Operation of gasoline engines on natural gas

The Association of European Vehicle Manufacturers (ACEA) has undertaken a commitment to reduce average CO_2 emissions to 140 g/km by the year 2008. This represents a reduction of 25 % when set against the figures recorded back in 1995. Vehicle concepts based on CNG (Compressed Natural Gas) contribute to lowering CO_2 emissions. Because natural gas is not yet extensively available at filling stations, it should also be possible for the engine to be run on gasoline.

The EU Commission has plans by 2020 to replace 23 % of gasoline and diesel consumption with alternative fuels in Europe. The main contribution to this reduction – at 10 % – is to be made by natural gas (Fig. 1).

Germany currently (as at: July 2005) has roughly 30,000 natural-gas vehicles and 603 natural-gas filling stations. Because natural gas exhibits better environmental properties than gasoline and diesel, its use in motor vehicles is to be encouraged up to 2020 in Germany by means of a lowered tax on mineral oil. Thus, equivalent-energy natural gas will be offered at filling stations at prices which are roughly 50 % cheaper than gasoline.

Local efforts are also being made to use alternative fuels in South America and parts of Asia. Natural gas is leading the way in these local schemes.

Overview

Properties of natural gas

The primary constituent of natural gas is methane (CH_4). Natural gas therefore has the highest hydrogen content of all the fossil fuels. When it is burned, it creates approximately 25 % fewer CO_2 emissions than gasoline while providing the same amount of energy.

Natural gas is available throughout the world. Its composition, however, varies depending on where it originates. These variations influence density, calorific value and knock resistance. The use of natural gas in motor vehicles has hitherto not been subject to standardization.

Another advantage is that methane can also be regeneratively manufactured from biomass. In this way, the CO_2 cycle is completed and long-term availability can be increased.

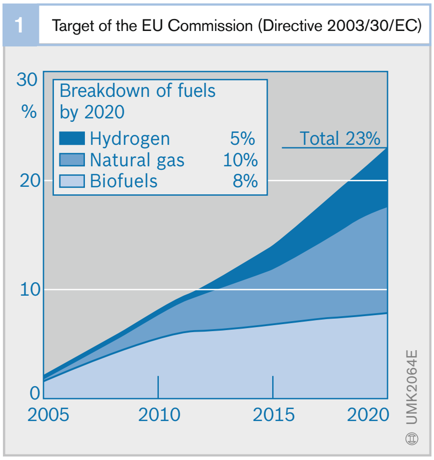
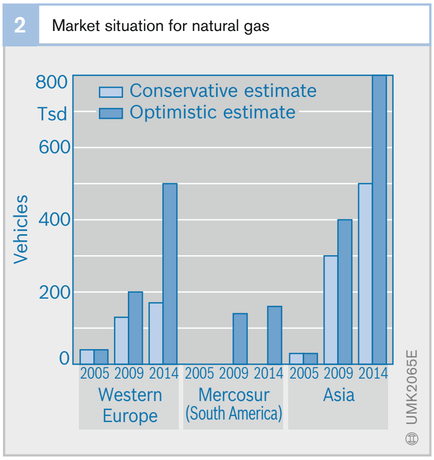

1 Target of the EU Commission (Directive 2003/30/EC)

Fig. 1
Replacement of approx. 23 % of gasoline/diesel demand with alternative fuels


2 Market situation for natural gas

K. Reif (Ed.), *Gasoline Engine Management,* Bosch Professional Automotive Information,
DOI 10.1007/978-3-658-03964-6_9, © Springer Fachmedien Wiesbaden 2015

Properties of natural-gas drives

Because of the simpler molecular structure of methane and due to the fact that it is introduced into the engine in gaseous form, the untreated emissions (HC, NO_X) from a natural-gas engine are significantly lower than those from a gasoline engine. The emission of non-limited pollutants (aldehydes, aromatic hydrocarbons, etc.) and the emission of sulfur dioxide and particulates is virtually avoided completely with natural gas.

Natural gas has a very high knock resistance of up to 130 RON (by comparison, gasoline: 91...100). It is therefore possible, by comparison with a gasoline engine, to increase compression by approximately 20 % and thus raise efficiency. At the same time, the natural-gas engine is ideally suited to supercharging. In combination with a downsizing concept, in which the engine displacement is reduced and at the same time the engine is supercharged to its original power output, it is possible to obtain an additional improvement in efficiency and with it a further CO_2 reduction.

Because natural gas is low in density, it is more complicated to store it in a tank than it is to store gasoline and diesel. It is usually stored in the vehicle in gas form at an overpressure of 200 bar in steel or carbon-fiber tanks (hence the designation CNG = *Compressed Natural Gas*). It requires four times the conventional gasoline or diesel tank volume for the same energy content. It is nevertheless possible through optimized installation of the pressure accumulators (e.g., locating the tanks under the vehicle floorpan) to achieve ranges of currently roughly 400 km without additionally having to reduce the size of the luggage compartment.

Alternatively, natural gas can also be liquified at temperatures of –162 °C (LNG = *Liquefied Natural Gas*). However, the process of liquifying the gas expends a great deals of energy and the tanks are expensive. Today, almost exclusively CNG tanks are used in passenger-car applications.

Because of the advantage of lower CO_2 emissions and the possibility of adapting gasoline engines to natural gas at relatively little expense, natural gas fulfills a good many of the conditions to be able to experience a dramatic upturn in use in the short term.

Use of natural-gas vehicles

In Europe, natural-gas-powered vehicles have up to now predominantly been used in commercial fleets (e.g. vehicle pools of larger companies or city buses). The consistent buildup of the CNG filling-station network in Germany and agreements to provide natural gas at interstate-highway filling stations is encouraging the further spread of natural-gas vehicles, even in private transport.

Today, the largest fleet of natural-gas vehicles is in South America. This market has been determined up to now by conversion systems. However, a trend towards the series production of natural-gas vehicles can also be foreseen here. The greatest potential for growth is to be anticipated in Asia, because here, in addition to CO_2 emission aspects, underlying economic conditions promote the use of natural gas. Natural-gas-producing countries, such as, for instance, Iran, have a strong interest in using the gas in mobile applications as well.

In the NAFTA region (North America), there are currently no significant developments to speak of because the market-structure incentives are lacking. Here the trend is more towards gasoline hybrid vehicles.

Design and method of operation

Because of the limited number of natural-gas filling stations, today's natural-gas vehicles are primarily designed as bivalent vehicles (bifuel and monovalent-plus vehicles), i.e. as well as running on gas, they can also be run on conventional gasoline. The basis for the natural-gas system is the spark-ignition engine with manifold injection (Fig. 3). Additional components for supplying and injecting natural gas are required. The Bifuel-Motronic ECU controls both fuel operating modes.

Monovalent-plus vehicles are optimized for running on natural gas and only have a 15-l emergency gasoline tank. Today's natural-gas tanks are made from steel or fiber composites. For strength reasons, the shape of the tank cannot be freely selected. This often gives rise to problems of space in the vehicle. A combination of several tanks, sometimes even of different sizes, is therefore used in many vehicles.

Method of operation of fuel supply in a natural-gas system

The natural gas stored at approximately 200 bar in the tanks (Fig. 3, Pos. 13) flows through individual tank shutoff valves (12) to the pressure-regulator module (6). The electromagnetically actuated high-pressure shutoff valve on the tank ensures that when it is de-energized the tank is sealed off tight when the vehicle is stationary. In the event of a system failure, the pressure-limiting valve ensures that unacceptably high pressures in the system can be reduced.

The pressure regulator reduces the gas pressure from a tank pressure of roughly 200 bar to a constant system pressure of approximately 7 bar. A coolant port serves to heat the natural gas cooled by expansion. The high-pressure sensor enables the tank fill level (fuel gage) to be determined and can be called on for system diagnosis. In the interests of increasing the accuracy of the fill-level measurement, the pressure measurement can be combined with a temperature measurement.

3 Bifuel-Motronic fuel system (natural gas/gasoline)

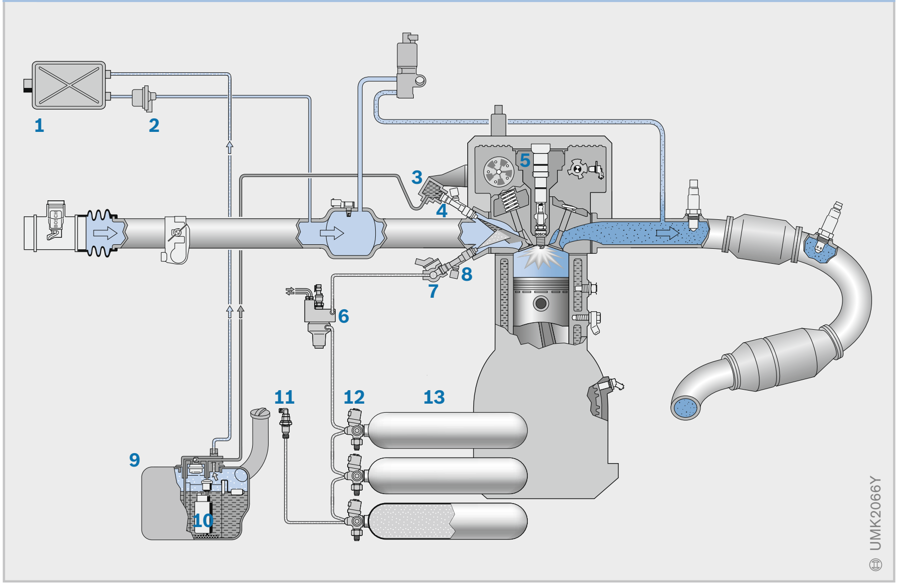


Fig. 3
1 Carbon canister with canister-purge valve
2 Canister-purge valve
3 Fuel rail
4 Gasoline injector
5 Ignition coil with spark plug
6 Natural-gas pressure regulator
7 Natural-gas rail with natural-gas pressure and temperature sensor
8 Natural-gas injector
9 Fuel tank
10 Fuel-supply module with electric fuel pump
11 Filler neck for gasoline and natural gas
12 Natural-gas-tank shutoff valves
13 Natural-gas tank

The gas is directed from the pressure-regulator module to the rail (7), which supplies one injector (8) per cylinder. Mixture formation is effected through the injection of fuel into the intake manifold. A combined low-pressure/temperature sensor (7) serves to correct the metering of the gas.

All the system components which may come into contact with natural gas must be certified for use in accordance with European Directive ECE-R110. In Germany, the necessary tests and inspections are carried out by TÜV (German Technical Inspection Agency).

Mixture formation

An unusual feature of the natural-gas engine is the injection of the fuel in gas form into the intake manifold (Fig. 4). This is effected along the same lines as gasoline by injection into the intake manifold ahead of the intake valves.

The natural-gas injectors are supplied via a common gas rail, which is connected to the pressure regulator. The system pressure regulated to 7 bar is monitored by a diagnostic function. For safety reasons, the gas-supply system features in addition to the injectors two gas shutoff valves on the tank and on the pressure regulator which are electromagnetically actuated by the engine-management system. The shutoff valves are only opened when both the ignition is switched on and engine running is detected. This safety function is necessary so that the gas supply can be immediately and safely interrupted in the event of a malfunction or an accident.

4 Installation positions of natural-gas and gasoline injectors

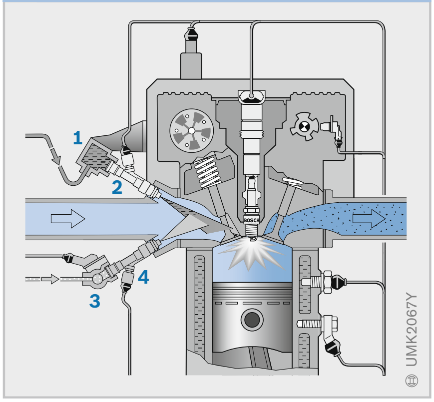


Fig. 4
1 Fuel rail
2 Gasoline injector
3 Natural-gas rail
4 Natural-gas injector

As with gasoline injection, the system utilizes sequential multipoint injection, whereby the fuel is injected through an injector for each cylinder in sequence into the respective intake port. This process provides for efficient mixture preparation by means of precision-timed injection control. The injector can be either completely opened or completely closed. The injected gas quantity is adjusted solely by way of the injector's opening duration. The injector is opened once for every induction stroke of the engine.

In contrast to gasoline injection, gas injection involves a noticeable amount of fresh air being displaced by the natural gas. Due to the lower density of natural gas, at full load approximately 10 % by volume of the inducted air/fuel mixture consists of natural gas. At the same time, however, this means that natural-gas engines have a lower air delivery ratio. In naturally aspirated engines, this can cause a reduction in power compared with a gasoline engine. This can, however, be compensated for by higher compression and turbocharging. With these measures – combined with the high knock resistance of natural gas – it is possible even to achieve an increase in power compared with a gasoline engine.

During the injection of natural gas – comparable with gasoline injection – the injection duration is calculated while taking into account the injector constant. The injector constant here is dependent on the design of the injectors and defines the static throughflow $mfng_0$, which obtains under the standard condition and with flow above critical.

The gaseous mass flow through the injector is essentially calculated differently from a liquid fuel.

The density of natural gas is much lower than that of gasoline. In terms of gas-injector design, this results in larger opening cross-sections. Furthermore, the density ϱ of gases is dependent on temperature T and pressure p to a much greater extent than liquid fuels.
The density ϱ_{NG} of natural gas is:

$$\varrho_{NG} = \varrho_{NG0} \cdot \frac{p_{NG}}{p_0} \cdot \frac{T_0}{T_{NG}} \qquad (1)$$

The index 0 denotes the status under the standard condition: $p_0 = 1013$ hPa, $T_0 = 273$ K

A defined flow velocity is obtained in the event of a gas flow above critical. This occurs when the pressure ratio at the injector is lower than 0.52. The gas then flows at the speed of sound. A natural-gas admission pressure in the gas rail of 7 bar (absolute pressure) ensures both the supply of the maximum natural-gas quantity required and a flow at the speed of sound at every engine operating point, even with supercharged engines. At the same time, it ensures that the gas is metered independently of the intake-manifold pressure.

The speed of sound is temperature-dependent. In natural gas, it is:

$$c_{NG} = c_{NG0} \sqrt{\frac{T_{NG}}{T_0}} \qquad (2)$$

The obtained gas mass flow *mfng* is then calculated with (1) and (2):

The natural-gas mass flow is dependent linearly on the pressure and with the index –1/2 on the temperature. The installation of a natural-gas pressure and temperature sensor in the natural-gas rail ensures that the variables which influence the mass flow are known. The injection duration is corrected accordingly and the injected gas quantity can thus be correctly introduced even under changing ambient conditions.

Two further corrections are needed for electrical actuation of the injectors. The opening delay of the injectors must be taken into account in the calculation of the opening duration; the opening delay is dependent on the battery voltage and also slightly on the admission pressure of the natural gas. Particularly in the case of injectors with metal/metal seals, the act of the injector closing can cause the valve needle to rebound as it contacts the valve seat, a motion which results in an undesired increase in the injected gas quantity. A correction based on the battery voltage and the natural-gas admission pressure compensates for these effects.

To ensure optimal combustion, it is necessary in addition to correct metering for the correct moment of injection to be determined as well. Generally, the fuel is injected into the intake manifold while the intake valves are still closed. The end of injection is determined by the pre-intake angle, the reference point of which is the closing of the intake valve. The pre-intake angle is specified as a function of the engine operating point. The start of injection can be calculated from the injection duration by means of the engine speed.

$$mfng = mfng_0 \cdot \frac{c_{NG}}{c_{NG0}} \cdot \frac{\varrho_{NG}}{\varrho_{NG0}} = mfng_0 \cdot \sqrt{\frac{T_{NG}}{T_0}} \cdot \frac{p_{NG}}{p_0} \cdot \frac{T_0}{T_{NG}} = mfng_0 \cdot \sqrt{\frac{T_0}{T_{NG}}} \cdot \frac{p_{NG}}{p_0}$$

Natural-gas injector NGI2

Development

Bosch has been making available an electromagnetic natural-gas injector on the CNG market for many years now. This injector, bearing the designation EV1.3A, is based on the gasoline injector and has been adapted for gas metering with an increased needle lift and a stronger magnetic circuit.

Bosch in the meantime has developed a new generation of gas injectors, bearing the designation NGI2 (Natural-Gas Injector 2). The NGI2 shares only its external shape and electrical actuation with its original source, the current EV14 gasoline injector for manifold injection. All the functional components have been specifically conceived for use in modern natural-gas vehicles and are entirely new in terms of design. The know-how from the EV14 and above all the knowledge and experience gained with the previous EV1.3A gas injector are reflected in the NGI2's design. New findings and discoveries stemming from advance development in the related field of components for hydrogen drives have also played a role. Thus, the NGI2 brings together a series of technical innovations which sets new standards in the field of gas metering.

5 Size comparison of NGI2 and EV1.3A

Design criteria

The maximum required natural-gas mass flow through the injectors, based on a defined engine spectrum, is specified for the development of the injectors. This maximum required natural-gas mass flow is derived from the inducted air-mass flow of the internal-combustion engine, the desired air/fuel ratio (lambda value) and the gas quality. The inducted air-mass flow is in turn dependent on the effective engine displacement, on the engine speed, on the mixture temperature and on the mixture pressure in the combustion chamber when the intake valves close.

A high percentage of CNG applications in the passenger-car field including turbocharged engines can be covered with a maximum natural-gas mass flow of 7.5 kg/h.

In order to supply the internal-combustion engine with this mass flow of gaseous fuel, it is necessary to meter through the gas injectors much more gas in terms of volume than gasoline in a conventional gasoline engine. This requirement places specific demands on the design of the gas injector, which must be adapted to the greater gas volume in its cross-sections. Even the high flow velocities that are encountered call for a special form of flow routing in order to reduce pressure losses ahead of the throttling point. Configuration for operation above critical (speed of sound in the narrowest cross-section) makes it possible even at higher intake-manifold pressures, such as, for example, on supercharged engines, to deliver a characteristic curve that is not dependent on the intake-manifold pressure.

In highly supercharged engines, the intake-manifold pressure can rise up to 2.5 bar (absolute). In order to suppress the influence of the intake-manifold pressure on the mass flow, it is necessary for the admission pressure at the narrowest cross-section accepted as the nozzle above critical to be at least twice as high as the maximum intake-manifold pressure. While taking into account possible pressure losses, this produces a minimum system pressure of 7 bar (absolute).

This design quantity forms the basis of the NGI2, since all applications are to be covered with a single design (principle of effective action).

Increasing the mass flow by raising the admission pressure is basically possible. At the same time, however, the opening force required in the injector increases with the result that the possible system pressure is limited in the upward direction by the restricted magnetic force. The NGI2 has been optimized for a system pressure of 7 bar (absolute) to its maximum mass flow. The injector can also be configured by simple modification to higher admission pressures with an identical mass flow. Even lowering the system pressure with smaller mass-flow demands is basically possible.

Design and method of operation

Individual parts and operation

The operating principles of the NGI2 are similar to those of the EV14 gasoline injector. The direction of fuel flow (top feed), the connections and the form of electrical actuation are identical. However, the individual parts have been adapted for use in the natural-gas system.

The solenoid armature (Fig. 6, Pos. 9) is guided in a sleeve (6). The armature has fuel flowing through it on the inside and has an elastomer seal at the discharge end. This seal closes on the flat seat (10) and thereby seals off the fuel supply from the intake manifold. When energized, the solenoid coil (7) effects the necessary force to lift the solenoid armature and open the metering cross-section (throttling point in the valve seat). When the coil is de-energized, the NGI2 is held closed by a resetting spring (8).

Size and weight

The outer shape of the NGI2 is the same as that of the EV14 gasoline injector. In comparison with established gas injectors, the NGI2 is extremely light and compact. These qualities make it easy to integrate in existing intake-manifold geometries.

Flow-optimized geometry

With regard to the routing of the flow in the NGI2, the pressure loss has been minimized ahead of the throttling point in order to ensure the greatest possible mass flow. Furthermore, the narrowest cross-section and thus the throttling point has been intentionally situated at the discharge end after the seal. The speed of sound is obtained here such that the injector conforms approximately to the physical description of an ideal nozzle. The injector is designed for operation above critical in order to minimize to the greatest possible extent the influence of the intake-manifold pressure on the mass flow. Thanks to a double routing of flow, the layout of the

6 NGI2 injector (section)

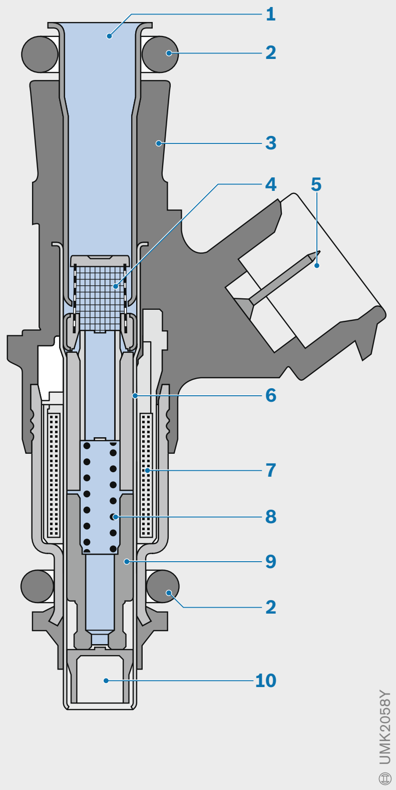


Fig. 6
1 Pneumatic port
2 O-ring
3 Valve housing
4 Filter strainer
5 Electrical connection
6 Sleeve
7 Solenoid coil
8 Valve spring
9 Solenoid armature with elastomer seal
10 Valve seat

valve seat allows a large cross-section to open with relatively low opening force.

Variant range

The NGI2 is available in different lengths and with different plug connectors. Furthermore, variants have been developed for different system pressures and with different flow rates. Thus, as is the case with gasoline injectors, a range of variants is available for different engines.

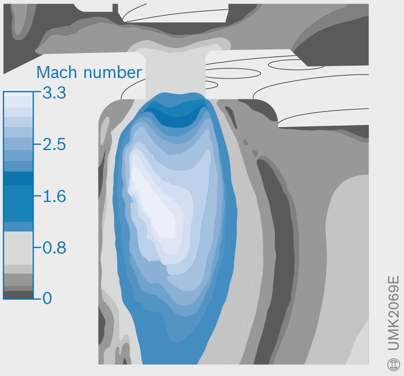
Sealing geometry

The NGI2 is fitted with an elastomer seal and is similar in terms of its seal-seat geometry to shutoff valves for pneumatic applications. Thus, the NGI2 leaks much less than the EV1.3A. Damping in the elastomer also prevents "rebounding", i.e., a repeated, unwanted opening of the solenoid armature during the closing operation, and thus increases metering precision.

Noise

The optimized routing of flow greatly reduces the armature stroke. This in turn reduces the speed of the solenoid armature as it reaches its stops. When combined with the damping properties of the elastomer seal in the seat stop, the NGI2 has an overall sound-pressure level which is 2 dB lower than its predecessor.

7 CFD simulation of seal-seat geometry, speed of sound in the narrowest cross-section



Solenoid coil

At 12 ohms, the NGI2's solenoid coil has the same resistance as the EV14 gasoline injector. Whereas, previously, complicated actuation arrangements, such as parallel-switched output stages or peak-and-hold control, were used to operate low-resistance gas injectors, a standard switching output stage can be used with the NGI2.

Variable oil content

Natural gas is becoming increasingly more widespread as a fuel and the number of natural-gas filling stations is growing constantly in Europe. Especially newer filling stations are equipped with modern compressors which inject less oil into the compressed gas than older compressor types. In future, therefore, it can no longer be assumed that natural gas will have a lubricating and thus wear-reducing effect in the injector.
A solid-lubricant layer on the surface of the solenoid armature ensures that the NGI2 is able to cope with variable oil content in natural gas right down to the detection limit with minimal wear.

Natural-gas rail

The function of the rail is to supply the gas injectors with natural gas in uniform quantities and with minimal pulsations. It is made from stainless steel or aluminum. Design and construction (volume, dimensions, weight, etc.) are engine- and system-specific. The gas is usually supplied to the rail via a flexible low-pressure line.

The rail has a screwed connection, through which it is supplied with gas in the middle or from the side (low-pressure side of the fuel-supply system).

The injectors are held in place with retaining clips in the injector receptacles on the rail. The rail is provided optionally with an attachment point at which a gas pressure and temperature sensor can be attached to the rail.

Combined natural-gas pressure and temperature sensor

Function

Monolithic silicon pressure sensors are high-precision measuring elements for determining absolute pressure. They are particularly suitable for use under rough ambient conditions, such as, for example, for measuring the absolute natural-gas pressure in the rail of CNG-powered vehicles.

The combined low-pressure/temperature sensor (DS-K-TF) measures pressure and temperature in the natural-gas rail and controls exact gas metering by means of the ECU.

Design and method of operation

The sensor consists of the following main components:

- Plug housing (Fig. 8, Pos. 1) with electrical connection (6)
- Sensor cell (2) with silicon chip (9) and etched-in pressure diaphragm (8)
- NTC sensor element (5)
- Fitting (4)
- Outer O-ring (3)

A change in the gas pressure causes the silicon-chip pressure diaphragm to elongate; this elongation is recorded by way of changes in resistance by resistors situated on the silicon chip. The evaluator circuit is likewise integrated together with the electronic compensating elements on the silicon chip.

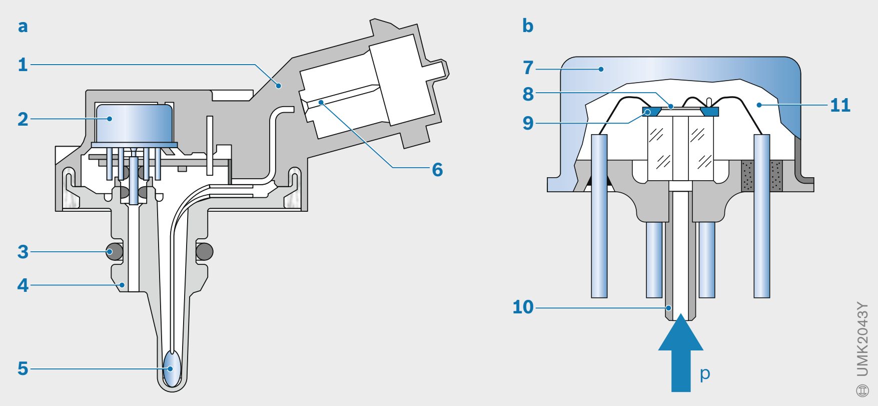
The silicon chip with glass base is soldered to a metal base with the pressure connecting tube (10). The gas pressure (CNG) is routed through this tube to the lower side of the pressure diaphragm. Underneath the cap (7) welded to the metal base is a reference

Fig. 8
a Overall view
b Sensor cell

1 Plug housing
2 Sensor cell
3 O-ring (outer)
4 Fitting
5 NTC (temperature sensor)
6 Electrical connection (plug)
7 Cap
8 Etched-in silicon-chip diaphragm
9 Silicon chip with glass base
10 Pressure connecting tube
11 Reference vacuum

p Gas pressure

8 DS-K-TF combined natural-gas pressure and temperature sensor



vacuum (11), which enables the absolute pressure to be measured and simultaneously protects the upper side (circuit side) of the chip diaphragm against harmful environmental influences. The finish-compensated sensor cell is mounted in a plug housing with an electrical connection.

The sensor incorporates an NTC sensor element for recording the gas temperature. The fitting is glued tightly onto the plug housing.

The sensor is sealed, for example from the gas rail, by a natural-gas-resistant O-ring.

Signal evaluation

The combined low-pressure/temperature sensor delivers an analog pressure output signal which is ratiometric to the supply voltage. An RC low-pass filter in the input section of the subsequent electronic circuitry ensures that potentially disruptive harmonic waves are suppressed.

The integrated temperature sensor consists of an NTC thermistor and must be operated with a corresponding series resistor as a voltage divider.

DS-HD-KV4 high-pressure sensor

Function

The high-pressure sensor in natural-gas-powered spark-ignition engines is integrated in the pressure-regulator module. Its function is to measure the pressure of the natural gas in the tank.

Design and method of operation

The core of the sensor is a steel diaphragm, which is welded tight on a threaded fitting (Fig. 9). The sensor is mounted in the pressure-regulator module by means of the thread. Strain gages are integrated in a bridge circuit on the upper side of the steel diaphragm.

When pressure is applied, the steel diaphragm elongates and the bridge circuit is detuned. The resulting bridge voltage is proportional to the applied pressure. It is directed via bonded wires to the evaluator circuit, amplified and converted into an output voltage of 0.5 V...4.5 V. From this signal, the engine ECU calculates the current tank pressure using a characteristic curve.

9 DS-HD-KV4 high-pressure sensor

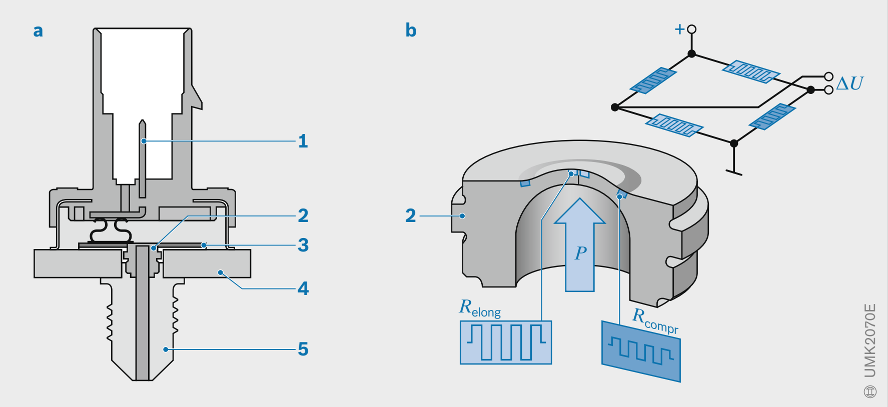


Fig. 9
a Sectional drawing
b Measurement principle

1 Plug
2 Sensor element
3 Circuit holder
4 Housing base
5 Threaded fitting

TV-NG1 tank shutoff valve

Function

The TV-NG1 tank shutoff valve is screwed directly into the natural-gas tank and serves as the interface to the fuel system in the vehicle. The function of the TV-NG1 is to open up and shut off the gas flow. A solenoid shutoff valve (SOV-NG1) is integrated in the TV-NG1 for this purpose.

In addition, various service and safety devices are mounted on the TV-NG1:

- The gas flow can be interrupted for repairs with a mechanical shutoff valve.
- A flow limiter ensures that the contents of the tank are drained under throttled conditions if the natural-gas high-pressure line is severed in the event of an accident.
- A fusible link provides protection in the event of fire. At a temperature of approximately 110 °C, the fuse blows and ensures that the contents of the tank are discharged under controlled conditions to atmosphere.
- A pressure-limiting valve or a temperature sensor can also be optionally installed.
- It is possible with the aid of the optional temperature sensor to measure the tank contents more precisely when compared with pure pressure measurement.

10 TV-NG1 tank shutoff valve

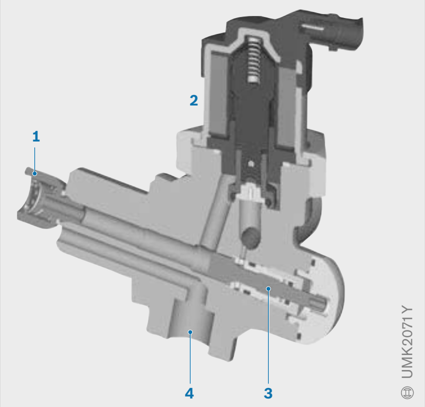


Fig. 10
1 Flow limiter
2 Electromagnetic valve
3 Manual shutoff valve
4 Port, safety valve

Design

Two different types of tank shutoff valve may be used: internal and external. On an external tank shutoff valve, the individual attachment parts are mounted outside the gas bottle, as on a conventional gas fitting. On an internal tank shutoff valve, all the devices are integrated in the valve block and project into the gas tank. From the outside, only a plate containing the connections can be seen. This design provides for enhanced crash safety when compared with an external tank shutoff valve, and at the same time the reduced height makes it possible to use longer tanks and thereby optimize the tank volume.

Method of operation

Fig. 10 shows the external TV-NG1, consisting of the valve block and the SOV-NG1 modular shutoff valve (2). The SOV-NG1 is a two-stage solenoid valve for shutting off natural gas and is closed when de-energized. The closing process is initiated after the current is deactivated by a spring, which forces the sealing element onto the seal seat. The valve is also held closed with the assistance of the system pressure.

The SOV-NG1 operates according to a two-stage opening principle, i.e., pressure equalization is established in the first opening stage (small cross-section) and only then is the full throughflow cross-section opened. From a system point of view, a peak-hold actuation proves to be effective. In this case, after actuation, the valve switches back with a high opening current to a lower holding current in order to reduce electrical power loss. However, the valve can also be permanently operated with the opening current. A trapezoidal plug serves as the electrical interface.

PR-NG1 pressure-regulator module

Function

The function of the PR-NG1 pressure-regulator module is to reduce the pressure of the natural gas from tank pressure to the nominal operating pressure. At the same time, the operating pressure must be kept constant within specific tolerances through all operating states. The operating pressure of present-day systems is usually about 7...9 bar (absolute). There are also systems which operate at pressures starting from 2 bar ranging up to 11 bar.

Design

Today, mainly diaphragm- or plunger-type pressure regulators are used. Pressure reduction is effected by means of throttle action and can occur either in one single stage or in several stages.

Figure 11 shows the sectional view of a single-stage diaphragm-type pressure regulator. A 40 µm sinter filter, a shutoff valve (SOV-NG1), and a high-pressure sensor are provided on the high-pressure side. The sinter filter is designed to retain solid particulates in the gas flow, while the SOV-NG1 serves to shut off the gas flow. A pressure sensor is incorporated to determine the fuel level in the tank.

A pressure-relief valve is mounted on the pressure regulator on the low-pressure side. In the event of a fault in the pressure regulator, this pressure-relief valve prevents damage to components in the low-pressure system. When the gas expands, the PR-NG1 cools down sharply in accordance with the Joule-Thompson effect. The PR-NG1 is therefore connected to the vehicle's heating circuit to prevent it from freezing up.

The operating pressure is preset by selecting the appropriate types of diaphragm and compression spring. An adjusting screw which is preset and sealed at the factory is used for fine adjustment of the spring preload.

11 PR-NG1 pressure-regulator module

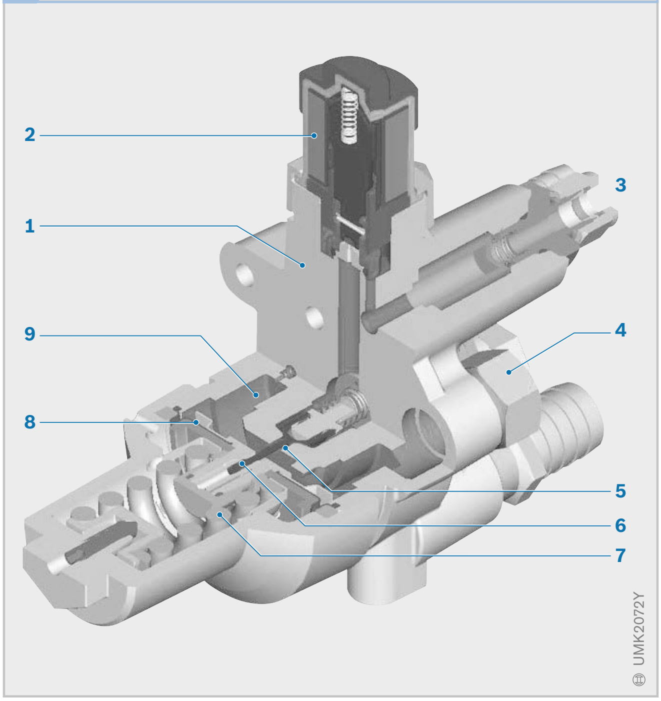


Fig. 11
1 Regulator housing
2 SOV-NG1 electromagnetic shutoff valve
3 CNG inlet
4 CNG outlet
5 Throttling orifice for pressure regulation
6 Control rod
7 Spring
8 Diaphragm
9 Low-pressure chamber

Method of operation

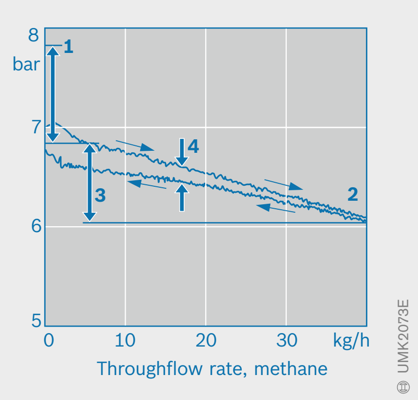
The gas flows from the high-pressure side through a variable throttling orifice (5) into the low-pressure chamber (9), where the diaphragm (8) is situated. The diaphragm controls the opening cross-section of the throttling orifice (5) via a control rod (6). When the pressure in the low-pressure chamber is low, the diaphragm is forced by the spring (7) in the direction of the throttling orifice, which opens to allow the pressure to increase on the low-pressure side. In the event of excessive pressure in the low-pressure chamber, the spring is compressed more sharply and the throttling orifice closes. The decreasing cross-section of the throttling orifice reduces the pressure on the low-pressure side. In stationary operation, the system levels out at a specific throttle opening and keeps the pressure in the low-pressure chamber constant.

If now the gas demand in the system increases, e.g., when the accelerator pedal is pressed, at first more gas is discharged from the pressure regulator than can follow up through the throttling orifice. As a result, the pressure in the low-pressure area drops briefly until the throttling orifice opens to such an extent as to re-establish a constant pressure for the increased throughflow. Minimal system-pressure fluctuations in the event of load changes testify to the quality of the pressure regulator.

When the pressure in the low-pressure chamber exceeds a specific value, e.g., because no gas is discharged into the system, the throttling orifice closes completely. This pressure is known as the lock-off pressure. The throttling orifice reopens when the pressure drops. The process of the throttling orifice opening and closing is accompanied by a buildup of noise and wear. In the interests of minimizing this, pressure regulators are normally designed in such a way that the lock-off pressure is so far above the system pressure that the throttling orifice always remains open in normal operation.

An ideal pressure regulator keeps the pressure constant, regardless of the throughflow. In reality, however, pressure regulators deviate from this ideal behavior on account of side effects. Figure 12 depicts a typical throughflow curve for a single-stage pressure regulator. The output pressure drops as throughflow increases, and hysteresis is also encountered between increasing and decreasing throughflow. This hysteresis arises on account of frictional and flow losses. Basically, the effects shown occur most clearly when the throughflow is high and the pressure regulator has a compact design.

12 Throughflow curve for the PR-NG1



Ⓑ UMK2073E

Fig. 12
1 Lock-off pressure
2 Setting pressure
3 Maximum pressure drop
4 Hysteresis

Real-world fuel economy

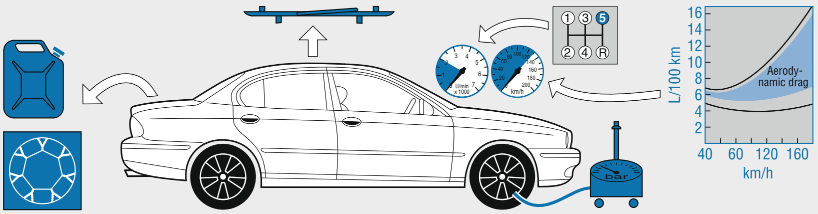
Manufacturers must furnish fuel-consumption data for their vehicles. The official figures are calculated based on the composition of the exhaust gases monitored during emissions testing. Emissions testing is conducted based on a standardised test procedure, or driving cycle. The standardized procedure provides emissions figures suitable for comparison among vehicles.

Motorists can make a major contribution to improved fuel economy by adopting a suitable driving style. Potential fuel savings vary according to a variety of factors.

By adopting the practices listed below, the “economy-minded” motorist can achieve fuel savings of 20...30 % compared to the “average” driver. The latitude available for enhancing fuel economy depends upon a number of factors. Especially significant among these are operating environment (urban traffic or long-distance cruising, etc.) and general traffic conditions. This is why attempts to quantify the precise savings potential represented by each individual factor are not always logical.

Increasing fuel economy

- Tire pressures: Remember to increase inflation pressures when vehicle is loaded to capacity (savings: roughly 5 %)
- Accelerate at wide throttle openings and low engine speeds, upshift at 2000 rpm
- Drive in the highest possible gear: even at engine speeds below 2000 rpm it is possible to apply full throttle
- Plan ahead to avoid continuous alternation between braking and acceleration
- Exploit the potential of the trailing-throttle fuel cutoff
- Switch off engine during extended stops, such as at traffic lights with extended red phases and at railroad crossings, etc. (3 minutes of idling consumes as much fuel as driving 1 kilometer)
- Use full-synthetic engine oils (savings of approximately 2 % according to the manufacturer)



Negative influences on fuel economy

- Added vehicle weight caused by unnecessary ballast in the luggage compartment (adds roughly 0.3 liters/100 km)
- High driving speeds
- Increased aerodynamic drag from roof-mounted racks and luggage carriers
- Activation of supplementary electrical accessories such as rear-screen defroster, fog lamps (approximately 1 liter/1 kW load)
- Contaminated air filter and worn spark plugs (observe service intervals)