumption benefit. Heat management using an electric coolant pump and mapped thermostat control contributes 1.5 %.

4 Efficiency

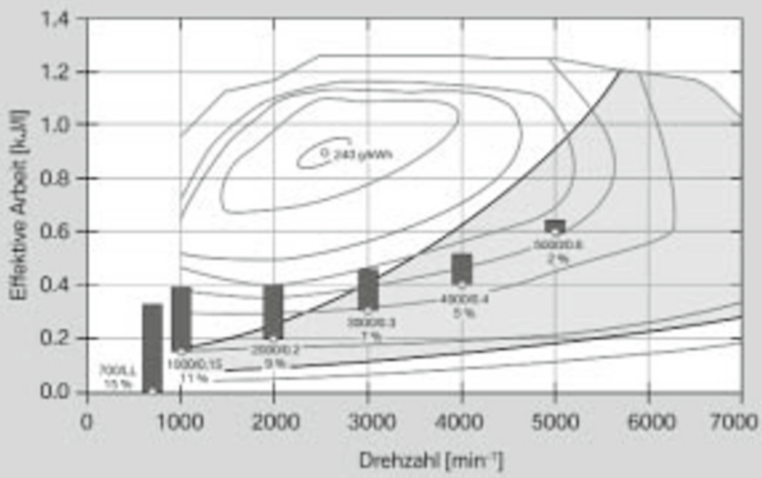


Figure 12: Brake specific fuel consumption map

5 Emissions

The new BMW inline six-cylinder engine with Valvetronic is intended for worldwide use and must therefore comply with all relevant exhaust emission regulations (Euro 4, Euro 5, ULEV II, SULEV II). The key to this is a low raw emissions level, highly efficient λ=1 exhaust after-treatment technology and careful application. To ensure that the limits are not exceeded either when the engine is new or throughout its lifetime, the following emission control measures are taken:

- high residual gas tolerance and stability of the combustion process
- spontaneous, reproducible cold-engine starting in Valvetronic operation
- increased injection pressure and optimised injection spray targeting
- exhaust manifold with close-coupled main catalysts
- linear lambda control activated 10 s after start.

The high residual gas tolerance when the engine is warm ensures very low raw NO_X emissions, and at the same time a low level of hydrocarbons, **Figure 14**. The charge motion created by phasing and masking also stabilizes the combustion in the catalyst heating mode with retarded ignition and a lean mixture. **Figure 15** shows the influence of different catalytic converter heating strategies on exhaust emissions and fuel consumption. Valvetronic operation with the maximum operationally acceptable residual gas content presents the best compromise between low raw HC and NO_X emission levels and favourable fuel consumption.

When the engine is started, targeted use of the Valvetronic functionality also helps to optimise exhaust emissions. **Figure 16** shows cylinder pressure curves from the 1D charge cycle calculation at n = 200 rpm ("starter turning") for the Valvetronic (part-lift) compared with the double-Vanos engine (full lift). Whereas the intake process for the double-Vanos engine at almost constant cylinder pressure runs at the ambient level, cylinder pressure during the intake phase with the Valvetronic at part-lift falls away sharply, so that an overcritical pressure ratio is achieved at the inlet valve. This improves atomisation of the injected fuel and creates clearly greater turbulence in the cylinder charge. Due to the reduced valve opening time compared with full lift, the "inlet closed" time at part-lift occurs earlier. This avoids the back-flow of fresh gas mixture at the start of the compression stroke, resulting in an increase of about 11 % in cylinder filling, which guarantees immediate, reproducible engine starts even at very low temperatures.

The increase in injection pressure from 3.5 bar to 5 bar and optimised injection spray targeting result in improved mixture formation and reduced wall wetting. Raw HC emissions in a cold engine are therefore reduced.

The exhaust system runs as a double flow system up to the centre silencer; the separate-pipe exhaust manifolds have lightweight flanges, **Figure 17**. The main catalytic converters are located close to the engine ("2-mono" system, thin wall ceramics, 600 cpsi) to ensure good light-off. The chosen high temperature-resistant coating with its Pd/Rh precious metal content guarantees low light-off temperatures as well as high conversion rates both when new and after ageing. The cost of the precious metal compared with the previous engine with the same catalytic converter volume has been reduced by more than 30 %.

The linear Bosch LSU 4.9 lambda probe is positioned in the joint area of the manifold pipes ahead of the catalytic converter in such as way that it lies in the exhaust gas flows from all the cylinders. Linear lambda control is activated 10 seconds after engine start. The lambda value supplied for each cylinder by the probe is used for cylinder-selective combustion control and other purposes. Taken together, the emission measures achieve robust, cost-efficient emission control in line with EU 4 and ULEV II without the need for a secondary air system. There is also the potential to comply with SULEV II limits.

6 Engine Control Functions – Functional Highlights

The larger number of engine variables compared with the predecessor called for the development of a completely new engine management control system. Consequently, an interface adjustment by Siemens VDO building on the MSV70 was integrated for the first time, which made it possible for BMW to implement its own software functionalities across all platforms. The most important BMW functions are shown briefly below, **Figure 18**.

Some of the functions can be described using physical models. As there are so many variables and parameters with highly complex relationships, it is often easier to replace the physical description of the model with neural networks, which can present high-dimensional dependencies in a simple way. Efficient interaction of physical and neural models is achieved with hybrid models that combine both approaches.

For example, the exhaust gas temperature model is composed of a neural network that describes the engine and a physical model that portrays the exhaust system.

In fully model-based load recording, a neural network is trained and connected permanently into the engine control unit. A second network runs continuously as an adaptive, self-learning network for the lifetime of the vehicle in order to compensate for environmental conditions and tolerances.

The basic ignition and valve timing functions are duplicated. The first part was optimised for fuel consumption and emissions (high residual gas content, optimum ignition timing). The other part was determined according to pure driving parameters. Depending on the smoothness of the engine (misfire detection), the function interpolates between the two part-states. This means that the engine always runs with the lowest fuel consumption in ideal conditions. In case of poor fuel quality or unfavourable environmental conditions, these ideal parameters are abandoned and converted to low residual gas content for the benefit of driveability.

On the basis of misfire detection, combustion control also becomes active when idling. The level of the different orders of engine vibration is determined in a simplified form. In the first step, targeted cylinder-selective ignition and mixture corrections are performed. If this action is insufficient, the second step is the correction of cylinder-selective charging, which works by cyclic adjustment of the eccentric valvegear shaft. This also allows idling quality to be guaranteed in the event of unfavourable tolerances.

The heat management coordinator permits demand control of the cooling system, including the electric coolant pump and the mapped-control thermostat.

The scope of BMW's own software functionalities ranges from basic thermodynamic functions to its own torque structure, which contains typical BMW performance functions, and is prepared for the future integration of drive train management strategies.

7 Summary

In terms of its functional properties, the new BMW inline six-cylinder engine with Valvetronic follows on smoothly from its successful precursor:

- specific power of 63.3 kW/litre and specific torque of 100 Nm/litre
- responsiveness typical of BMW and further improved ability to run up to high engine speeds
- up to 12 % CO_2 reduction in the NEDC
- Euro 4 and ULEV II compliance without secondary air system, potential for SULEV II.

The increased dynamics and improved efficiency, **Figure 19, Figure 20** and **Figure 21**, while complying with the most stringent exhaust emission limits, strengthen the competitive position of the new BMW inline six-cylinder spark-ignition engine, which will be used in nearly all BMW vehicles worldwide.

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