Basic principles of the diesel engine

The diesel engine is a compression-ignition engine in which the fuel and air are mixed inside the engine. The air required for combustion is highly compressed inside the combustion chamber. This generates high temperatures which are sufficient for the diesel fuel to spontaneously ignite when it is injected into the cylinder. The diesel engine thus uses heat to release the chemical energy contained within the diesel fuel and convert it into mechanical force.

The diesel engine is the internal-combustion engine that offers the greatest overall efficiency (more than 50% in the case of large, slow-running types). The associated low fuel consumption, its low-emission exhaust and quieter running characteristics assisted, for example, by pre-injection have combined to give the diesel engine its present significance.

Diesel engines are particularly suited to aspiration by means of a turbocharger or supercharger. This not only improves the engine's power yield and efficiency, it also reduces pollutant emissions and combustion noise.

In order to reduce NO_x emissions on cars and commercial vehicles, a proportion of the exhaust gas is fed back into the engine's intake manifold (exhaust-gas recirculation). An even greater reduction of NO_x emissions can be achieved by cooling the recirculated exhaust gas.

Diesel engines may operate either as two-stroke or four-stroke engines. The types used in motor vehicles are generally four-stroke designs.

Method of operation

A diesel engine contains one or more cylinders. Driven by the combustion of the air/fuel mixture, the piston (Fig. 1, 3) in each cylinder (5) performs up-and-down movements. This method of operation is why it was named the "reciprocating-piston engine".

The connecting rod, or conrod (11), converts the linear reciprocating action of the piston into rotational movement on the part of the crankshaft (14). A flywheel (15) connected to the end of the crankshaft helps to maintain continuous crankshaft rotation and reduce unevenness of rotation caused by the periodic nature of fuel combustion in the individual cylinders. The speed of rotation of the crankshaft is also referred to as engine speed.

1 Four-cylinder diesel engine without auxiliary units (schematic)

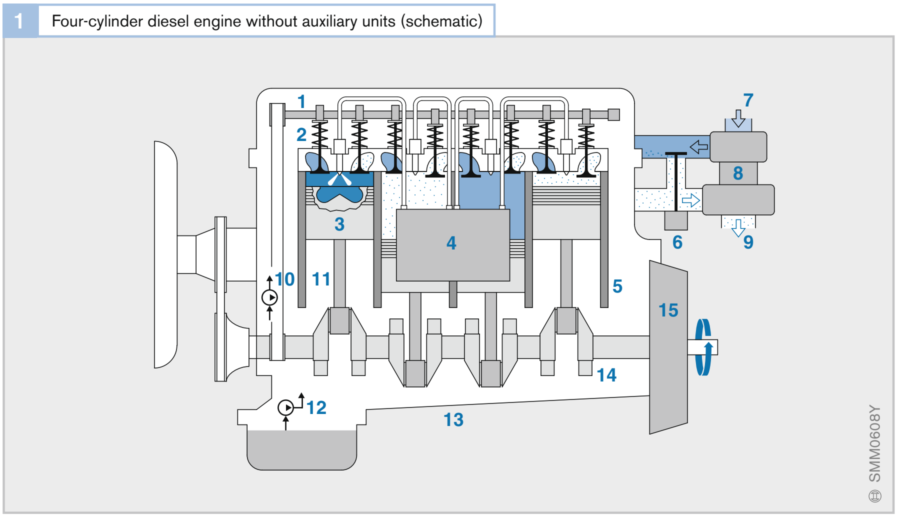

Fig. 1
1 Camshaft
2 Valves
3 Piston
4 Fuel-injection system
5 Cylinder
6 Exhaust-gas recirculation
7 Intake manifold
8 Turbocharger
9 Exhaust pipe
10 Cooling system
11 Connecting rod
12 Lubrication system
13 Cylinder block
14 Crankshaft
15 Flywheel

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2 Operating cycle of a four-stroke diesel engine

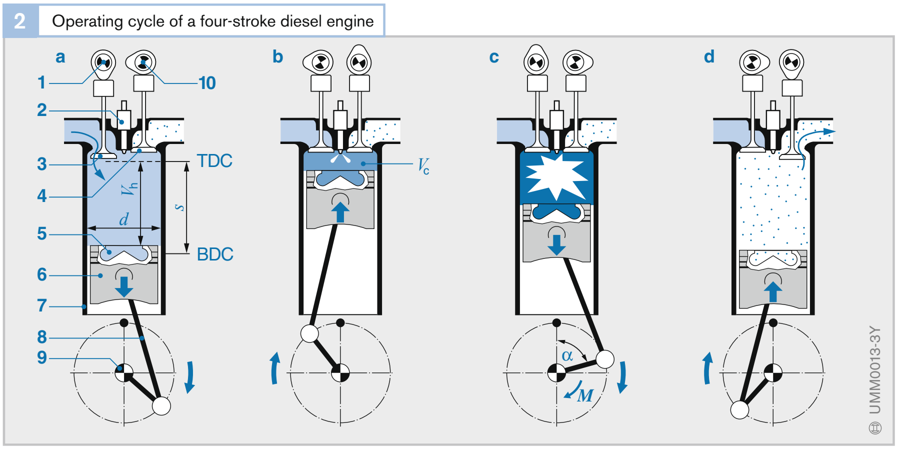


Fig. 2

a	Induction stroke
b	Compression stroke
c	Ignition stroke
d	Exhaust stroke
1	Inlet-valve camshaft
2	Fuel injector
3	Inlet valve
4	Exhaust valve
5	Combustion chamber
6	Piston
7	Cylinder wall
8	Connecting rod
9	Crankshaft
10	Exhaust-valve camshaft
α	Crankshaft angle of rotation
d	Bore
M	Turning force
s	Piston stroke
V_c	Compression volume
V_h	Swept volume
TDC	Top dead center
BDC	Bottom dead center

Four-stroke cycle

On a four-stroke diesel engine (Fig. 2), inlet and exhaust valves control the intake of air and expulsion of burned gases after combustion. They open and close the cylinder's inlet and exhaust ports. Each inlet and exhaust port may have one or two valves.

1. Induction stroke (a)

Starting from **T**op **D**ead **C**enter (TDC), the piston (6) moves downwards increasing the capacity of the cylinder. At the same time the inlet valve (3) is opened and air is drawn into the cylinder without restriction by a throttle valve. When the piston reaches **B**ottom **D**ead **C**enter (BDC), the cylinder capacity is at its greatest (V_h+V_c).

2. Compression stroke (b)

The inlet and exhaust valves are now closed. The piston moves upwards and compresses the air trapped inside the cylinder to the degree determined by the engine's compression ratio (this can vary from 6 : 1 in large-scale engines to 24 : 1 in car engines). In the process, the air heats up to temperatures as high as 900°C. When the compression stroke is almost complete, the fuel-injection system injects fuel at high pressure (as much as 2,000 bar in modern engines) into the hot, compressed air. When the piston reaches top dead center, the cylinder capacity is at its smallest (compression volume, V_c).

3. Ignition stroke (c)

After the ignition lag (a few degrees of crankshaft rotation) has elapsed, the ignition stroke (working cycle) begins. The finely atomized and easily combustible diesel fuel spontaneously ignites and burns due to the heat of the compressed air in the combustion chamber (5). As a result, the cylinder charge heats up even more and the pressure in the cylinder rises further as well. The amount of energy released by combustion is essentially determined by the mass of fuel injected (quality-based control). The pressure forces the piston downwards. The chemical energy released by combustion is thus converted into kinetic energy. The crankshaft drive translates the piston's kinetic energy into a turning force (torque) available at the crankshaft.

4. Exhaust stroke (d)

Fractionally before the piston reaches bottom dead center, the exhaust valve (4) opens. The hot, pressurized gases flow out of the cylinder. As the piston moves upwards again, it forces the remaining exhaust gases out.

On completion of the exhaust stroke, the crankshaft has completed two revolutions and the four-stroke operating cycle starts again with the induction stroke.

Valve timing

The cams on the inlet and exhaust camshafts open and close the inlet and exhaust valves respectively. On engines with a single camshaft, a rocker-arm mechanism transmits the action of the cams to the valves.

Valve timing involves synchronizing the opening and closing of the valves with the rotation of the crankshaft (Fig. 4). For that reason, valve timing is specified in degrees of crankshaft rotation.

The crankshaft drives the camshaft by means of a toothed belt or a chain (the timing belt or timing chain) or sometimes by a series of gears. On a four-stroke engine, a complete operating cycle takes two revolutions of the crankshaft. Therefore, the speed of rotation of the camshaft is only half that of the crankshaft. The transmission ratio between the crankshaft and the camshaft is thus 2 : 1.

At the changeover from exhaust to induction stroke, the inlet and exhaust valves are open simultaneously for a certain period of time. This “valve overlap” helps to “flush out” the remaining exhaust and cool the cylinders.

4 Valve-timing diagram for a four-stroke diesel engine

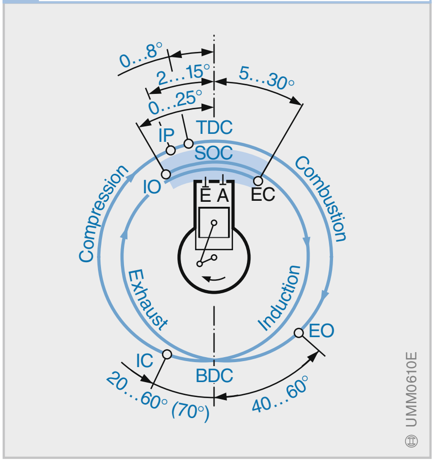


Fig. 4
EO Exhaust opens
EC Exhaust closes
SOC Start of combustion
IO Inlet opens
IC Inlet closes
IP Injection point
TDC Top dead center
BDC Bottom dead center

■ Valve overlap

3 Temperature rise during compression

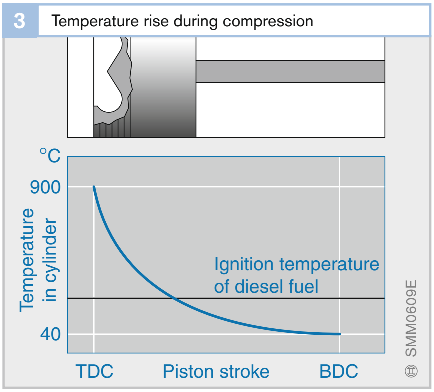


Fig. 3
TDC Top dead center
BDC Bottom dead center

Compression

The compression ratio, ε, of a cylinder results from its swept volume, V_h, and its compression volume, V_c, thus:

$$\varepsilon = \frac{V_h + V_c}{V_c}$$

The compression ratio of an engine has a decisive effect on the following:

- The engine’s cold-starting characteristics
- The torque generated
- Its fuel consumption
- How noisy it is and
- The pollutant emissions

The compression ratio, ε, is generally between 16:1 and 24:1 in engines for cars and commercial vehicles, depending on the engine design and the fuel-injection method.
It is therefore higher than in gasoline engines ($\varepsilon = 7:1...13:1$). Due to the susceptibility of gasoline to knocking, higher compression ratios and the resulting higher combustion-chamber temperatures would cause the air/fuel mixture to spontaneously combust in an uncontrolled manner.

The air inside a diesel engine is compressed to a pressure of 30...50 bar (conventionally aspirated engine) or 70...150 bar (turbocharged/supercharged engine). This generates temperatures ranging from 700 to 900°C (Fig. 3). The ignition temperature of the most easily combustible components of diesel fuel is around 250°C.

Torque and power output

Torque

The conrod converts the linear motion of the piston into rotational motion of the crankshaft. The force with which the expanding air/fuel mixture forces the piston downwards is thus translated into rotational force or torque by the leverage of the crankshaft.

The output torque M of the engine is, therefore, dependent on mean pressure p_e (mean piston or operating pressure).
It is expressed by the equation:

$$M = p_e \cdot V_H / (4 \cdot \pi)$$

where
V_H is the cubic capacity of the engine and
$\pi \approx 3.14$.

The mean pressure can reach levels of 8...22 bar in small turbocharged diesel engines for cars. By comparison, gasoline engines achieve levels of 7...11 bar.

The maximum achievable torque, M_{max}, that the engine can deliver is determined by its design (cubic capacity, method of aspiration, etc.). The torque output is adjusted to the requirements of the driving situation essentially by altering the fuel and air mass and the mixing ratio.

Torque increases in relation to engine speed, n, until maximum torque, M_{max}, is reached (Fig. 1). As the engine speed increases beyond that point, the torque begins to fall again (maximum permissible engine load, desired performance, gearbox design).

Engine design efforts are aimed at generating maximum torque at low engine speeds (under 2,000 rpm) because at those speeds fuel consumption is at its most economical and the engine's response characteristics are perceived as positive (good "pulling power").

Power output

The power P (work per unit of time) generated by the engine depends on torque M and engine speed n. Engine power output increases with engine speed until it reaches its maximum level, or rated power P_{rated} at the engine's rated speed, n_{rated}. The following equation applies:

$$P = 2 \cdot \pi \cdot n \cdot M$$

Figure 1a shows a comparison between the power curves of diesel engines made in 1968 and in 1998 in relation to engine speed.

Due to their lower maximum engine speeds, diesel engines have a lower displacement-related power output than gasoline engines. Modern diesel engines for cars have rated speeds of between 3,500 and 5,000 rpm.

1 Torque and power curves for two diesel car engines with a capacity of approx. 2.2 *l* (example)

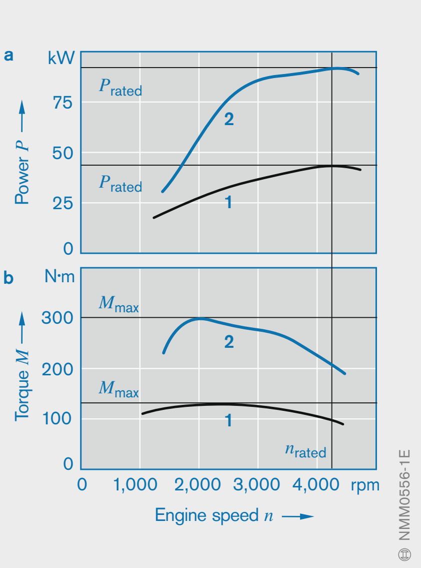


Fig. 1
a Power curve
b Torque curve

1 1968 engine
2 1998 engine

M_{max} Maximum torque
P_{rated} Rated power
n_{rated} Rated speed

Engine efficiency

The internal-combustion engine does work by changing the pressure and volume of a working gas (cylinder charge).

Effective efficiency of the engine is the ratio between input energy (fuel) and useful work. This results from the thermal efficiency of an ideal work process (Seiliger process) and the percentage losses of a real process.

Seiliger process

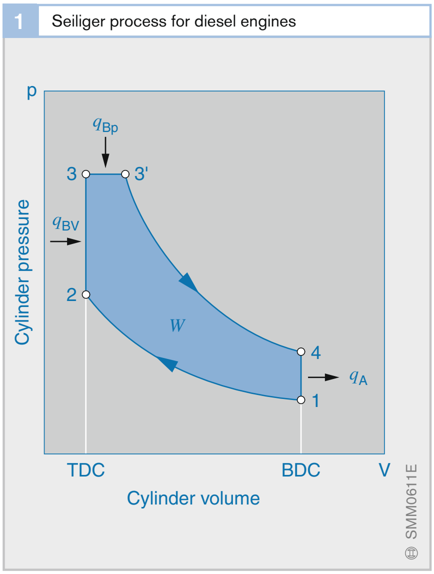
Reference can be made to the Seiliger process as a thermodynamic comparison process for the reciprocating-piston engine. It describes the theoretically useful work under ideal conditions. This ideal process assumes the following simplifications:

- Ideal gas as working medium
- Gas with constant specific heat
- No flow losses during gas exchange

Fig. 1

1-2	Isentropic compression
2-3	Isochoric heat propagation
3-3′	Isobaric heat propagation
3′-4	Isentropic expansion
4-1	Isochoric heat dissipation
TDC	Top dead center
BDC	Bottom dead center
q_{A}	Quantity of heat dissipated during gas exchange
q_{Bp}	Combustion heat at constant pressure
q_{BV}	Combustion heat at constant volume
W	Theoretical work

1 Seiliger process for diesel engines



The state of the working gas can be described by specifying pressure (p) and volume (V). Changes in state are presented in the p-V chart (Fig. 1), where the enclosed area corresponds to work that is carried out in an operating cycle.

In the Seiliger process, the following process steps take place:

Isentropic compression (1-2)

With isentropic compression (compression at constant entropy, i.e. without transfer of heat), pressure in the cylinder increases while the volume of the gas decreases.

Isochoric heat propagation (2-3)

The air/fuel mixture starts to burn. Heat propagation (q_{BV}) takes place at a constant volume (isochoric). Gas pressure also increases.

Isobaric heat propagation (3-3′)

Further heat propagation (q_{Bp}) takes place at constant pressure (isobaric) as the piston moves downwards and gas volume increases.

Isentropic expansion (3′-4)

The piston continues to move downwards to bottom dead center. No further heat transfer takes place. Pressure drops as volume increases.

Isochoric heat dissipation (4-1)

During the gas-exchange phase, the remaining heat is removed (q_{A}). This takes place at a constant gas volume (completely and at infinite speed). The initial situation is thus restored and a new operating cycle begins.

p-V chart of the real process

To determine the work done in the real process, the pressure curve in the cylinder is measured and presented in the p-V chart (Fig. 2). The area of the upper curve corresponds to the work present at the piston.

2 Real process in a turbocharged/supercharged diesel engine represented by p-V indicator diagram (recorded using a pressure sensor)

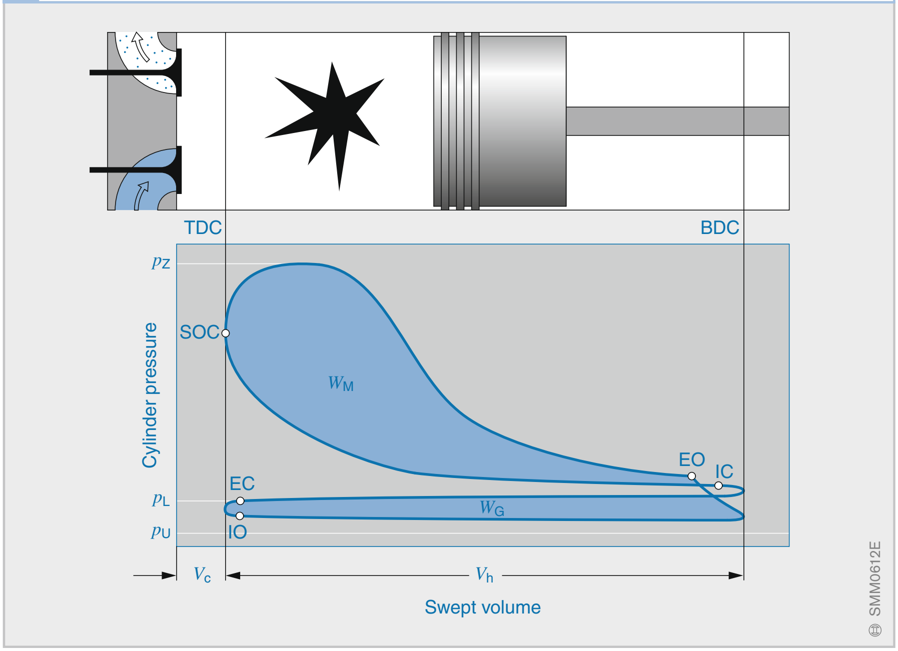


Fig. 2

EO	Exhaust opens
EC	Exhaust closes
SOC	Start of combustion
IO	Inlet opens
IC	Inlet closes
TDC	Top dead center
BDC	Bottom dead center

p_U	Ambient pressure
p_L	Charge-air pressure
p_Z	Maximum cylinder pressure
V_c	Compression volume
V_h	Swept volume
W_M	Indexed work
W_G	Work during gas exchange (turbocharger/ supercharger)

3 Pressure vs. crankshaft rotation curve (p-α diagram) for a turbocharged/supercharged diesel engine

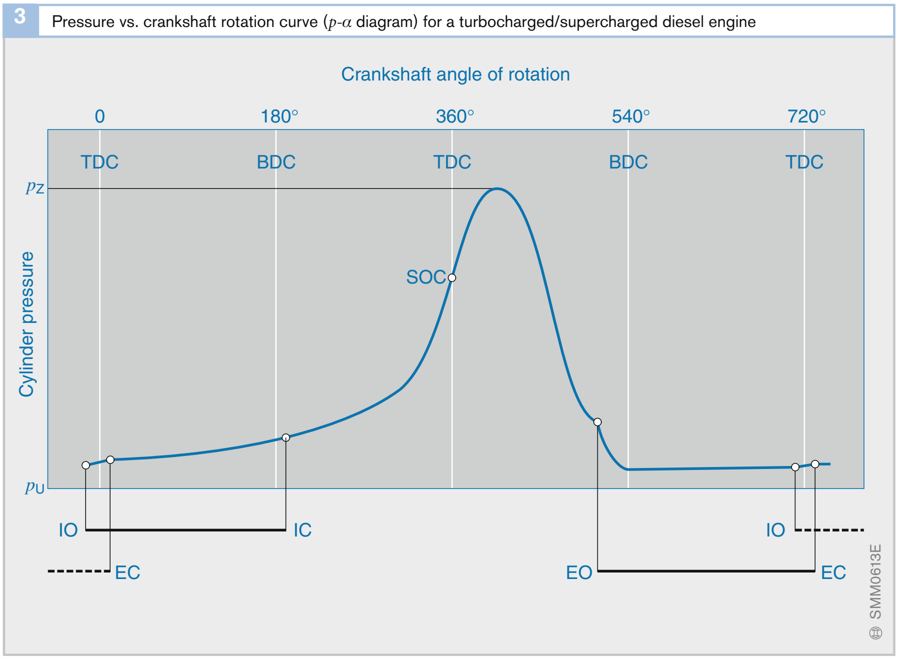


Fig. 3

EO	Exhaust opens
EC	Exhaust closes
SOC	Start of combustion
IO	Inlet opens
IC	Inlet closes
TDC	Top dead center
BDC	Bottom dead center

p_U	Ambient pressure
p_L	Charge-air pressure
p_Z	Maximum cylinder pressure

For assisted-aspiration engines, the gas-exchange area (W_G) has to be added to this since the compressed air delivered by the turbocharger/supercharger also helps to press the piston downwards on the induction stroke.

Losses caused by gas exchange are overcompensated at many operating points by the supercharger/turbocharger, resulting in a positive contribution to the work done.

Representation of pressure by means of the crankshaft angle (Fig. 3, previous page) is used in the thermodynamic pressure-curve analysis, for example.

Efficiency

Effective efficiency of the diesel engine is defined as:

$$\eta_e = \frac{W_e}{W_B}$$

W_e is the work effectively available at the crankshaft.
W_B is the calorific value of the fuel supplied.

Effective efficiency η_e is representable as the product of the thermal efficiency of the ideal process and other efficiencies that include the influences of the real process:

$$\eta_e = \eta_{th} \cdot \eta_g \cdot \eta_b \cdot \eta_m = \eta_i \cdot \eta_m$$

η_{th}: thermal efficiency

η_{th} is the thermal efficiency of the Seiliger process. This process considers heat losses occurring in the ideal process and is mainly dependent on compression ratio and excess-air factor.

As the diesel engine runs at a higher compression ratio than a gasoline engine and a high excess-air factor, it achieves higher efficiency.

η_g: efficiency of cycle factor

η_g specifies work done in the real high-pressure work process as a factor of the theoretical work of the Seiliger process.

Deviations between the real and the ideal processes mainly result from use of a real working gas, the finite velocity of heat propagation and dissipation, the position of heat propagation, wall heat loss, and flow losses during the gas-exchange process.

η_b: fuel conversion factor

η_b considers losses occurring due to incomplete fuel combustion in the cylinder.

η_m: mechanical efficiency

η_m includes friction losses and losses arising from driving ancillary assemblies. Frictional and power-transmission losses increase with engine speed. At nominal speed, frictional losses are composed of the following:

- Pistons and piston rings approx. 50%
- Bearings approx. 20%
- Oil pump approx. 10%
- Coolant pump approx. 5%
- Valve-gear approx. 10%
- Fuel-injection pump approx. 5%

If the engine has a supercharger, this must also be included.

η_i: efficiency index

The efficiency index is the ratio between "indexed" work present at the piston W_i and the calorific value of the fuel supplied.

Work effectively available at the crankshaft W_e results from indexed work taking mechanical losses into consideration:
$W_e = W_i \cdot \eta_m$.

Operating statuses

Starting

Starting an engine involves the following stages: cranking, ignition and running up to self-sustained operation.

The hot, compressed air produced by the compression stroke has to ignite the injected fuel (combustion start). The minimum ignition temperature required for diesel fuel is approx. 250°C.

This temperature must also be reached in poor conditions. Low engine speeds, low outside temperatures, and a cold engine lead to relatively low final compression temperatures due to the fact that:

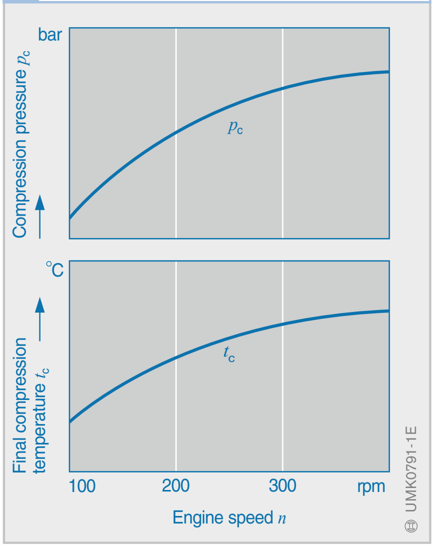
- The lower the engine speed, the lower the ultimate pressure at the end of the compression stroke and, accordingly, the ultimate temperature (Fig. 1). The reasons for this phenomenon are leakage losses through the piston ring gaps between the piston and the cylinder wall and the fact that when the engine is first started, there is no thermal expansion and an oil film has not formed. Due to heat loss during compression, maximum compression temperature is reached a few degrees before TDC (thermodynamic loss angle, Fig. 2).
- When the engine is cold, heat loss occurs across the combustion-chamber surface area during the compression stroke. On indirect-injection (IDI) engines, this heat loss is particularly high due to the larger surface area.
- Internal engine friction is higher at low temperatures than at normal operating temperature because of the higher viscosity of the engine oil. For this reason, and also due to low battery voltage, the starter-motor speed is only relatively low.
- The speed of the starter motor is particularly low when it is cold because the battery voltage drops at low temperatures.

The following measures are taken to raise temperature in the cylinder during the starting phase:

Fuel heating

A filter heater or direct fuel heater (Fig. 3 on next page) can prevent the precipitation of paraffin crystals that generally occurs at low

1 Compression pressure and ultimate temperature relative to engine speed



2 Compression temperature as a factor of crankshaft angle

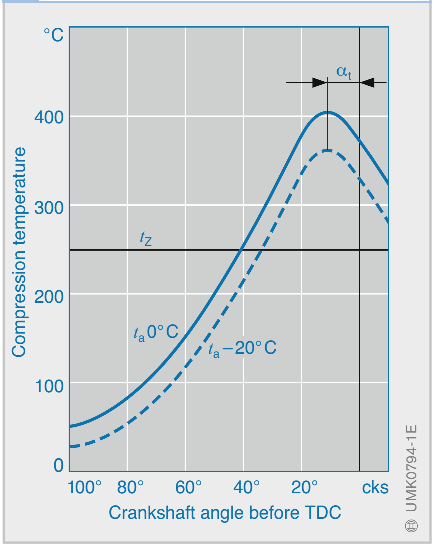


Fig. 2

t_a	Outside temperature
t_Z	Ignition temperature of diesel fuel
α_T	Thermodynamic loss angle

$n \approx 200$ rpm

temperatures (during the starting phase and at low outside temperatures).

Start-assist systems

The air/fuel mixture in the combustion chamber (or in the prechamber or whirl chamber) is normally heated by sheathed-element glow plugs in the starting phase on direct-injection (DI) engines for passenger cars, or indirect-injection engines (IDI). On direct-injection (DI) engines for commercial vehicles, the intake air is preheated. Both the above methods assist fuel vaporization and air/fuel mixing and therefore facilitate reliable combustion of the air/fuel mixture.

Glow plugs of the latest generation require a preheating time of only a few seconds (Fig. 4), thus allowing a rapid start. The lower post-glow temperature also permits longer post-glow times. This reduces not only harmful pollutant emissions but also noise levels during the engine's warm-up period.

Injection adaptation

Another means of assisted starting is to inject an excess amount of fuel for starting to compensate for condensation and leakage losses in the cold engine, and to increase engine torque in the running-up phase.

Advancing the start of injection during the warming-up phase helps to offset longer ignition lag at low temperatures and to ensure reliable ignition at top dead center, i.e. at maximum final compression temperature.

The optimum start of injection must be achieved within tight tolerance limits. As the internal cylinder pressure (compression pressure) is still too low, fuel injected too early has a greater penetration depth and precipitates on the cold cylinder walls. There, only a small proportion of it vaporizes since then the temperature of the air charge is too low.

If the fuel is injected too late, ignition occurs during the downward stroke (expansion phase), and the piston is not fully accelerated, or combustion misses occur.

3 Diesel fuel heater

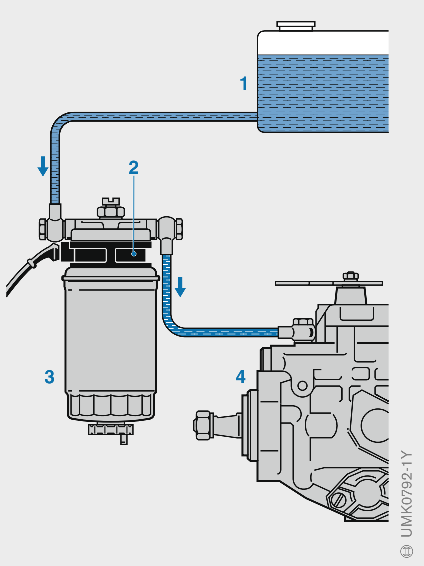


Fig. 3
1 Fuel tank
2 Fuel heater
3 Fuel filter
4 Fuel-injection pump

4 Temperature progression of two glow plugs in still air

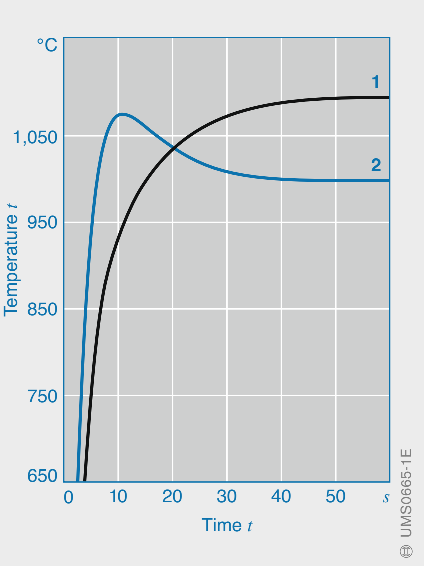


Fig. 4
Filament material:
1 Nickel (conventional glow plug type S-RSK)
2 CoFe alloy (2nd-generation glow plug type GSK2)

No load
No load refers to all engine operating statuses in which the engine is overcoming only its own internal friction. It is not producing any torque output. The accelerator pedal may be in any position. All speed ranges up to and including breakaway speed are possible.

Idle
The engine is said to be idling when it is running at the lowest no-load speed. The accelerator pedal is not depressed. The engine does not produce any torque. It only overcomes its internal friction. Some sources refer to the entire no-load range as idling. The upper no-load speed (breakaway speed) is then called the upper idle speed.

Full load
At full load (or Wide-Open Throttle (WOT)), the accelerator pedal is fully depressed, or the full-load delivery limit is controlled by the engine management dependent on the operating point. The maximum possible fuel volume is injected and the engine generates its maximum possible torque output under steady-state conditions. Under non steady-state conditions (limited by turbocharger/ supercharger pressure) the engine develops the maximum possible (lower) full-load torque with the quantity of air available. All engine speeds from idle speed to nominal speed are possible.

Part load
Part load covers the range between no load and full load. The engine is generating an output between zero and the maximum possible torque.

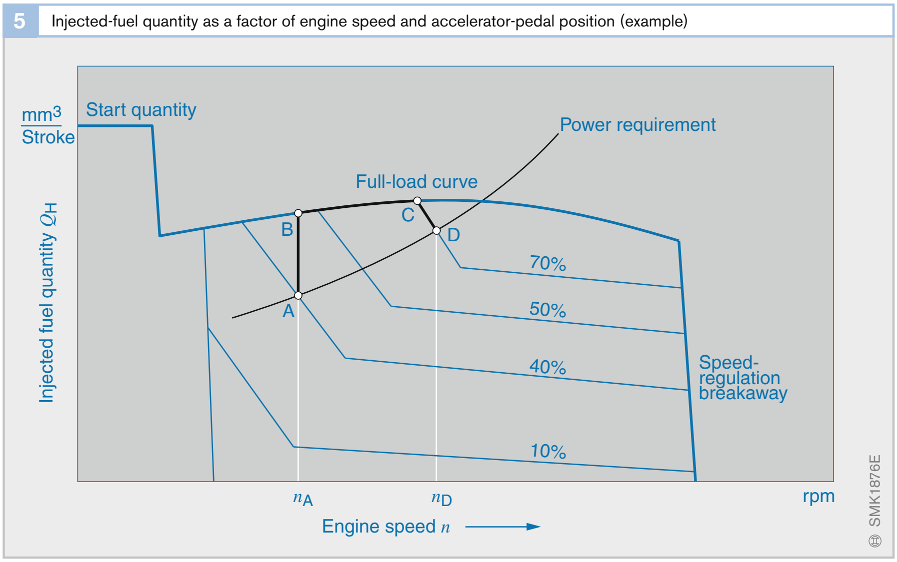
Lower part-load range
This is the operating range in which the diesel engine's fuel consumption is particularly economical in comparison with the gasoline engine. "Diesel knock" that was a problem on earlier diesel engines – particularly when cold – has virtually been eliminated on diesels with pre-injection.

As explained in the "Starting" section, the final compression temperature is lower at lower engine speeds and at lower loads. In comparison with full load, the combustion chamber is relatively cold (even when the engine is running at operating temperature) because the energy input and, therefore, the temperatures, are lower. After a cold start, the combustion chamber heats up very slowly in the lower part-load range. This is particularly true for engines with prechamber or whirl chambers because the larger surface area means that heat loss is particularly high.

At low loads and with pre-injection, only a few mm^3 of fuel are delivered in each injection cycle. In this situation, particularly high demands are placed on the accuracy of the start of injection and injected fuel quantity. As during the starting phase, the required combustion temperature is reached also at idle speed only within a small range of piston travel near TDC. Start of injection is controlled very precisely to coincide with that point.

During the ignition-lag period, only a small amount of fuel may be injected since, at the point of ignition, the quantity of fuel in the combustion chamber determines the sudden increase in pressure in the cylinder.

5 Injected-fuel quantity as a factor of engine speed and accelerator-pedal position (example)



The greater the increase in pressure, the louder the combustion noise. Pre-injection of approx. 1 mm³ (for cars) of fuel virtually cancels out ignition lag at the main injection point, and thus substantially reduces combustion noise.

Overrun

The engine is said to be overrunning when it is driven by an external force acting through the drivetrain (e.g. when descending an incline). No fuel is injected (overrun fuel cut-off).

Steady-state operation

Torque delivered by the engine corresponds to the torque required by the accelerator-pedal position. Engine speed remains constant.

Non-steady-state operation

The engine's torque output does not equal the required torque. The engine speed is not constant.

Transition between operating statuses

If the load, the engine speed, or the accelerator-pedal position change, the engine's operating state changes (e.g. its speed or torque output).

The response characteristics of an engine can be defined by means of characteristic data diagrams or maps. The map in Figure 5 shows an example of how the engine speed changes when the accelerator-pedal position changes from 40% to 70% depressed. Starting from operating point A, the new part-load operating point D is reached via the full-load curve (B-C). There, power demand and engine power output are equal. The engine speed increases from n_A to n_D.

Operating conditions

In a diesel engine, the fuel is injected directly into the highly compressed hot air which causes it to ignite spontaneously. Therefore, and because of the heterogeneous air/fuel mixture, the diesel engine – in contrast with the gasoline engine – is not restricted by ignition limits (i.e. specific air-fuel ratios λ). For this reason, at a constant air volume in the cylinder, only the fuel quantity is controlled.

The fuel-injection system must assume the functions of metering the fuel and distributing it evenly over the entire charge. It must accomplish this at all engine speeds and loads, dependent on the pressure and temperature of the intake air.

Thus, for any combination of engine operating parameters, the fuel-injection system must deliver:

- The correct amount of fuel
- At the correct time
- At the correct pressure
- With the correct timing pattern and at the correct point in the combustion chamber

In addition to optimum air/fuel mixture considerations, metering the fuel quantity also requires taking account of operating limits such as:

- Emission restrictions (e.g. smoke emission limits)
- Combustion-peak pressure limits
- Exhaust temperature limits
- Engine speed and full-load limits
- Vehicle or engine-specific load limits, and
- Altitude and turbocharger/supercharger pressure limits

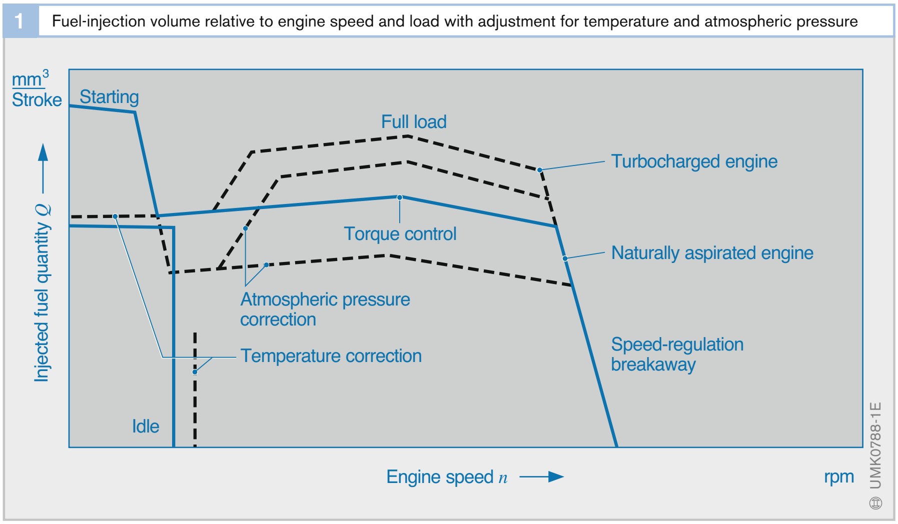
Smoke limit

There are statutory limits for particulate emissions and exhaust-gas turbidity. As a large part of the air/fuel mixing process only takes place during combustion, localized over-enrichment occurs, and, in some cases, this leads to an increase in soot-particle emissions, even at moderate levels of excess air. The air-fuel ratio usable at the statutory full-load smoke limit is a measure of the efficiency of air utilization.

Combustion pressure limits

During the ignition process, the partially vaporized fuel mixed with air burns at high compression, at a rapid rate, and at a high

1 Fuel-injection volume relative to engine speed and load with adjustment for temperature and atmospheric pressure



initial thermal-release peak. This is referred to as “hard” combustion. High final compression peak pressures occur during this phenomenon, and the resulting forces exert stresses on engine components and are subject to periodic changes. The dimensioning and durability of the engine and drivetrain components, therefore, limit the permissible combustion pressure and, consequently, the injected fuel quantity. The sudden rise in combustion pressure is mostly counteracted by pre-injection.

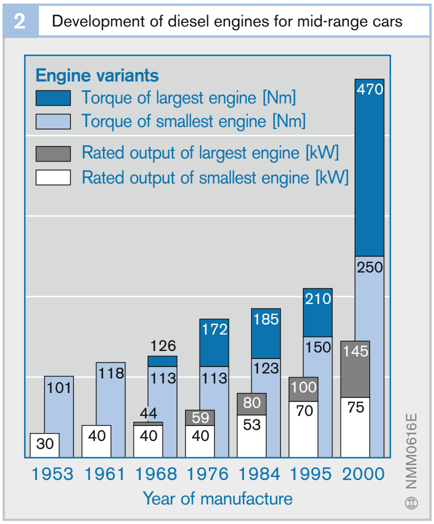
Exhaust-gas temperature limits

The high thermal stresses placed on the engine components surrounding the hot combustion chamber, the heat resistance of the exhaust valves and of the exhaust system and cylinder head determine the maximum exhaust temperature of a diesel engine.

Engine speed limits

Due to the existing excess air in the diesel engine, power at constant engine speed mainly depends on injected fuel quantity. If the amount of fuel supplied to a diesel engine is increased without a corresponding increase in the load that it is working against, then the engine speed will rise. If the fuel supply is not reduced before the engine reaches a critical speed, the engine may exceed its maximum permitted engine speed, i.e. it could self-destruct. Consequently, an engine speed limiter or governor is absolutely essential on a diesel engine.

2 Development of diesel engines for mid-range cars



On diesel engines used to drive road-going vehicles, the engine speed must be infinitely variable by the driver using the accelerator pedal. In addition, when the engine is under load or when the accelerator pedal is released, the engine speed must not be allowed to drop below the idling speed to a standstill. This is why a minimum-maximum-speed governor is fitted. The speed range between these two points is controlled using the accelerator-pedal position. If the diesel engine is used to drive a machine, it is expected to keep to a specific speed constant, or remain within permitted limits, irrespective of load. A variable-speed governor is then fitted to control speed across the entire range.

A program map is definable for the engine operating range. This map (Fig. 1, previous page) shows the fuel quantity in relation to engine speed and load, and the necessary adjustments for temperature and air-pressure variations.

Altitude and turbocharger/supercharger pressure limits

The injected fuel quantity is usually designed for sea level. If the engine is operated at high elevations (height above mean sea level), the fuel quantity must be adjusted in relation to the drop in air pressure in order to comply with smoke limits. A standard value is the barometric elevation formula, i.e. air density decreases by approximately 7% per 1,000 m of elevation.

With turbocharged engines, the cylinder charge in dynamic operation is often lower than in static operation. Since the maximum injected fuel quantity is designed for static operation, it must be reduced in dynamic operation in line with the lower air-flow rate (full-load limited by charge-air pressure).

Fuel-injection system

The low-pressure fuel supply conveys fuel from the fuel tank and delivers it to the fuel-injection system at a specific supply pressure. The fuel-injection pump generates the fuel pressure required for injection. In most systems, fuel runs through high-pressure delivery lines to the injection nozzle and is injected into the combustion chamber at a pressure of 200...2,200 bar on the nozzle side.

Engine power output, combustion noise, and exhaust-gas composition are mainly influenced by the injected fuel mass, the injection point, the rate of discharge, and the combustion process.

Up to the 1980s, fuel injection, i.e. the injected fuel quantity and the start of injection on vehicle engines, was mostly controlled mechanically. The injected fuel quantity is then varied by a piston timing edge or via slide valves, depending on load and engine speed. Start of injection is adjusted by mechanical control using flyweight governors, or hydraulically by pressure control (see section entitled "Overview of diesel fuel-injection systems").

Now electronic control has fully replaced mechanical control – not only in the automotive sector. **E**lectronic **D**iesel **C**ontrol (EDC) manages the fuel-injection process by involving various parameters, such as engine speed, load, temperature, geographic elevation, etc. in the calculation. Start of injection and fuel injection quantity are controlled by solenoid valves, a process that is much more precise than mechanical control.

▶ Size of injection

An engine developing 75 kW (102 HP) and a specific fuel consumption of 200 g/kWh (full load) consumes 15 kg fuel per hour. On a 4-stroke 4-cylinder engine, the fuel is distributed by 288,000 injections at 2,400 revs per minute. This results in a fuel volume of approx. 60 mm^3 per injection. By comparison, a raindrop has a volume of approximately 30 mm^3.

Even greater precision in metering requires an idle with approx. 5 mm^3 fuel per injection and a pre-injection of only 1 mm^3. Even the minutest variations have a negative effect on the smooth running of the engine, noise, and pollutant emissions.

The fuel-injection system not only has to deliver precisely the right amount of fuel for each individual, it also has to distribute the fuel evenly to the individual cylinder of an engine. Electronic Diesel Control (EDC) adapts the injected fuel quantity for each cylinder in order to achieve a particularly smooth-running engine.

Combustion chambers

The shape of the combustion chamber is one of the decisive factors in determining the quality of combustion and therefore the performance and exhaust characteristics of a diesel engine. Appropriate design of combustion-chamber geometry combined with the action of the piston can produce whirl, squish, and turbulence effects that are used to improve distribution of the liquid fuel or air/fuel vapor spray inside of the combustion chamber.

The following technologies are used:

- Undivided combustion chamber (**D**irect **I**njection (DI) engines) and
- Divided combustion chamber (**I**ndirect **I**njection (IDI) engines)

The proportion of direct-injection engines is increasing due to their more economical fuel consumption (up to 20% savings). The harsher combustion noise (particularly under acceleration) can be reduced to the level of indirect-injection engines by pre-injection. Engines with divided combustion chambers now hardly figure at all among new developments.

1 Direct injection

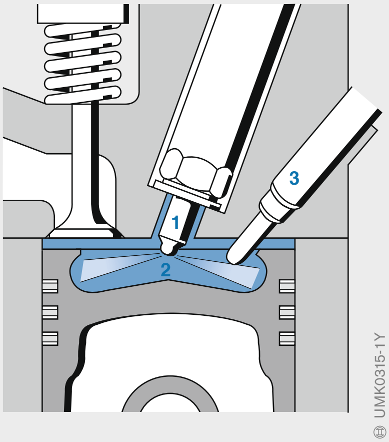


Fig. 1
1 Multihole injector
2 ω piston recess
3 Glow plug

Undivided combustion chamber (direct-injection engines)

Direct-injection engines (Fig. 1) have a higher level of efficiency and operate more economically than indirect-injection engines. Accordingly, they are used in all types of commercial vehicles and most modern diesel cars.

As the name suggests, the direct-injection process involves injecting the fuel directly into the combustion chamber, part of which is formed by the shape of the piston crown (piston crown recess, 2). Fuel atomization, heating, vaporization and mixing with the air must therefore take place in rapid succession. This places exacting demands on fuel and air delivery. During the induction and compression strokes, the special shape of the intake port in the cylinder head creates an air vortex inside of the cylinder. The shape of the combustion chamber also contributes to the air flow pattern at the end of the compression stroke (i.e. at the moment of fuel injection). Of the combustion chamber designs used over the history of the diesel engine, the most widely used at present is the ω piston crown recess.

In addition to creating effective air turbulence, the technology must also ensure that fuel is delivered in such a way that it is evenly distributed throughout the combustion chamber to achieve rapid mixing. A multihole nozzle is used in the direct-injection process and its nozzle-jet position is optimized as a factor of combustion-chamber design. Direct fuel injection requires very high injection pressures (up to 2,200 bar).

In practice, there are two types of direct fuel injection:

- Systems in which mixture formation is assisted by specifically created air-flow effects and
- Systems which control mixture formation virtually exclusively by means of fuel injection and largely dispense with any air-flow effects

In the latter case, no effort is expended in creating air-turbulence effects and this is evident in smaller gas replacement losses and more effective cylinder charging. At the same time, however, far more demanding requirements are placed on the fuel-injection system with regard to injection-nozzle positioning, the number of nozzle jets, the degree of atomization (dependent on spray-hole diameter), and the intensity of injection pressure in order to obtain the required short injection times and quality of the air/fuel mixture.

Divided combustion chamber (indirect injection)

For a long time diesel engines with divided combustion chambers (indirect-injection engines) held an advantage over direct-injection engines in terms of noise and exhaust-gas emissions. That was the reason why they were used in cars and light commercial vehicles. Now direct-injection engines are more economical than IDI engines, with comparable noise emissions as a result of their high injection pressures, electronic diesel control, and pre-injection. As a result, indirect-injection engines are no longer used in new vehicles.

2 Precombustion chamber system

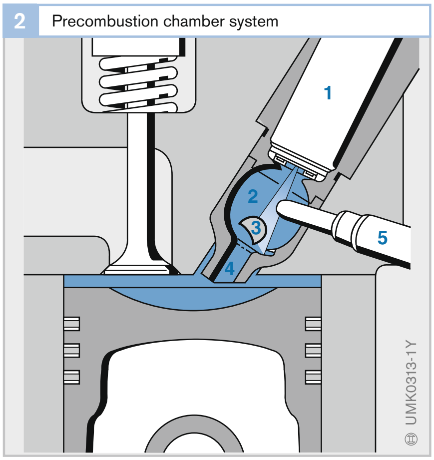


Fig. 2
1 Nozzle
2 Precombustion chamber
3 Baffle surface
4 Connecting channel
5 Glow plug

There are two types of processes with divided combustion chamber:

- The precombustion chamber system and
- The whirl-chamber system

Precombustion chamber system

In the prechamber (or precombustion chamber) system, fuel is injected into a hot prechamber recessed into the cylinder head (Fig. 2, 2). The fuel is injected through a pintle nozzle (1) at a relatively low pressure (up to 450 bar). A specially shaped baffle (3) in the center of the chamber diffuses the jet of fuel that strikes it and mixes it thoroughly with the air.

Combustion starting in the prechamber drives the partly combusted air/fuel mixture through the connecting channel (4) into the main combustion chamber. Here and further down the combustion process, the injected fuel is mixed intensively with the existing air. The ratio of precombustion chamber volume to main combustion chamber volume is approx. 1 : 2.

The short ignition lag ¹) and the gradual release of energy produce a soft combustion effect with low levels of noise and engine load.

A differently shaped prechamber with an evaporation recess and a different shape and position of the baffle (spherical pin) apply a specific degree of whirl to the air that passes from the cylinder into the prechamber during the compression stroke. The fuel is injected at an angle of 5 degrees in relation to the prechamber axis.

So as not to disrupt the progression of combustion, the glow plug (5) is positioned on the “lee side” of the air flow. A controlled post-glow period of up to 1 minute after a cold start (dependent on coolant temperature) helps to improve exhaust-gas characteristics and reduce engine noise during the warm-up period.

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¹) Time from start of injection to start of ignition

Swirl-chamber system

With this process, combustion is also initiated in a separate chamber (swirl chamber) that has approx. 60% of the compression volume. The spherical and disk-shaped swirl chamber is linked by a connecting channel that discharges at a tangent into the cylinder chamber (Fig. 3, 2).

During the compression cycle, air entering via the connecting channel is set into a swirling motion. The fuel is injected so that the swirl penetrates perpendicular to its axis and meets a hot section of the chamber wall on the opposite side of the chamber.

As soon as combustion starts, the air/fuel mixture is forced under pressure through the connecting channel into the cylinder chamber where it is turbulently mixed with the remaining air. With the swirl-chamber system, the losses due to gas flow between the main combustion chamber and the swirl chamber are less than with the precombustion chamber system because the connecting channel has a larger cross-section. This results in smaller throttle-effect losses and consequent benefits for internal efficiency and fuel consumption. However, combustion noise is louder than with the precombustion chamber system.

It is important that mixture formation takes place as completely as possible inside the swirl chamber. The shape of the swirl chamber, the alignment and shape of the fuel jet and the position of the glow plug must be carefully matched to the engine in order to obtain optimum mixture formation at all engine speeds and under all operating conditions.

Another demand is for rapid heating of the swirl chamber after a cold start. This reduces ignition lag and combustion noise as well as preventing unburned hydrocarbons (blue smoke) during the warm-up period.

3 Swirl-chamber system

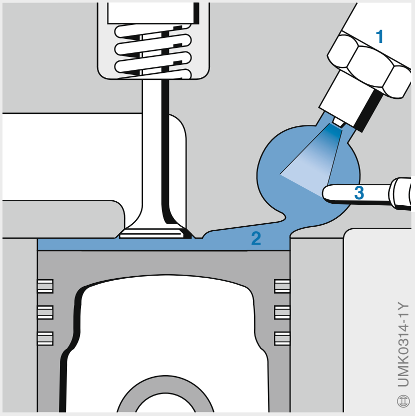
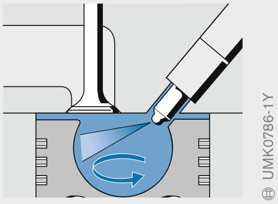


Fig. 3
1 Fuel injector
2 Tangential connecting channel
3 Glow plug

M System

In the direct-injection system with recess-wall deposition (M system) for commercial-vehicle and fixed-installation diesel engines and multi-fuel engines, a single-jet nozzle sprays the fuel at a low injection pressure against the wall of the piston crown recess. There, it vaporizes and is absorbed by the air. This system thus uses the heat of the piston recess wall to vaporize the fuel. If the air flow inside of the combustion chamber is properly adapted, an extremely homogeneous air/fuel mixture with a long combustion period, low pressure increase and, therefore, quiet combustion can be achieved. Due to its consumption disadvantages compared with the air-distributing direct injection process, the M system is no longer used in modern applications.



Fuel consumption in everyday practice

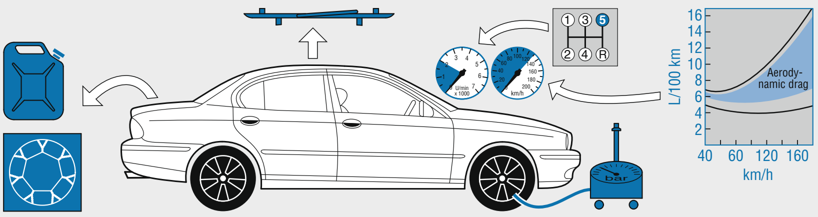
Automotive manufacturers are obliged by law to specify the fuel consumption of their vehicles. This figure is determined from the exhaust-gas emissions during the exhaust-gas test when the vehicle travels a specific route profile (test cycle). The fuel consumption figures are therefore comparable for all vehicles.

Every driver makes a significant contribution to reducing fuel consumption by his or her driving style. Reducing the fuel consumption that the driver can achieve with a vehicle depends on several factors.

Applying the measures listed below, an “economical” driver can reduce fuel consumption in everyday traffic by 20 to 30% compared to an average driver. The reduction in fuel consumption achievable by applying the individual measures depends on a number of factors, mainly the route profile (city streets, overland roads), and on traffic conditions. For this reason, it is not always practical to specify figures for fuel-consumption savings.

Positive influences on fuel consumption

- Tire pressure: Remember to increase tire pressure when the vehicle is carrying a full payload (saving: approx. 5%).
- When accelerating at high load and low engine speed, shift up at 2,000 rpm.
- Drive in the highest possible gear. You can even drive at full-load at engine speeds below 2,000 rpm.
- Avoid braking and re-accelerating by adopting a forward-looking style of driving.
- Use overrun fuel cutoff to the full.
- Switch off the engine when the vehicle is stopped for an extended period of time, e.g. at traffic lights with a long red phase, or at closed railroad crossings (3 minutes at idle consumes as much fuel as driving 1 km).
- Use high-lubricity engine oils (saving: approx. 2% according to manufacturer specifications).



Negative influences on fuel consumption

- Greater vehicle weight due to ballast, e.g. in the trunk (additional approx. 0.3 *l*/100 km).
- High-speed driving.
- Greater aerodynamic drag from carrying objects on the roof.
- Additional electrical equipment, e.g. rear-window heating, foglamps (approx. 1 *l*/1 kW).
- Dirty air filter.

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