New 6- and 4-Cylinder Petrol Engines with High Precision Injection and Stratified Combustion *

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According to its powertrain strategy, BMW introduces the new 6- and 4-cylinder inline petrol engine generation, featuring a stratified DI combustion system with High Precision Injection. The spray-guided combustion system eliminates the disadvantages of the wall- and air-guided 1st generation DI combustion systems, providing a stratified mixture at the spark plug and significantly reduced wall wetting. The piezo injector permits an extremely fast actuation, providing high flexibility for the calibration strategy to supply a very efficient combustion with low unburnt hydrocarbon and carbon monoxide emissions. The paper presents the realised potentials and technical features of this new engine generation.

Keywords: BMW inline petrol engines, high precision injection, spray-guided combustion

1. Introduction

In the development of its new engines the BMW Group is pursuing a course of optimising fuel consumption, dynamics and weight (Fig. 1). At the same time, reliable compliance with the exhaust emission limits of the respective markets as well as the uncompromising realisation of the BMW characteristic "Sheer Driving Pleasure" are, of course, indisputable development objectives.

First generation wall/air-guided DI combustion systems met these requirements only incompletely and were not used by BMW in series production as the advantages gained in terms of fuel consumption were achieved to the same extent by VALVETRONIC technology already introduced worldwide by BMW [1].

The BMW spray-guided DI combustion system with centrally positioned fuel injector and High Precision Injection effectively avoids the disadvantages of the first generation direct injection processes while enabling maximum utilisation of thermodynamic potentials.

The technical data and the specific design features of the new generation of engines are presented in the following.

2. Technical Data and Design Features

2.1 Engine Data

Table 1 lists the technical data of the new BMW spark ignition engines shown in Fig. 2.


1) 2) 3) 4) BMW Group, Munich, Germany
2.2 Fuel System

The 200 bar high-pressure fuel system High Precision Injection, as used in the new BMW six-cylinder engine and illustrated in Fig. 3 consists of the high-pressure pump with volume control valve, fuel rail with fuel pressure sensor as well as piezo-injectors all connected by the fuel lines. The low-pressure system operates at a pressure of 5 bar. Controlled by the volume control valve, the 3-piston high-pressure pump delivers the fuel mass flow required by the engine at the specific fuel pressure.

The needle of the outward-opening nozzle of the fuel injector (Fig. 4) is activated directly by the piezo actuator and releases an annular gap, through which the fuel is injected. A thermal compensator is used for the purpose of equalising the differences in thermal expansion between the piezo-stack and housing and therefore to ensure constant needle lift at all injector temperatures. The use of piezo-electric actuation ensures rapid, delay-free and reproducible opening and closing of the needle, thus enabling the shortest injection times and the injection of minimum quantities. At the same time, the piezo-injector features high volume dynamics, i.e. it can inject large masses of fuel in a very short space of time. Multiple injection with very short pause times and the possibility of injector operation in the partial-needle lift range provide the degree of flexibility required for the stratified combustion process in line with the optimum injection strategy.

Table 1: Engine data

<table>
<thead>
<tr>
<th>Type</th>
<th>Inline 6</th>
<th>Inline 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke</td>
<td>88 mm</td>
<td>90 mm</td>
</tr>
<tr>
<td>Bore</td>
<td>85 mm</td>
<td>84 mm</td>
</tr>
<tr>
<td>Stroke/bore</td>
<td>1.035</td>
<td>1.071</td>
</tr>
<tr>
<td>Displacement</td>
<td>2.996 l</td>
<td>1.995 l</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Cylinder spacing</td>
<td>91 mm</td>
<td></td>
</tr>
<tr>
<td>Valves per cylinder</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Combustion system</td>
<td>BMW DI2 spray-guided</td>
<td></td>
</tr>
<tr>
<td>Crankcase</td>
<td>Magnesium crankcase with aluminium insert, Alusil cylinder face</td>
<td>Aluminium crankcase with cast iron liners</td>
</tr>
<tr>
<td>Valve train</td>
<td>Roller cam follower, double VANOS</td>
<td></td>
</tr>
<tr>
<td>Intake system</td>
<td>3-stage resonance intake manifold</td>
<td>2-stage intake manifold</td>
</tr>
<tr>
<td>Engine management</td>
<td>Digital engine management MSD80 High Precision Injection individual ignition coils</td>
<td></td>
</tr>
<tr>
<td>Mixture preparation Ignition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exhaust system</td>
<td>Single-tube manifold with lightweight flange, 2 close-coupled 3-way catalytic converters</td>
<td></td>
</tr>
<tr>
<td>2 NOx storage catalytic converters</td>
<td>1 NOx storage catalytic converter</td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>Electric coolant pump, electrically controlled thermostat</td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>RON98-91</td>
<td></td>
</tr>
<tr>
<td>Engine weight according DIN70020-GZ</td>
<td>163 kg</td>
<td>136 kg</td>
</tr>
<tr>
<td>Emission standard</td>
<td>EU4</td>
<td></td>
</tr>
<tr>
<td>Effective power output</td>
<td>200 kW @ 6700 rpm</td>
<td>125 kW @ 6700 rpm</td>
</tr>
<tr>
<td>Effective torque</td>
<td>320 Nm @ 2750-3000 rpm</td>
<td>210 Nm @ 4250 rpm</td>
</tr>
</tbody>
</table>

Fig. 2(b): New 2 I four-cylinder petrol engine with high-precision injection and stratified combustion

Fig. 3: High-pressure fuel system for high-precision injection

Fig. 4: Sectional view of piezo-injector for high-precision injection
2.3 Exhaust Gas Recirculation System

For the purpose of reducing NOx raw emissions at stratified engine operation, the new six-cylinder and four-cylinder petrol engines are equipped with an external exhaust gas recirculation system. The exhaust gas is taken from the second cylinder bank after the close-coupled catalytic converter and the recirculated exhaust gas is introduced centrally at the throttle valve. The EGR valve is arranged beneath the intake manifold and is water-cooled. It is actuated by means of a rotary magnet that actively controls the EGR mass flow. The design of the EGR piping system with expansion bellows decouples vibration between the intake manifold and exhaust system.

3. Combustion System

3.1 Components

The BMW spray-guided DI combustion process of the new six-cylinder and four-cylinder petrol engines consists of the following main components (Fig. 5):

- DI cylinder head with squish area combustion chamber
- Centrally positioned injector, spark plug on exhaust side, filling ports
- High Precision Injection with piezo-injector
- Ignition system with DI specific spark plug and high energy ignition coil
- DI piston with central piston bowl
- Valve train with double VANOS

![Fig. 5: Components of the BMW spray-guided DI combustion system](image)

The fuel injector is positioned centrally in the combustion chamber and tilted slightly towards the intake side. The spark plug is arranged tilted towards the exhaust side. The intake ports are designed as filling ports with low tumble to enable high specific power output levels.

The injection creates a stable hollow cone spray with limited penetration depth and a well-defined recirculation zone. The spray cone angle is virtually independent of the injection pressure and cylinder pressure, thus ensuring stable combustion both in homogenous mode as well as in stratified combustion mode. The selected spray layout ensures rapid mixture preparation and effective homogenisation within the mixture cloud located at the spark plug, thus ensuring complete combustion. The outward-opening nozzle is fundamentally resistant to the formation of deposits and changes in the spray configuration during operation. The homogenisation is further improved and the penetration depth reduced by multiple injections with up to 3 injections per operating cycle. Injector operation in connection with partial-needle lifts utilises additional degrees of freedom for the injection process.

The injection system is specifically adapted to the requirements of stratified combustion. The spark plug design includes measures to provide effective robustness, thus improving ignition of both rich as well as lean mixture. The modified ignition coil makes available higher ignition energy levels thus additionally increasing the robustness of the combustion process.

The piston with centrally arranged piston bowl minimises wall wetting during injection in the compression stroke and ensures secondary charge motion via specifically arranged squish areas.

The variability of the valve train made possible by the double VANOS is effectively utilised in the partial load range for internal exhaust gas recirculation and for fine-tuning the charge movement.

3.2 Mixture Formation, Ignition and Thermodynamics

The development of the BMW spray-guided DI combustion process was made possible by the closely coordinated, combined use of "conventional" test rig measurement technology (e.g. pressure indication, exhaust gas analysis), high resolution optical processes (high-speed visualisation, endoscopy, LIF, PDA), special measurement procedures (e.g. ignition voltage analysis) as well as by the consistent use of CFO tools for 3D simulation of all relevant physical processes, ranging from internal nozzle flow through spray disintegration, evaporation, mixture formation through to combustion.

Under ambient conditions without the influence of engine-related charge motion, the visualisation of the liquid fuel (Fig. 6) shows that a hollow cone shaped, stable spray with a virtually constant cone angle is formed over the injection period. The bottom view shows a streaky spray structure which is created as the result of the design layout of the inner nozzle geometry and has a stabilising effect. In stratified combustion mode, fuel is injected in the compression stroke so that the penetration depth is significantly reduced while the spray cone angle remains constant so as to form a clearly visible recirculation zone. The streaky structure is less clearly visible in the bottom view due to the high spray density.

![Fig. 6: Spray propagation into quiescent air](image)
Analysis of the mixture formation in the optical engine confirms the high stability of the spray cone under the influence of in-cylinder charge motion (Fig. 7). The recirculation zone of the evaporated fuel from the first injection makes available an ignitable mixture directly at the spark while the second injection stabilises the ignition and the burn-out characteristics.

Fig. 7: Mixture formation at stratified operation in the optical engine

In addition to the layout of the spray, adaptation of the ignition system to the specific requirements of stratified combustion is a fundamental prerequisite for ensuring reliable ignition. A surface discharge spark plug with 3 ground electrodes is used which exhibits advantageous self-cleaning properties in combination with a multi-spark ignition system. The design layout of the insulator tip and ground electrodes ensures excellent accessibility of the mixture and charge motion to the ignition spark so that the ignition spark from the electrodes is deflected into the ignitable mixture by the spray-induced charge movement thus preventing the occurrence of creepage spark or surface discharge (Fig. 8).

Fig. 8: Influence of the spark plug geometry on the deflection of the ignition spark in simulation and test

Thermodynamic analysis of the partial load operating point \( n = 2000 \text{ rpm}; \, w_e = 0.2 \text{ kJ/l} \) shows the potential of the BMW spray-guided DI combustion process with High Precision Injection (Fig. 9). Compared to a basic four-valve engine with intake manifold injection with no variabilities and to the current BMW VALVETRONIC system, lean operation and an increased compression ratio result in substantially higher efficiency of the ideal process and reduce charge cycle losses (Fig. 10). In addition, compared to wall/air-guided DI combustion systems, the second generation BMW spray-guided DI combustion system exhibits significantly reduced losses due to incomplete combustion and therefore considerably lower HC raw emission levels due to improved stratification of the mixture (Fig. 11). These features relate to an effective efficiency of almost 30% at this operating point.

Fig. 9: Thermodynamic analysis at 2000 rpm; \( w_e = 0.2 \text{ kJ/l} \)

Fig. 10: Gas exchange work
4V conventional vs. BMW DI spray-guided

Fig. 11: Hydrocarbon emissions at \( n=2000 \text{ rpm}; \, w_e = 0.2 \text{ kJ/l} \)

4. Efficiency and Dynamics

4.1 Fuel Consumption Engine Map and Operating Modes

Compared to wall/air-directed combustion systems, the BMW spray-guided DI combustion system with High Precision Injection permits a significant expansion of the engine map range calibrated in stratified combustion mode (Fig. 12). As the illustrated driving resistance curve shows, the engine operates with optimum fuel consumption in stratified mode at a constant driving speed of up to approx. 160 kmph. Above this classic stratified
mode of operation, a characteristic map range with hybrid injection strategy cuts in which additionally utilises the thermodynamic advantages of lean engine operation. Over the remaining characteristic map, the engine is operated homogeneously such that the potentials made available by High Precision Injection for improving the mixture homogenisation and for reducing wall wetting are fully utilized.

The dynamics typical of BMW engines is realised not only by stationary full load values but is also predominantly determined by properties such as rotary power and response that characterise the instationary attributes of the engine. The free-revving characteristics of the new engines are noticeably improved by the expansive torque progressions and the expansion of the effective engine speed range up to 7000 rpm. Since the engine operates virtually unthrottled in the idle and partial load range due to the lean operation, the intake system is not charged as the engine load increases so that the time required to build up the torque for the load jump from \( w_i = 0.2 \text{ kJ/l} \) to \( w_i = 0.6 \text{ kJ/l} \) at \( n = 1500 \text{ rpm} \) is distinctly shortened as the required torque is already reached in the next operating cycle (Fig. 15). This characteristic therefore makes it possible to achieve outstanding engine response.

The exhaust gas treatment system must ensure that market-specific emission limits are reliably met over the engine life time. Fig. 16 shows the dual-flow exhaust treatment system used for the new six-cylinder engine. Linear oxygen sensors are positioned ahead of the close-coupled 3-way catalytic converters while binary oxygen sensors undertake the trim control and catalytic converter diagnosis. An exhaust gas temperature sensor that is used for the purpose of controlling the exhaust gas temperature is arranged upstream of one of the two NOx storage catalytic converters. The exhaust gas temperature of the second cylinder bank is modeled. The NOx sensor that is used for controlling the regeneration process is arranged in the junction downstream of the NOx storage catalytic converters.

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The specific requirements of the emission system should not significantly diminish the fuel consumption advantage. Fig. 17 shows that this is possible with an emission control strategy adapted to the combustion process and overall system. In NEDC, engine start is followed by a short catalytic converter heating phase which in turn is followed by the engine warm-up phase in homogeneous mode. As part of the further test procedure, including the idle phases, the engine is operated in stratified combustion mode for optimum fuel consumption. Stratified combustion mode is not employed during the regeneration phases of the NOx storage catalytic converter. This strategy makes it possible to both conform to EU4 limits as well as to limit the consumption-increasing influence of all emission measures to approx. 4% in NEDC.

With the market introduction of the new six-cylinder and four-cylinder engines with High Precision Injection and stratified combustion BMW has further consolidated its leading position in terms of efficient dynamics while at the same time making a significant contribution to reducing CO₂ fleet emissions by using the engines in high-volumes. Efficiently managing the operating modes and exhaust gas treatment both in homogenous as well as in stratified mode in combination with exhaust gas recirculation ensures reliable compliance with emission limits that go beyond the currently applicable EU4 requirements. In the future, additional engine variants will go into series production to complete the product portfolio. The combination of High Precision Injection in stratified combustion mode with turbocharging could effectively develop and utilise significant additional consumption and performance potentials [2]. This development substantiates the BMW strategy of basing future engine concepts on a centrally positioned, fast and precise fuel injector in combination with turbocharging.

6. Performance and Fuel Consumption

Despite the great complexity of combustion system and the exhaust treatment system, it has been possible to convert the engine potentials into significant advantages for the customer in terms of performance and fuel consumption. An all-encompassing energy management system that includes measures for reducing engine warm-up, intelligent generation of electrical energy for the system network in the overrun and braking phases with the newly developed Brake Energy Regeneration as well as an Auto Start Stop Function used in the four-cylinder engine also makes a significant contribution. By way of example and as a comparison with the predecessor, Fig. 18 shows the fuel consumption and performance figures realised for the 530i with the 3 litre six-cylinder engine as well as for the 120i with the 2 litre four-cylinder engine in manual transmission vehicles.

8. References
