Gasoline direct injection

Gasoline direct-injection engines generate the air/fuel mixture in the combustion chamber. During the induction stroke, only the combustion air flows through the open intake valve. The fuel is injected directly into the combustion chamber by special fuel injectors.

Overview

The demand for higher-power spark-ignition engines, combined with the requirement for reduced fuel consumption, were behind the "rediscovery" of gasoline direct injection. The principle is not a new one. As far back as 1937, an engine with mechanical gasoline direct injection took to the air in an airplane. In 1951 the "Gutbrod" was the first passenger car with a series-production mechanical gasoline direct-injection engine, and in 1954 the "Mercedes 300 SL" with a four-stroke engine and direct injection followed.

At that time, designing and building a direct-injection engine was a very complicated business. Moreover, this technology made extreme demands on the materials used. The engine's service life was a further problem. These facts all contributed to it taking so long for gasoline direct injection to achieve its breakthrough.

Method of operation

Gasoline direct-injection systems are characterized by injecting the fuel directly into the combustion chamber at high pressure (Fig. 1). As in a diesel engine, air/fuel-mixture formation takes place inside the combustion chamber (internal mixture formation).

High-pressure generation

The electric fuel pump (Fig. 2, Pos. 19) delivers fuel to the high-pressure pump (4) at a presupply pressure of 3...5 bar. The latter pump generates the system pressure depending on the engine operating point (requested torque and engine speed). The highly pressurized fuel flows into and is stored in the fuel rail (Fig. 1, Pos. 6).

1 Gasoline direct injection (engine section)

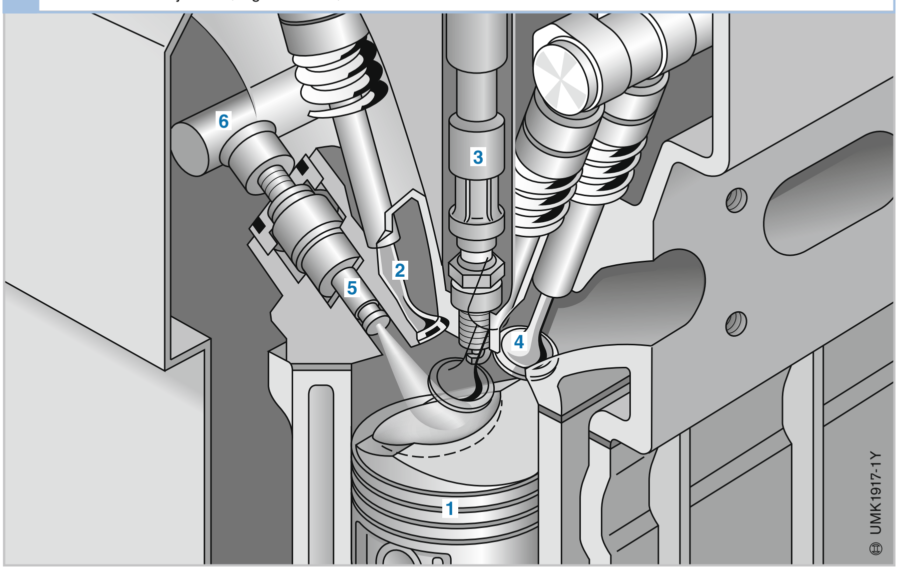

Fig. 1
1 Piston
2 Intake valve
3 Ignition coil and spark plug
4 Exhaust valve
5 High-pressure fuel injector
6 Fuel rail

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The fuel pressure is measured with the high-pressure sensor and adjusted via the pressure-control valve (in the HDP1) or the fuel-supply control valve integrated in the HDP2/HDP5 to values ranging between 50 and 200 bar.

The high-pressure fuel injectors (5) are mounted on the fuel rail, also known as the "common rail". These injectors are actuated by the engine ECU and spray the fuel into the cylinder combustion chambers.

Combustion process

In the case of gasoline direct injection, the combustion process is defined as the way in which mixture formation and energy conversion take place in the combustion chamber. The mechanisms are determined by the geometries of the combustion chamber and the intake manifold, and the injection point and the moment of ignition. Depending on the combustion process concerned, flows of air are generated in the combustion chamber. The relationship between injected fuel and air flow is extremely important, above all in relation to those combustion processes which work with charge stratification (stratified concepts). In order to obtain the required charge stratification, the injector fuel injects the fuel into the air flow in such a manner that it evaporates in a defined area. The air flow then transports the mixture cloud in the direction of the spark plug so that it arrives there at the moment of ignition.

A combustion process is often made up of several different operating modes between which the process switches as a function of the engine operating point. Basically, the combustion processes are divided into two categories: stratified-charge and homogeneous combustion processes.

Homogeneous combustion process

In the case of the homogeneous combustion process, usually a generally stoichiometric mixture is formed in the combustion chamber in the engine map (Fig. 3a), i.e. an air ratio of $\lambda = 1$ always exists. In this way, the expensive exhaust-gas treatment of NO_X emissions which is required with lean mixtures is avoided. Homogeneous concepts are therefore set out to be emission-reducing concepts.

2 Components of gasoline direct-injection system

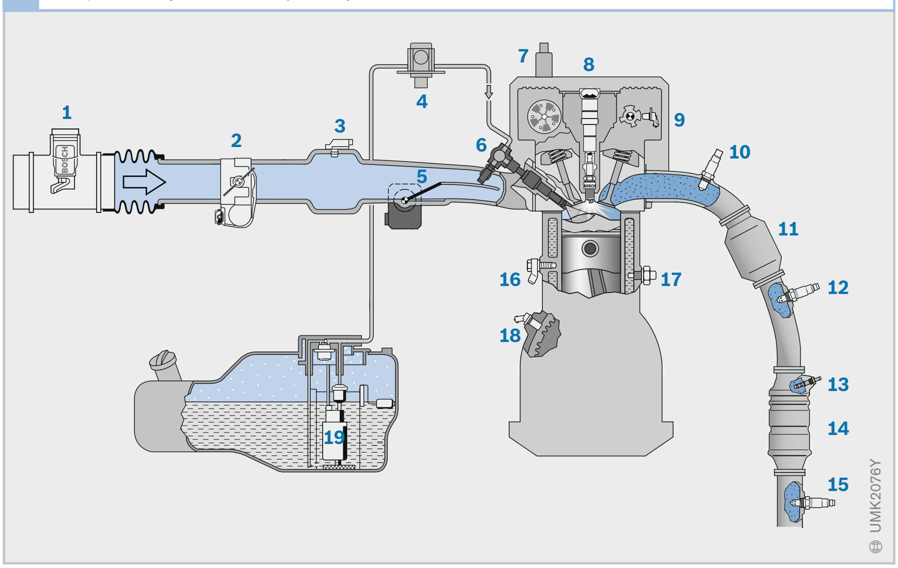


Fig. 2
1 Hot-film air-mass meter
2 Throttle device (ETC)
3 Intake-manifold pressure sensor
4 High-pressure pump
5 Charge-flow control valve
6 Fuel rail with high-pressure injector
7 Camshaft adjuster
8 Ignition coil with spark plug
9 Camshaft phase sensor
10 Lambda sensor
11 Primary catalytic converter
12 Lambda sensor
13 Exhaust-gas temperature sensor
14 NO_X accumulator-type catalytic converter
15 Lambda sensor
16 Knock sensor
17 Engine-temperature sensor
18 Speed sensor
19 Fuel-supply module with electric fuel pump

The homogeneous combustion process is always run in homogeneous mode; there may, however, also be a few special operating modes which can be used differently from engine to engine for specific application purposes (see section entitled "Operating modes").

3 Mixture distribution in the combustion chamber

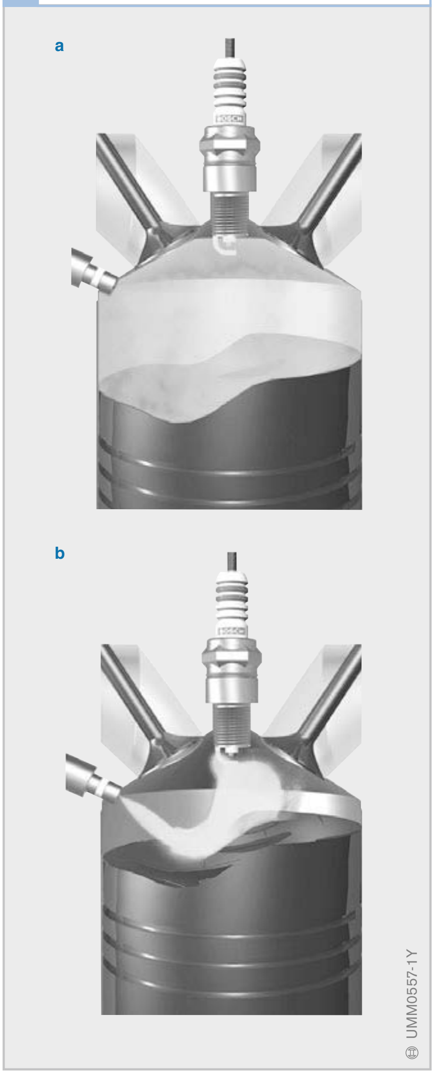


Fig. 3
a Homogeneous mixture distribution
b Stratified mixture distribution

Stratified-charge combustion process

In the case of the stratified-charge combustion process, the fuel is injected in a specific map range (small load, low engine speed) first during the compression stroke into the combustion chamber, and transported as a stratified-charge cloud to the spark plug (Fig. 3b, shown here in the wall-guided combustion process). The cloud here is ideally surrounded by pure fresh air. In this way, an ignitable mixture is only present in the local cloud. An air ratio of greater than 1 exists generally in the combustion chamber. This enables the engine to be operated unthrottled in greater ranges, which results in increased efficiency on account of the reduced pumping losses. Stratified-charge combustion processes are therefore run predominantly as a fuel-consumption concept.

Two different stratified-charge concepts may be used: the wall/air-guided process and the spray-guided process.

Wall/air-guided combustion process

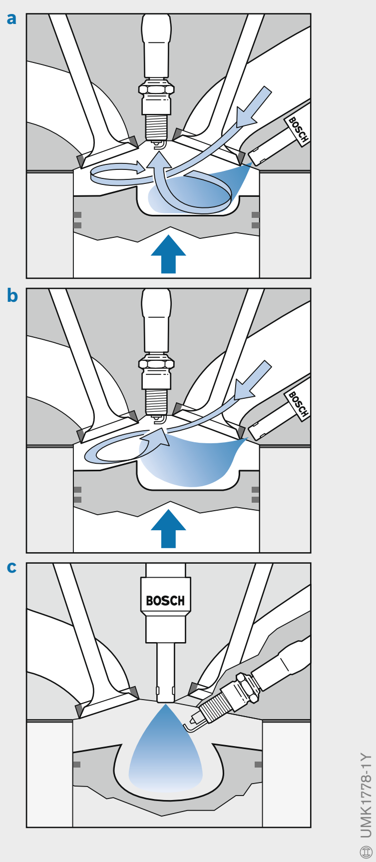
In wall/air-guided stratified-charge mode, the injector is usually situated between the intake valves. In this combustion process, the fuel is usually injected at a pressure of 50 to 150 bar. The mixture is transported via the piston recess, which either interacts directly with the fuel (wall-guided) or guides the air flow in the combustion chamber in such a way that the fuel is directed on an air cushion to the spark plug (air-guided). Real stratified-charge combustion processes with side injector installation usually combine both processes, depending on the installation angle of the injectors and the injected fuel quantity. At idle (low injected fuel quantity), a wall-guided combustion process barely strikes the piston recess; at higher loads (high injected fuel quantity), a certain quantity of fuel strikes the piston directly, even in the case of the air-guided combustion process.

The air flow can be configured as a swirl or tumble flow.

Swirl air flow
The air drawn in through the open intake valve generates a turbulent flow (rotational air movement) along the cylinder wall (Fig. 4a). This process is also known as the "swirl combustion process".

Tumble air flow
This process produces a tumbling air flow, which in its movement from top to bottom is deflected by a pronounced piston recess so that it then moves upwards in the direction of the spark plug (Fig. 4b).

4 Combustion process



Spray-guided combustion process

In the case of the spray-guided combustion process, the injector is situated centrally at the top in the roof of the combustion chamber. The spark plug is installed next to the injector (Fig. 4c). The advantage of this arrangement is the possibility of the fuel spray being directly guided to the spark plug without having to take a circuitous route through the piston or air flows. The disadvantage, however, is the short amount of time available for mixture preparation. Spray-guided stratified-charge combustion processes therefore require a fuel pressure increased to approximately 200 bar.

In order to be able to ignite the mixture at the correct moment in time, the spray-guided combustion process requires that the spark plug and fuel injector be exactly positioned, and that the spray be precisely targeted. With this process, the spark plug is subjected to considerable thermal stressing since under certain circumstances the hot spark plug can be directly impacted by the relatively cold jet of injected fuel.

When the combustion process is properly configured, the spray-guided combustion process demonstrates greater efficiency than the other stratified-charge combustion processes to such an extent that it can achieve even greater consumption savings in comparison with stratified-charge mode with the wall/air-guided combustion process.

Outside the stratified-charge-mode range, the engine is also run homogeneous mode in the case of the stratified-charge combustion process.

Fig. 4
a Wall-guided swirl air flow
b Wall-guided tumble air flow
c Spray-guided combustion process

Operating modes

The different operating modes which are used in gasoline direct injection are described in the following. The appropriate operating mode is set by the engine-management system, depending on the engine operating point (Fig. 1).

Homogeneous

In homogeneous mode, the injected fuel quantity is metered precisely to the fresh air in the stoichiometric ratio of 14.7:1. Here, the fuel is injected during the induction stroke so that there is sufficient time remaining to homogenize the entire mixture. For the purpose of protecting the catalytic converter or increasing power at full load, the engine is also operated with a slight fuel excess in parts of the operating map ($\lambda < 1$).

Since the whole of the combustion chamber is utilized, the homogeneous mode is required when high levels of torque are demanded. Because of the stoichiometric air/fuel mixture, emissions of untreated pollutants are low in this operating mode; these pollutants can also be fully converted by the three-way catalytic converter.

In homogeneous operation, combustion to a great extent corresponds to the combustion for manifold injection.

Stratified charge

In stratified-charge mode, the fuel is first injected during the compression stroke. Here, the fuel is prepared only with part of the air. A stratified-charge cloud which is ideally surrounded by pure fresh air is created. The start of injection is very important in stratified-charge mode. The stratified-charge cloud must be not only sufficiently homogenized at the moment of ignition but also positioned at the spark plug.

Because a stoichiometric mixture is only present locally in stratified-charge mode, the mixture is on average lean on account of the surrounding fresh air. This setup requires more expensive exhaust-gas treatment since the three-way catalytic converter is unable to reduce NO_X emissions in lean-burn operation.

Stratified-charge mode can only be run within certain limits because at higher loads

1 Operating-mode map

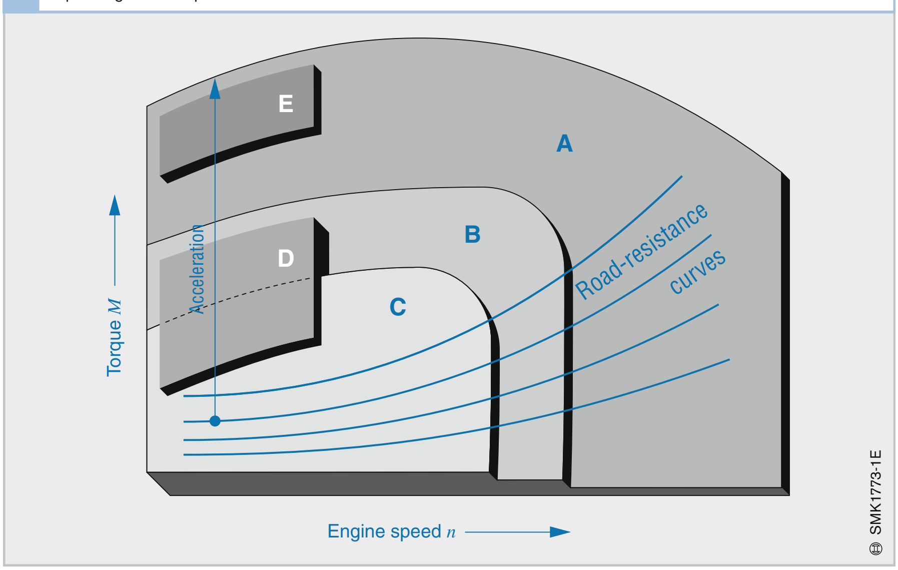


Fig. 1
- A Homogeneous mode at $\lambda = 1$, this operating mode is possible in all operating ranges
- B Lean-burn or homogeneous mode $\lambda = 1$ with EGR; this operating mode is possible in area C and area D
- C Stratified-charge mode with EGR

Operating modes with dual injection:
- C Stratified-charge/cat.-heating mode, same area as stratified-charge mode with EGR
- D Homogeneous stratified-charge mode
- E Homogeneous knock-protection mode

soot and/or NO_X emissions increase dramatically and the fuel-consumption advantages over homogeneous mode are lost. At lower loads, stratified-charge mode is limited by low exhaust-gas enthalpy, i.e., the exhaust-gas temperatures become so low that the catalytic converter cannot be kept at operating temperature by the exhaust gas alone. The speed range is limited to approximately 3000 rpm in stratified-charge mode because at speeds above this threshold the time available is no longer sufficient to homogenize the stratified-charge cloud.

The stratified-charge cloud becomes lean in the peripheral zone adjoining the surrounding air. For this reason, there is an increase in untreated NO_X emissions in this zone during combustion. A high exhaust-gas-recirculation rate provides a remedy in this operating mode. The recirculated exhaust gases lower the combustion temperature and thereby reduce the temperature-dependent NO_X emissions.

Homogeneous lean

In the transitional range between stratified-charge and homogeneous mode, the engine can be run with a homogeneous lean air/fuel mixture ($\lambda > 1$). Since the pumping losses are lower due to "non-throttling", fuel consumption is lower in homogeneous lean mode than in standard homogeneous mode with $\lambda \leq 1$. However, this mode is accompanied by increased NO_X emissions since the three-way catalytic converter is unable to reduce these emissions in this range. Additional NO_X accumulator-type catalytic converters mean further efficiency losses as a result of the catalytic converter's regeneration phases.

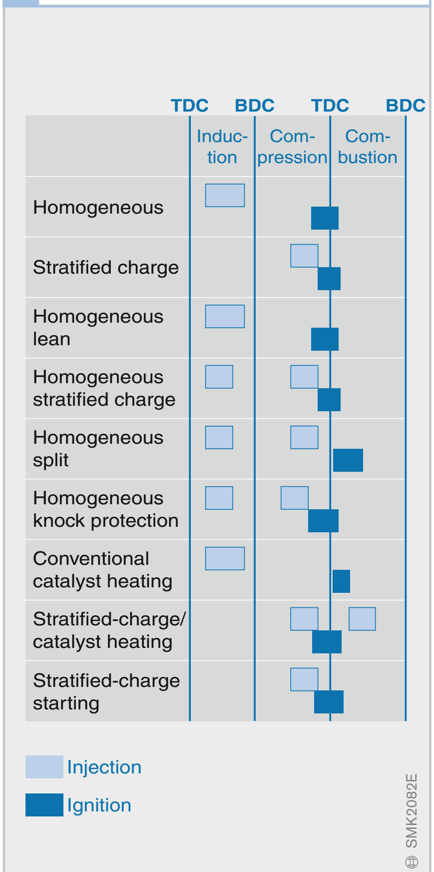
Homogeneous stratified charge

In homogeneous stratified-charge mode, the complete combustion chamber is filled with a homogeneous lean basic mixture. This mixture is created by injecting a basic quantity of fuel during the induction stroke.

Fuel is injected a second time (dual injection) during the compression stroke. This leads to a richer zone forming in the area of the spark plug. This stratified charge is easily ignitable and can ignite the homogeneous lean mixture in the remainder of the combustion chamber with the flame along the same lines as torch ignition.

The homogeneous stratified-charge mode is activated for a number of cycles during the transition between stratified-charge and homogeneous modes. This enables the engine-management system to better adjust the torque during the transition. Due to the conversion to energy of the very lean basic mixture at $\lambda > 2$, the NO_X emissions are also reduced.

2 Injection points and moments of ignition of the different operating modes



The distribution factor between the two injections is approximately 75 %, i.e., 75 % of the fuel is injected in the first injection, which is responsible for the homogeneous basic mixture.

Steady-state operation using dual injection at low engine speeds in the transitional range between stratified-charge and homogeneous modes reduces the soot emissions compared to stratified-charge mode, and lowers fuel consumption compared to homogeneous mode.

Homogeneous split

Homogeneous-split mode is a special application of homogeneous stratified-charge dual injection. It is used after the starting phase to bring the catalytic converter up to operating temperature as quickly as possible. Ignition can be significantly retarded (15...30° crankshaft after firing TDC) by the stabilizing effect of the second injection during the compression stroke. A large proportion of the combustion energy will then no longer influence an increase in torque, but rather increases exhaust-gas enthalpy. Due to this high exhaust-gas heat flow, the catalytic converter is already ready for operation just a few seconds after starting.

Homogeneous knock protection

In this operating mode, in view of the fact that charge stratification hinders knock, ignition-timing retardation as needed to avoid knocking can be dispensed with through the use of dual injection at full load. At the same time, the more favorable ignition point also leads to higher torque. In reality, the potential of this operating mode is very limited.

Stratified-charge/catalyst heating

Another form of dual injection makes it possible to heat up the exhaust system quickly, although the exhaust system must be optimized to accommodate this application. Here, in stratified-charge mode with a high level of excess air, injection is effected first during the compression stroke (as in stratified-charge mode) and then once again during the power stroke. This fuel is combusted very late and causes the engine's exhaust side and the exhaust manifold to heat up dramatically. When the engine is cold, however, this operating mode proves to be very limited in its potential for application to the extent that in this case homogeneous-split mode is significantly superior.

A further important application is for heating up the NO_X catalytic converter to temperatures in excess of 650 °C in order to initiate desulfurization of the catalytic converter. It is absolutely essential to use dual injection here since this high temperature cannot always be reached in all operating modes with conventional heating methods.

Stratified-charge starting

During stratified-charge starting, the quantity of fuel for starting is introduced during the compression stroke instead of conventional injection during the induction stroke. The advantage of this injection strategy is based on the fact that fuel is injected into air that is already compressed and therefore heated. In this way, more fuel evaporates in percentage terms than under cold ambient conditions, where a significantly larger proportion of the injected fuel remains as liquid wall-applied film in the combustion chamber and does not take part in combustion. The fuel quantity to be injected can therefore be reduced dramatically during stratified-charge starting. This results in greatly reduced HC emissions during starting. Because the catalytic converter cannot yet operate at the moment of starting, this is an important operating mode for developing low-emission concepts.

In order to facilitate mixture preparation in the short time available, stratified-charge starting is performed at fuel pressures of roughly 30...40 bar. These pressures can already be made available by the high-pressure pump by way of the starter revolutions.

Mixture formation

Function
It is the function of mixture formation to provide a combustible air/fuel mixture which is as homogeneous as possible.

Requirements
In homogeneous operating mode (homogeneous $\lambda \leq 1$ and also homogeneous lean), the mixture should be homogeneous throughout the entire combustion chamber. In stratified-charge mode, on the other hand, the mixture is only homogeneous within a limited area, while the remaining areas of the combustion chamber are filled with inert gas or fresh air.

All fuel must have evaporated before a gas mixture or gas/fuel-vapor mixture can be termed homogeneous. Evaporation is influenced by numerous factors, above all
- Combustion-chamber temperature
- Fuel-droplet size, and
- Time available for evaporation

Influencing factors
Depending on the engine's temperature, pressure and combustion-chamber geometry, a mixture containing gasoline is combustible within a range of $\lambda = 0.6...1.6$.

Temperature influence
The temperature has a decisive influence on fuel evaporation. At lower temperatures, fuel does not evaporate completely. More fuel must therefore be injected under these conditions in order to obtain a combustible mixture.

Pressure influence (fuel pressure)
The size of the droplets in the injected fuel is dependent on injection pressure and combustion-chamber pressure. Higher injection pressures result in smaller droplets, which then evaporate more quickly.

Geometry influence
With a constant combustion-chamber pressure and increasing injection pressure, the so-called penetration depth increases. The penetration depth is defined as the distance traveled by an individual fuel droplet before it evaporates completely. The cylinder wall or the piston will be wetted with fuel if the distance needed for full evaporation exceeds the distance from the fuel injector to the combustion-chamber wall. If this wall-applied film fails to evaporate in good time by the point of ignition, it does not, or only incompletely, takes part in combustion.

The geometry of the engine (intake manifold and combustion chamber) is also responsible for the air flow and the turbulence in the combustion chamber. Both factors have a significant influence on mixture formation because they determine both mixture preparation and transportation of the ignitable mixture during charge stratification to the spark plug.

Mixture formation in homogeneous mode
The fuel should be injected as early as possible so that the maximum length of time is available for mixture formation. This is why the fuel is injected during the induction stroke in homogeneous mode. The intake air helps the fuel to evaporate quickly and ensures that the mixture is well homogenized. Mixture preparation is assisted above all by high flow velocities and their aerodynamic forces in the area of the opening and closing intake valve.

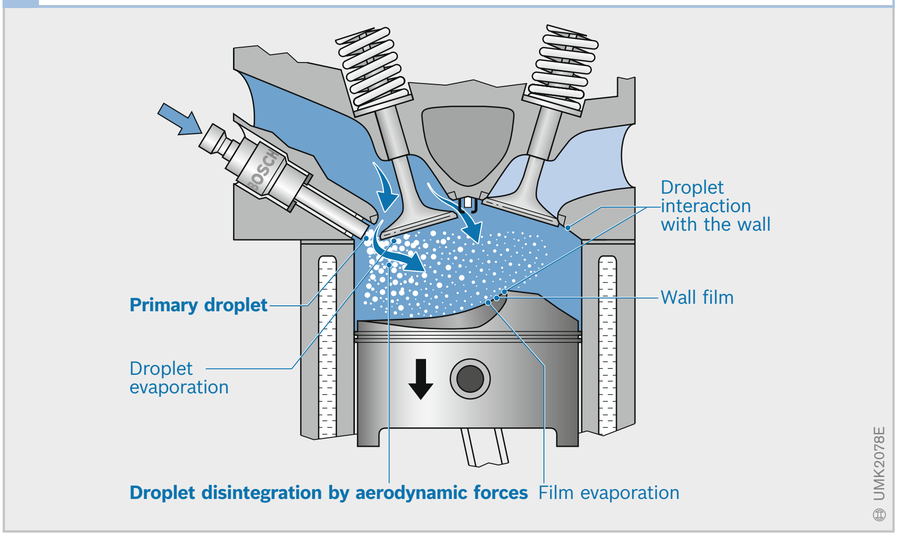
Wall interaction is not desired and the associated evaporation of wall-applied film plays a subordinate role here (Fig. 1).

Mixture formation in stratified-charge mode
The configuration of the combustible mixture cloud which is in the vicinity of the spark plug at the moment of ignition is crucial to stratified-charge mode. This is why the fuel is injected during the compression stroke so that a mixture cloud is created which can be transported to the vicinity of the spark plug by the air flows in the combustion chamber and by the upward stroke of the piston. The injection point is dependent on the engine speed and the requested torque.

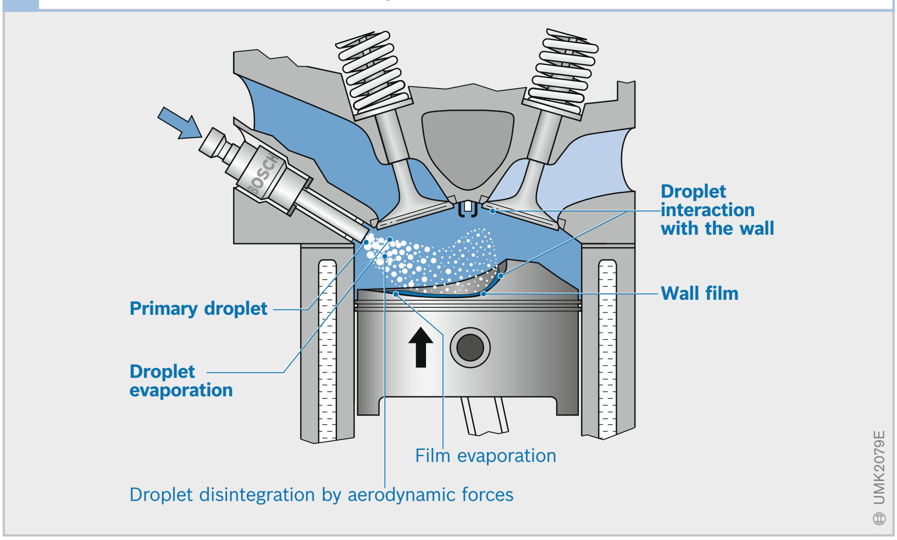
In stratified-charge injection, mixture preparation profits from the higher temperature and the already increased pressure in the combustion chamber during the compression phase.

In the case of the wall-guided combustion process, condensation of fuel on the piston wall cannot be avoided, to such an extent that some mixture preparation takes place in the form of wall-applied-film evaporation (Fig. 2).

1 Mixture-formation mechanisms in homogeneous mode



2 Mixture-formation mechanisms in stratified-charge mode



Ignition

Homogeneous mixtures

The ignition conditions for homogeneous mixtures with gasoline direct injection are to a large extent that same as those with manifold injection (see chapter entitled "Manifold injection").

Stratified-charge mixtures

When engine operation is dethrottled, from a general point of view, extremely lean air/fuel mixtures must be ignited in the lower part-load range. This is made possible by the creation of charge stratification in the area of the spark plug at the moment of ignition. Ideally, this stratified air/fuel charge is a virtually stoichiometric and thus easily ignitable mixture.

After ignition, a flame core is formed in the area of the stoichiometric stratified charge. The amount of energy released here is four times greater than that of an ignition spark. In this way, mixture in lean peripheral areas of the combustion chamber can also be ignited.

Wall/air-guided combustion process

In the case of the wall/air-guided combustion process, the injection time window must be chosen such that the piston directs the mixture cloud safely to the spark plug. This transportation movement is usually assisted by combustion-chamber flows. The mixture must be ignited when it reaches the spark plug, i.e. the moment of ignition is permanently linked in terms of time to the piston position – injection – mixture transportation sequence and is no longer available as a controlled variable of the combustion process.

When the piston surface is wetted with fuel, this surface acts as a mixture-formation component through its interaction with the liquid fuel. Here, the fuel that adheres to the surface evaporates at a relatively slow rate. When the flame front arrives at the piston surface, which is cold in comparison to the flame, the flame goes out as a result of high heat dissipation (quenching effect). The fuel that has still not evaporated at this time is not combusted and results in increased HC emissions.

The design of the piston surface, the combustion-chamber flow forming in the vicinity of the spark plug, and the injector quality thus have a direct influence on the ignition and burning performance.

Spray-guided combustion process

The close proximity of the spark plug and the injector ensures that an ignitable mixture concentration is available at the spark plug, even in the event of small injected fuel quantities. However, this also means that only a very small time window is available for evaporation and mixture preparation.

Fuel directly after it has left the injector is still unable to ignite since it has still not evaporated sufficiently and is mixed with surrounding air. Ignition significantly later than injection is barely possible since the mixture is increasingly removed from the spark plug and therefore becomes lean. Ideal ignition conditions are therefore only present during a relatively short period of time. Typically, a rapidly growing flame core in the now combustible air/fuel-vapor mixture initiated by the ignition spark is formed at the end of the injection process.

The following factors, among others, are crucial to safe ignition:

- An ignition spark lasting as long as possible
- The quality of mixture preparation
- The correct allocation of spark location and fuel spray
- Relatively precise adherence to the distance between spray and ignition location
- Constancy of the spray in relation to the combustion-chamber pressure
- Invariance of the spray over the engine's entire service life

High-pressure injector

Function

It is the function of the high-pressure fuel injector (HDEV) on the one hand to meter the fuel and on the other hand by means of its atomization to achieve controlled mixing of the fuel and air in a specific area of the combustion chamber. Depending on the desired operating mode, the fuel is either concentrated in the vicinity of the spark plug (stratified charge) or evenly distributed throughout the combustion chamber (homogeneous distribution).

Design and method of operation

The high-pressure injector (Fig. 1) comprises the following components:

- Inlet with filter (1)
- Electrical connection (2)
- Spring (3)
- Coil (4)
- Valve sleeve (5)
- Nozzle needle with solenoid armature (6), and
- Valve seat (7)

A magnetic field is generated when current passes through the coil. This lifts the valve needle off the valve seat against the force of the spring and opens the injector outlet passages (8). The system pressure now forces the fuel into the combustion chamber. The injected fuel quantity is essentially dependent on the opening duration of the injector and the fuel pressure.

When the energizing current is switched off, the valve needle is pressed by spring force back down against its seat and interrupts the flow of fuel.

Excellent fuel atomization is achieved thanks to the suitable nozzle geometry at the injector tip.

Requirements

Compared with manifold injection, gasoline direct injection differs mainly in its higher fuel pressure and the far shorter time which is available for directly injecting the fuel into the combustion chamber.

1 Design of HDEV5 high-pressure injector

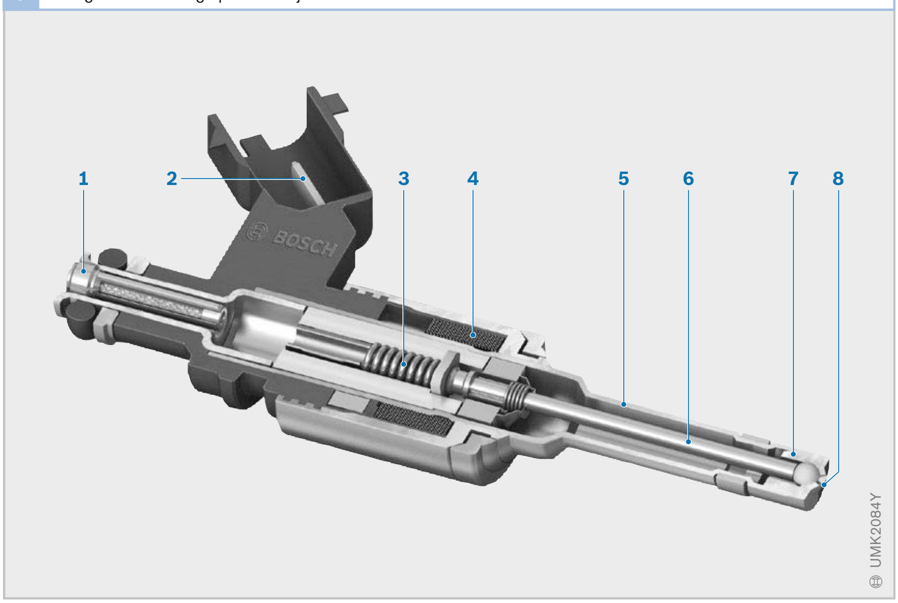


Fig. 1
1 Fuel inlet with filter
2 Electrical connection
3 Spring
4 Coil
5 Valve sleeve
6 Nozzle needle with solenoid armature
7 Valve seat
8 Injector outlet passages

Figure 2 underlines the technical demands made on the injector. In the case of manifold injection, two revolutions of the crankshaft are available for injecting the fuel into the manifold. This corresponds to an injection duration of 20 ms at an engine speed of 6000 rpm.

In the case of gasoline direct injection, however, considerably less time is available. In homogeneous operation, the fuel must be injected during the induction stroke. In other words, only a half crankshaft rotation is available for the injection process. At 6000 rpm, this corresponds to an injection duration of 5 ms.

With gasoline direct injection, the fuel requirement at idle in relation to that at full load is far lower than with manifold injection (factor 1:12). This results in an injection duration at idle of roughly 0.4 ms.

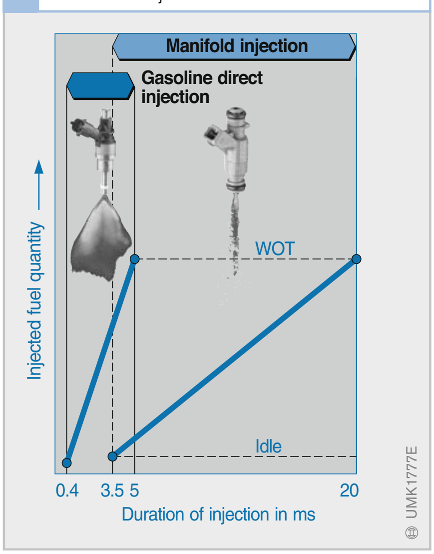
Actuation of HDEV high-pressure injector

The injector must be actuated with a highly complex current characteristic in order to comply with the requirements for defined, reproducible fuel-injection processes (Fig. 3). The microcontroller in the engine ECU delivers only a digital actuating signal (a). An output module (ASIC) uses this signal to generate the actuating signal (b) for the injector.

A DC/DC converter in the engine ECU generates the booster voltage of 65 V. This voltage is required in order to bring the current up as quickly as possible in the booster phase to a high current value. This is necessary in order to accelerate the injector needle as quickly as possible. In the pickup phase (t_{on}), the valve needle then achieves the maximum opening lift (c). When the injector is open, a small actuating current (holding current) is sufficient to keep the injector open.

With a constant injector-needle lift, the injected fuel quantity (d) is proportional to the injection duration.

2 Comparison between gasoline direct injection and manifold injection



3 Actuation of HDEV high-pressure injector

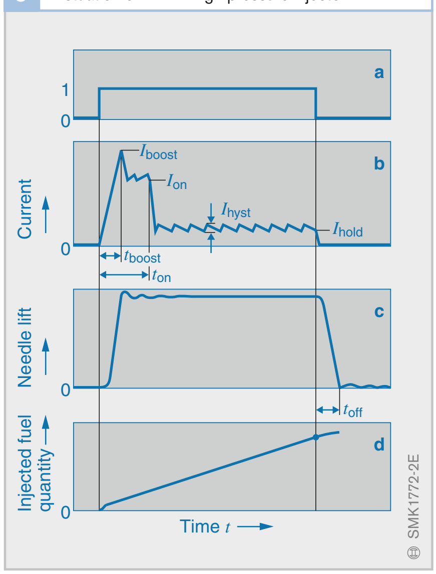


Fig. 2
Injected fuel quantity as a function of injection duration

Fig. 3
- a Actuating signal
- b Current characteristic in injector
- c Needle lift
- d Injected fuel quantity