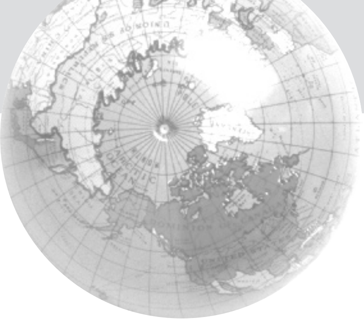
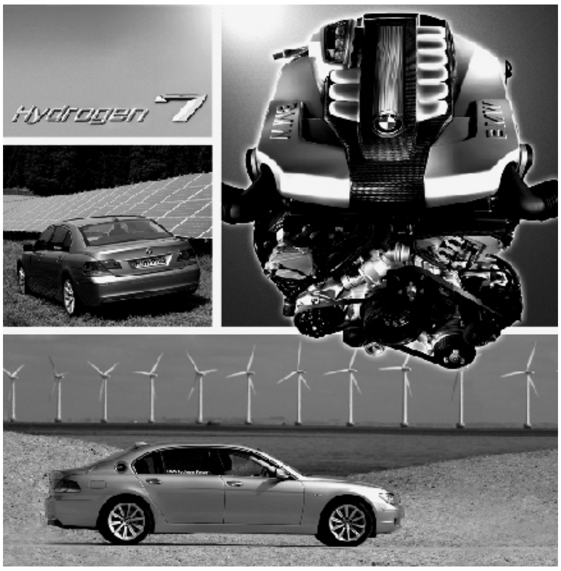


You will find the figures mentioned in this article in the German issue of MTZ 06|2007 beginning on page 000.

Der bivalente V12-Motor des BMW Hydrogen 7

The Bi-fuel V12 Engine of the new BMW Hydrogen 7



The V12 engine of world‘s first hydrogen-powered luxury saloon car, which was created in a series development process, represents a further landmark along the road to the hydrogen age. Thanks to sequential hydrogen injection, combined with Valvetronic and a complex operating strategy, the 6.0 l engine develops 390 Nm of torque and a power output of 260 bhp. At the same time it clearly undercuts the toughest emissions regulation worldwide.

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1 Introduction

Hydrogen generated by renewable means, as a carbon-free energy carrier, offers greatest potential for securing the individual mobility of future generations. The development of the BMW Hydrogen 7 represents an important step towards this goal. This was the first time in the world that a premium hydrogen vehicle underwent the entire series development process, where the identical standards as for all other production models of the BMW Group applied.

The BMW Hydrogen 7 will be built on a small scale of 100 units, which are destined for use worldwide by decision-makers in the fields of politics, business and research. One aim is to gain their support for the establishment of the infrastructures and the pioneering of the technologies needed to smooth the way for hydrogen mobility.

Due to the lack of a supply infrastructure network for mono-fuel hydrogen vehicles, the BMW Group decided in favour of a bi-fuel power train.

2 Design Features

2.1 Basic Engine

The engine is based on the 6.0 l V12 petrol engine with Valvetronic and petrol direct injection from the BMW 760i [3], **Table**.

To keep irregular combustion phenomena (knocking, self-ignition, backfiring) under control, the compression ratio was lowered to ε = 9.5. This involved shortening the connecting rod by 1.5 mm as well as adapting the geometry of the piston head.

Slits were made in the aluminium cylinder block at the gussets between the cylinder liners in order to achieve more consistent heat dissipation around TDC (top dead centre) by increasing the coolant flow in this area. A specially developed four-layer metal gasket establishes the sealing with the cylinder head.

Engine Data	Petrol	Bi-Fuel
Type	V-12 / 60°	
Firing Order	1-7-5-11-3-9-6-12-2-8-4-10	
Displacement	5972 cm^3	
Bore / Stroke	89 / 80 mm	
Cylinder Spacing	98 mm	
Number of Valves per Cylinder	4	
Intake Valve Diameter	35 mm	
Exhaust Valve Diameter	29 mm	
Intake Valve Lift	0.3 - 9.85 mm	
Exhaust Valve Lift	10.3 mm	
Main Bearing Diameter	70 mm	
Big-end Bearing Diameter	54 mm	
Compression Ratio	11.3 : 1	9.5 : 1
Connecting Rod Length	140 mm	138.5 mm
Fuel Frade	RON 98	H_2 or RON 98

Table 1: V12 engine's key data for petrol (basis) and bi-fuel (H_2 and petrol)

The particularities of the stoichiometric combustion of hydrogen at full load, such as the higher flame propagation speed, the smaller flame quenching distance and the more intensive heat transfer rate than with petrol, imply that the piston and the piston rings are subjected to quite higher thermal and mechanical stress.

The new designed piston was therefore configured for higher peak pressures (up to 170 bar), **Figure 1**. Moreover, the thermal stress on the ring groove area has been relieved trough the inclusion of a cooling duct.

In configuring the new piston rings, one had to keep the blow-by gases as low as possible to avoid the adverse effects arising from a high hydrogen and water content in the crankcase. The 1.2 mm thick compression ring represents a compromise between good shape adaptability and mechanical robustness.

The blow-by gases are lead back into the combustion chamber through the intake manifold. In order to exclude the occurrence of backfiring in the crankcase, an additional shutoff valve has been fitted in the supply line of the crankcase ventilation system.

The engine oil quality selection had to be optimised for the hydrogen operating mode.

Like for all gaseous-fuel engines, it was necessary to thoroughly tune the valves with their seat rings due to the absence of additives. A specially developed wear-optimised alloy was adopted for the seat rings.

At operating conditions close to the knock limit, knock control requires retarded ignition timing. This implies higher exhaust gas temperatures, which consequently leads to higher thermal stress on the exhaust valves. For that reason, these valves are made of a high thermal resistance Nimonic alloy. Both, the intake and the exhaust valves have also an additional reinforcement in order to minimise wear.

2.2 Hydrogen Supply and Mixture Formation

In contrast to the petrol mode, hydrogen-mixture formation is based on a cylinder-selective intake manifold injection with a relatively low overpressure of 1 bar. This pressure is generated exclusively by evaporation of cryogenic hydrogen in the tank, and therefore no hydrogen feed pump is needed. The amount of required heat for evaporation is drawn from the engine coolant and regulated by means of an electric pump.

Due to its molecular weight, hydrogen handling demands high leak tightness in the fuel system. All detachable connections, as well as O-ring seals and sealing surfaces on the pressure regulator and on the feed line are therefore of a double-wall design. Eventual leakage occurring is identified by a central hydrogen gas sensor.

The gaseous hydrogen reaches the rail of the intake manifold (3), **Figure 2**, trough an electromagnetic pressure regulating valve (1) and the partly flexible stainless steel feed line (2). The injection valves (4) supply then the hydrogen sequentially to the intake air.

The rail pressure regulation is performed by means of pressure and temperature sensors (5). This simplifies map-controlled gas metering.

The aluminium intake manifold with the integrated hydrogen collector is manufactured by precision sand casting. The high standard of gas-tightness required means that the casting has to be of a supremely high quality.

The entire hydrogen supply system is designed to remain intact in the event of a crash.

The metering precision of the hydrogen injection valves, **Figure 3**, directly influences the idling quality, the load control, the emissions performance and engine‘s tendency to backfire. The valve design with radial gas admission and axial discharge provides an optimum basis for handling large cross-sectional areas within a very short period.

2.3 Ignition System

The ignition system with solid-state ignition distribution has been adopted from the petrol engine. A racing surface ignition spark plug without protrusive ground electrode avoids self-ignition in the hydrogen mode. To reduce the hotspot effect, the spark plug calorific value has been selected to be lower than for a petrol-only engine.

2.4 Thermal Management

One particular feature of the hydrogen operating mode is the broad variation in heat input between stoichiometric combustion at full load and lean combustion at part load. That fact, together with the high water content in the blow-by gas, implies that the engine thermal management has to be of a high standard. It must ensure trough the oil conditioning optimum tribological conditions at all times.

The hydrogen heat exchanger of the LH_2 (liquid hydrogen) tank is connected to the engine coolant circuit, **Figure 4**. This additional circuit is a self-regulating system that uses engine‘s heat to increase the hydrogen pressure inside the tank. A control thermostat maintains the temperature in the circuit at about 50 °C. The hydrogen tank and safety control unit (see chapter 4.3), which also manages the system diagnosis (freeze-protection), activates the auxiliary water pump in the small circuit depending on the heat requirements of the hydrogen heat exchanger.

3 Functional Features

3.1 Full Load

The maximum torque and power output level will be achieved at stoichiometric hydrogen operation with very low emissions and high efficiency.

One characteristic effect of intake manifold injection of gaseous hydrogen is, however, a charge loss, since at stoichiometric operation the hydrogen displaces approximately 30 % of the aspirated air.

Moreover, the lower weight and higher sonic speed of hydrogen also affect manifold dynamics, worsening the degree of charging. This can, nevertheless, be partly compensated by optimisation measures, and in the case of the V12 hydrogen engine a compromise between petrol and hydrogen operation had to be found.

The characteristic of hydrogen combustion strongly depends on the mixture composition. At a λ (relative air/fuel ratio) value close to 1, the ignition energy and the ignition advance demand decrease rapidly, while the combustion speed and the gradient of the combustion pressure increase steeply. At a stoichiometric mixture of hydrogen and air, the pressure build-up gradient and the combustion speed are significantly higher than for that of petrol and air. The ignition timing for optimum combustion is approximately 1 CA (crank angle) before TDC.

At stoichiometric operation, the V12 hydrogen engine achieves nevertheless a power output of 191.2 kW (260 bhp) and a peak torque of 390 Nm, **Figure 5**.

3.2 Emissions

No primary CO_2, CO or HC emissions occur in the hydrogen operating mode. Minimal amounts of HC occur solely as a result of engine‘s oil consumption, but these are then oxidised in the three-way catalytic converter. The residual concentration at the tailpipe is negligible.

For hydrogen engines the only relevant emissions are NO_x (nitrogen oxides), which occur as a result of the very high process temperatures achieved during stoichiometric combustion of hydrogen.

However, since hydrogen engines can be operated homogeneously over a broad λ range, the wide ignition limits of hydrogen/air mixtures (4 to 76 vol.-% in air) open up entirely new perspectives for the avoidance of NO_x, inclusively without charge stratification. While operating the engine with very lean mixtures ($\lambda > 1.8$) NO_x emissions are minimal due to the low process temperature.

In the range of maximum power output, with a mixture slightly richer than stoichiometric, the NO_x can be reduced in the three-way catalytic converter using the slight hydrogen surplus (approximately 1%). The high reactivity of hydrogen allows conversion rates of more than 99.9 % and therefore very low tailpipe NO_x concentrations. A modified catalytic coating improved the rate of conversion even further. At λ values of approximately 0.97, the residual concentration of hydrogen after the catalytic converter is likewise lower than 0.1%, **Figure 6**.

At λ values between 1 and 1.8 the three-way catalytic converter is ineffective due to the lack of reaction partners. No efficient exhaust after-treatment is possible for this range without additionally added substances. Due to the very high NO_x emissions and restricted temperature limits at this λ range, the use of NO_x-storage converters proved to be not successful.

The engine always starts on hydrogen. This avoids consumption-intensive heating-up strategies for the catalytic converter.

3.3 Operating Strategy

The operating strategy is divided into three ranges, **Figure 7**:

- Range 1: in the upper load range, the engine is operated at $\lambda = 0.97$. Exhaust after-treatment is performed by the three-way catalytic converter, which uses unburned hydrogen to reduce NO_x raw emissions.
- Range 2: at low loads, the engine is operated at $\lambda > 1.8$. The extremely low NO_x raw emissions do not require exhaust after-treatment.
- Range 3: Operation at the λ range between 0.97 and 1.8 in a hydrogen internal combustion engine is excluded, as no effective exhaust after-treatment is possible.

Thanks to this strategy, the BMW Hydrogen 7 undercuts the currently toughest emission regulation world-wide – SULEV – by approximately 70 %.

The driver must not notice the automatic switch between the operating ranges. However, since as much as 25 % of the torque has to be compensated in a switch process, high demands are placed on the engine management.

Even before the switch threshold is reached, the throttle valves and the Valvetronic are pre-positioned. As soon as a switch becomes necessary, the engine management changes to the other mixture between two combustion cycles. Instead of passing through the excluded range, a sudden changeover takes place. In order to compensate the torque leap, the ignition timing has also to be simultaneously adjusted to the λ value. The throttle valve, which responds more slowly to adjustments than the mixture and the ignition timing, must be tracked. While the throttle valve is moving to the target position, the torque is adjusted by the ignition timing. Once the throttle valve reaches the position, the ignition timing returns back to the optimum combustion range.

3.4 Bi-Fuel Operation

A simultaneous operation of the engine on hydrogen and petrol must be absolutely excluded. The fuel switch itself represents a particular challenge, and it will be required under the following circumstances:

- manually switching by the driver
- automatic switching if one of the two fuel tanks is detected empty
- automatic switching to petrol mode in the event of a defect in the hydrogen system (backup solution).

Before performing the switching, the system checks whether the tank level of the target fuel and its pressure are adequate. If so, the engine management switches over the cylinders of one cylinder bank to the selected fuel in the same sequence as the firing order. The bank is then synchronised by torque alignment. Afterwards, the same is performed on the second cylinder bank.

3.5 Avoiding Irregular Combustion

The position of the injection valves in the intake manifold is a decisive factor to manage engine‘s operating behaviour. To prevent backfiring due to hot residual gas, it is important to ensure that when it opens there is only air, and no combustible mixture, at the intake valve. The hydrogen must be injected into the intake manifold in such a way that it is drawn completely into the combustion chamber by the charge cycle.

Mixtures of undefined composition can result in irregular combustion behaviour. Injection therefore must be always carried out at an over-critical pressure ratio in order to optimise metering precision.

3.6 Knock Control

The basic functions of knock control and sensing technology originate from the petrol engine. Due to the higher demands of the hydrogen operation, however, the functionalities needed to be extended and adapted.

The same applies to the filter frequencies of the engine management, since the noise signature of knocking hydrogen combustion differs from the known variables for petrol operation. As the engine is operated across a broad λ range, the knock detection parameters such as filter frequency, knock measuring window and knock intensity vary considerably.

In view of the very rapid combustion and the associated high pressure build-up gradient in stoichiometric operation, very fast detection and response times are required in an event of knocking.

3.7 Catalytic Converter Protection Function

In case of high exhaust-gas temperatures exceeding the maximum permissible admission temperature of the catalytic converter, a function to protect it must actuate. As mixture enrichment has no effect in gaseous-fuel engines, the following strategy is applied in the hydrogen mode: when the critical exhaust-gas temperature is reached, one cylinder per bank is switched, cyclically in the firing order, to the leaner mixture NO_x negligible range. If a higher reduction in the temperature is needed, a further cylinder is made leaner. The resulting drop in performance is of a similar magnitude of the protection function in the petrol mode.

3.8 Fuel Consumption and Driving Performance

The hydrogen engine still offers considerable potential for reduction of fuel consumption due to the special characteristics of the hydrogen/air mixture. In stoichiometric operation, high thermodynamic efficiency levels can be achieved thanks to the extremely rapid combustion. Load control is nevertheless susceptible to losses due to the quantitative regulation, but the increased use of BMW's Valvetronic should bring about further improvements on that.

In lean operation ($\lambda > 1.8$) the engine runs unthrottled and load control is performed by means of qualitative regulation. The combustion speed and therefore the thermodynamic efficiency fall sharply, though, as the mixture becomes leaner. From $\lambda \cong 4$ on, one combustion cycle no longer suffices to fully complete the combustion. In order to achieve optimum consumption in the lean operation, a combination of qualitative and quantitative control is required above a certain air surplus level.

The vehicle achieves a hydrogen consumption of 3.6 kg per 100 km. This equates to approximately 13 l of petrol per 100 km. The consumption is lower than in the petrol mode (13.9 l per 100 km) due to the thermodynamic advantages and the wider range of unthrottled load control. The vehicle mileage in the hydrogen operating mode is around 200 kilometres.

The BMW Hydrogen 7 with 6-speed automatic transmission accelerates from 0 to 100 km/h in 9.5 seconds. The top speed is electronically governed at 230 km/h.

There's room for further substantial consumption improvements through the development of a hydrogen mono-fuel engine design.

4 Electronic Control Units

4.1 Engine Management's Software Development

Existing developments and functions served as the basis for the new software. These were taken as the starting point in developing the functions for hydrogen and bi-fuel operation with load-neutral switch between petrol and hydrogen operating modes.

Innovations in the project:
- general functions for operating the hydrogen combustion engine
- functions for bi-fuel operation and compensation between the petrol and hydrogen operating modes
- special torque structure for hydrogen
- hydrogen rail pressure control
- calculation of the injection times from the relative fuel amount for hydrogen
- realisation of torque-neutral operating mode switch (petrol/hydrogen) at all load points
- hydrogen rich operation ($\lambda \cong 1$)
- hydrogen lean operation ($\lambda > 1.8$)
- switch between lean/rich mixture operation
- exhaust temperature limiting for hydrogen
- knock control for hydrogen
- backfiring detection
- hydrogen safety concept according to the German Association of the Automotive Industry (VDA)
- acceleration monitoring in hydrogen lean operation
- diagnosis for hydrogen operation.

4.2 Auxiliary Control Unit for Hydrogen

The V12 petrol engine of the BMW 760i has two cylinder banks each with six high-pressure petrol injectors, actuated by two auxiliary control units, **Figure 8**. The bi-fuel V12 engine has been equipped with six hydrogen injection valves per bank and with several sensors. This required the development of an auxiliary control unit for hydrogen operation.

4.3 Hydrogen Tank and Safety Control Unit

A further control unit was developed in order to cover all hydrogen supply functions and vehicle's hydrogen safety monitoring. The software was developed on the basis of the International Electrochemical Commission's norm IEC61508 SIL3 (safety integrity level 3) to comply with the highest possible safety standards.

The main functions of this control unit include the management of the operating mode (petrol / hydrogen), of the refuelling procedure, the supply of hydrogen to the engine, the pressure regulation in the tank during hydrogen withdrawal, calculation of the mileage and also other safety, monitoring, diagnostic and service functions.

5 Summary

The BMW Hydrogen 7 has completed all the necessary and customary procedures in a series development process. The special features of hydrogen as the fuel have been taken into account. Basis framework conditions had to be established, such as:
- training the personnel working on the project
- qualifying and equipping the workshops
- integration into the plants‘ production processes
- setting up hydrogen engine and component test rigs
- creating the hydrogen infrastructure at the various test locations.

Altogether, it has been proved that the hydrogen-powered combustion engine vehicle is ready for production on an industrial scale. The same production facilities as for petrol engines are used. All quality and safety requirements are satisfied to an identical standard.

The full expertise for the development and production of hydrogen-powered combustion engines is consequently available.

The insignificantly higher weight (<10 %) of the engine can be offset by a mono-fuel concept. The production costs of a mono-fuel power train are on a par with those of a petrol engine provided the necessary production scale can be achieved.

Higher specific power outputs are possible with supercharging and/or direct injection. This has already been proved on the test rig with real engines.

Even if the BMW Hydrogen 7 is not comparable to the BMW 760i in terms of road performance, it demonstrates that sustainable mobility and the proverbial sheer driving pleasure are not mutually exclusive.

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Figure 1: Cooling duct piston
Figure 2: Engine's hydrogen supply system
Figure 3: Hydrogen injection valve
Figure 4: Coolant circuit for the hydrogen heat exchanger
Figure 5: Full-load characteristic curves
Figure 6: NO_x diagrams for $\lambda = 0.97$
Figure 7: Operating strategy with λ leap
Figure 8: Auxiliary control unit for hydrogen - functional diagram