Injection nozzles

The injection nozzle injects the fuel into the combustion chamber of the diesel engine. It is a determining factor in the efficiency of mixture formation and combustion and, therefore has a fundamental effect on engine performance, exhaust-gas behavior, and noise. In order that injection nozzles can perform their function as effectively as possible, they have to be designed to match the fuel-injection system and engine in which they are used.

The injection nozzle is a central component of any fuel-injection system. It requires highly specialized technical knowledge on the part of its designers. The nozzle plays a major role in:
- Shaping the rate-of-discharge curve (precise progression of pressure and fuel distribution relative to crankshaft rotation)
- Optimum atomization and distribution of fuel in the combustion chamber, and
- Sealing off the fuel-injection system from the combustion chamber

Due to its exposed position in the combustion chamber, the nozzle is subjected to constant pulsating mechanical and thermal stresses from the engine and the fuel-injection system. The fuel flowing through the nozzle must also cool it. When the engine is overrunning, when no fuel is being injected, the nozzle temperature increases steeply. Therefore, it must have sufficient high-temperature resistance to cope with these conditions.

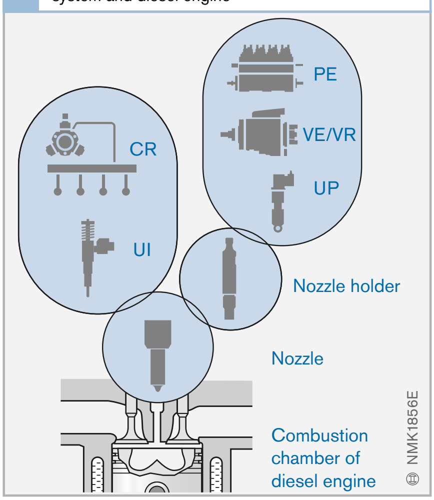
In fuel-injection systems based on in-line injection pumps (Type PE) and distributor injection pumps (Type VE/VR), and in unit pump (UP) systems, the nozzle is combined with the nozzle holder to form the nozzle-and-holder assembly (Fig. 1) and installed in the engine. In high-pressure fuel-injection systems, such as the **C**ommon **R**ail (CR) and unit injector (UI) systems the nozzle is a single integrated unit so that the nozzle holder is not required.

Indirect-**I**njection (IDI) engines use pintle nozzles, while direct-injection engines have hole-type nozzles.

The nozzles are opened by the fuel pressure. The nozzle opening, injection duration, and rate-of-discharge curve (injection pattern) are the essential determinants of injected fuel quantity. The nozzles must close rapidly and reliably when the fuel pressure drops. The closing pressure is at least 40 bar above the maximum combustion pressure in order to prevent unwanted post-injection or intrusion of combustion gases into the nozzle. The nozzle must be designed specifically for the type of engine in which it is used as determined by:
- The injection method (direct or indirect)
- The geometry of the combustion chamber
- The required injection-jet shape and direction
- The required penetration and atomization of the fuel jet
- The required injection duration, and
- The required injected fuel quantity relative to crankshaft rotation

Standardized dimensions and combinations provide the required degree of adaptability combined with the minimum of component diversity. Due to the superior performance combined with lower fuel consumption that it offers, all new engine designs use direct injection (and therefore hole-type nozzles).

1 The nozzle as the interface between fuel-injection system and diesel engine



K. Reif (Ed.), *Diesel Engine Management,* Bosch Professional Automotive Information,
DOI 10.1007/978-3-658-03981-3_14, © Springer Fachmedien Wiesbaden 2014

Dimensions of diesel fuel-injection technology

The world of diesel fuel injection is a world of superlatives.

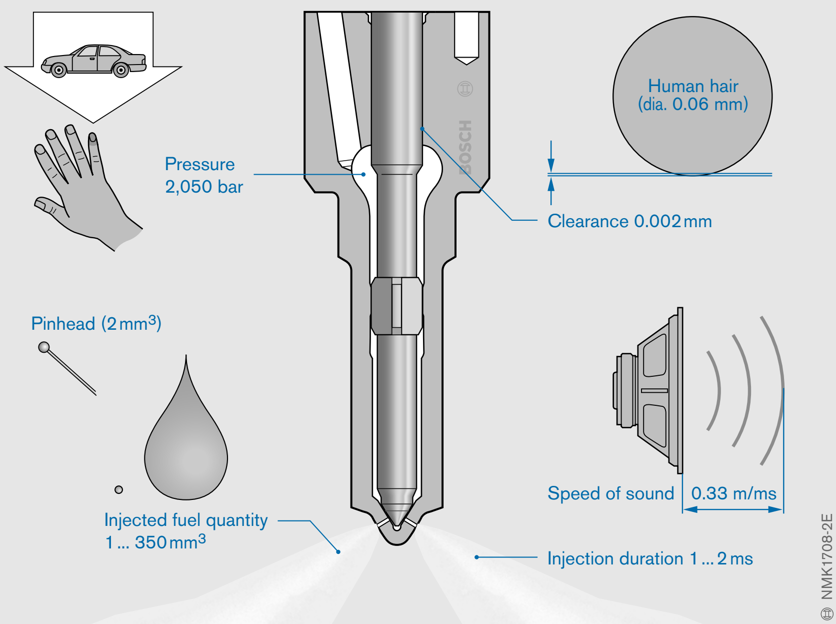
The valve needle of a commercial-vehicle nozzle will open and close the nozzle more than a billion times in the course of its service life. It provides a reliable seal at pressures as high as 2,050 bar as well as having to withstand many other stresses such as:

- The shocks caused by rapid opening and closing (on cars, this can take place as frequently as 10,000 times a minute if there are pre- and post-injection phases)
- The high flow-related stresses during fuel injection, and
- The pressure and temperature of the combustion chamber

The facts and figures below illustrate what modern nozzles are capable of:

- The pressure in the fuel-injection chamber can be as high as 2,050 bar. That is equivalent to the pressure produced by the weight of a large luxury sedan acting on an area the size of a fingernail.
- The injection duration is 1...2 milliseconds (ms). In one millisecond, the sound wave from a loudspeaker only travels about 33 cm.
- The injection durations on a car engine vary between 1 mm^3 (pre-injection) and 50 mm^3 (full-load delivery); on a commercial vehicle, between 3 mm^3 (pre-injection) and 350 mm^3 (full-load delivery). 1 mm^3 is equivalent to half the size of a pinhead. 350 mm^3 is about the same as 12 large raindrops (30 mm^3 per raindrop). That amount of fuel is forced at a velocity of 2,000 km/h through an opening of less than 0.25 mm^2 in the space of only 2 ms.
- The valve-needle clearance is 0.002 mm (2 µm). A human hair is 30 times thicker (0.06 mm).

Such high-precision technology demands an enormous amount of expertise in development, materials, production, and measurement techniques.



Pintle nozzles

Usage

Pintle nozzles are used on Indirect Injection (IDI) engines, i.e. engines that have prechambers or whirl chambers. In this type of engine, the mixing of fuel and air is achieved primarily by the whirl effects created inside the cylinder. The shape of the injection jet can also assist the process. Pintle nozzles are not suitable for direct-injection engines as the peak pressures inside the combustion chamber would open the nozzle. The following types of pintle nozzle are available:

- Standard pintle nozzles
- Throttling pintle nozzles and
- Flatted-pintle nozzles

Design and method of operation

The fundamental design of all pintle nozzles is virtually identical. The differences between them are to be found in the geometry of the pintle (Fig. 1, 7). Inside the nozzle body is the nozzle needle (3) It is pressed downwards by the force F_F exerted by the spring and the pressure pin in the nozzle holder so that it seals off the nozzle from the combustion chamber. As the pressure of the fuel in the pressure chamber (5) increases, it acts on the pressure shoulder (6) and forces the nozzle needle upwards (force F_D). The pintle lifts away from the injector orifice (8) and opens the way for fuel to pass through into the combustion chamber (the nozzle "opens"; opening pressure 110...170 bar). When the pressure drops, the nozzle closes again. Opening and closing of the nozzle is thus controlled by the pressure inside the nozzle.

Design variations

Standard pintle nozzle

The nozzle needle of (Fig. 1, 3) of a standard pintle nozzle has a pintle (7) that fits into the injector orifice (8) of the nozzle with a small degree of play. By varying the dimensions and geometry of the of the pintle, the characteristics of the injection jet produced can be modified to suit the requirements of different engines.

Throttling pintle nozzle

One of the variations of the pintle nozzle is the throttling pintle nozzle. The profile of the pintle allows a specific rate-of-discharge curve to be produced. As the nozzle needle opens, at first only a very narrow annular orifice is provided which allows only a small amount of fuel to pass through (throttling effect).

As the pintle draws further back with increasing fuel pressure, the size of the gap through which fuel can flow increases. The greater proportion of the injected fuel quantity is only injected as the pintle approaches the limit of its upward travel. By modifying the rate-of-discharge curve in this way, "softer" combustion is produced because the pressure in the combustion chamber does not rise so quickly. As a result, combustion noise is reduced in the part-load range. This means that the shape of the pintle in combination with the throttling gap and the characteristic of the compression spring in the nozzle holder produces the desired rate-of-discharge curve.

1 Standard pintle nozzle

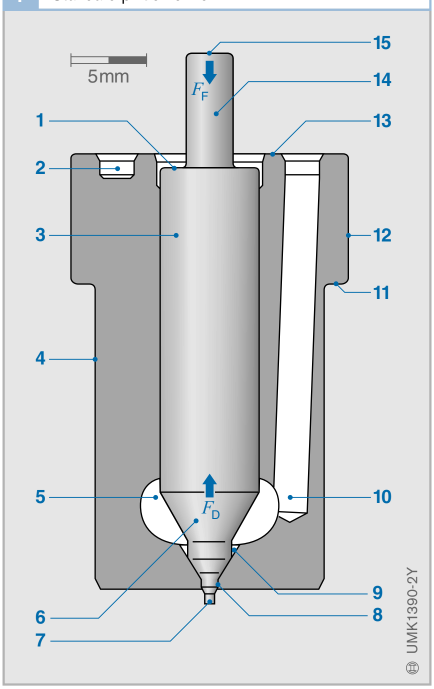


Fig. 1
1 Stroke-limiting shoulder
2 Ring groove
3 Nozzle needle
4 Nozzle body
5 Pressure chamber
6 Pintle shoulder
7 Pintle
8 Injection orifice
9 Seat lead-in
10 Inlet port
11 Nozzle-body shoulder
12 Nozzle-body collar
13 Sealing face
14 Pressure pin
15 Pressure-pin contact face

F_F Spring force
F_D Force acting on pressure shoulder due to fuel pressure

Flatted-pintle nozzle

The flatted-pintle nozzle (Fig. 3) has a pintle with a flatted face on its tip which, as the nozzle opens (at the beginning of needle lift travel) produces a wider passage within the annular orifice. This helps to prevent deposits at that point by increasing the volumetric flow rate. As a result, flatted-pintle nozzles "coke" to a lesser degree and more evenly. The annular orifice between the jet orifice and the pintle is very narrow (< 10 µm). The flatted face is frequently parallel to the axis of the nozzle needle. By setting the flatted face at an angle, the volumetric flow rate, Q, can be increased in the flatter section of the rate-of-discharge curve (Fig. 4). In this way, a smoother transition between the initial phase and the fully-open phase of the rate-of-discharge curve can be obtained. Specially designed variations in pintle geometry allow the flow-rate pattern to be modified to suit particular engine requirements. As a result, engine noise in the part-load range is reduced and engine smoothness improved.

Heat shielding

Temperatures above 220°C also promote nozzle coking. Thermal-protection plates or sleeves (Fig. 2) help to overcome this problem by conducting heat from the combustion chamber into the cylinder head.

2 Thermal-protection sleeve

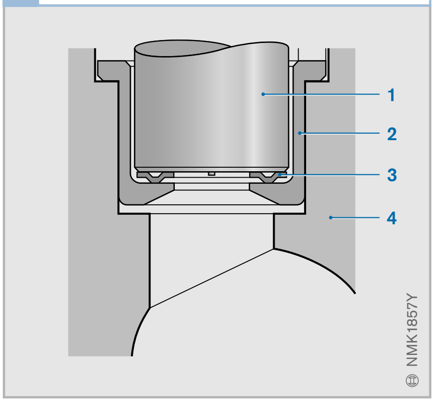


Fig. 2
1 Pintle nozzle
2 Thermal-protection sleeve
3 Protective disc
4 Cylinder head

3 Flatted-pintle nozzle

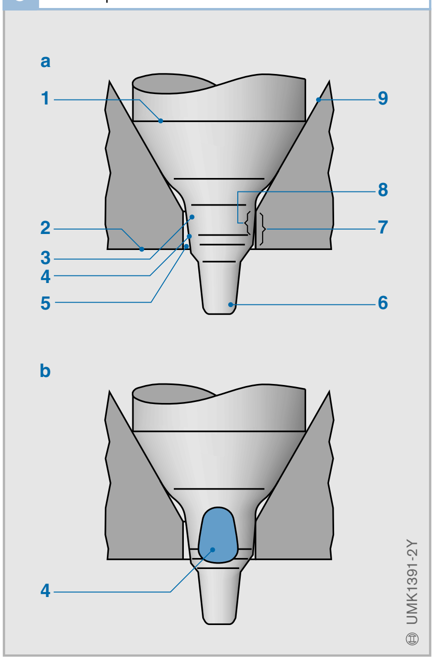


Fig. 3
a Side view
b Front view (rotation of 90° relative to side view)

1 Pintle seat face
2 Nozzle-body base
3 Throttling pintle
4 Flatted face
5 Injection orifice
6 Profiled pintle
7 Total contact ratio
8 Cylindrical overlap
9 Nozzle-body seat face

4 Volumetric flow rate as a function of pintle travel and nozzle design

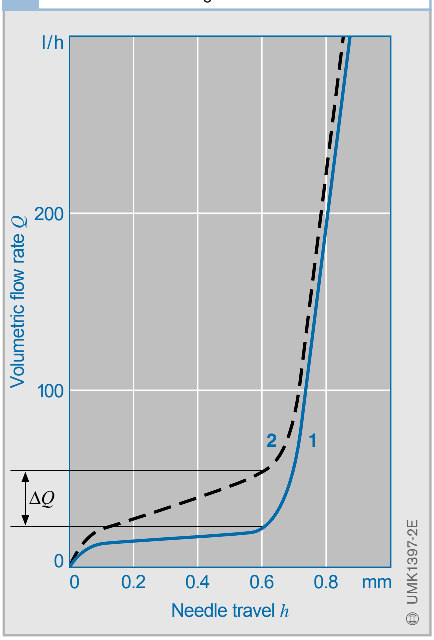


Fig. 4
1 Throttling pintle nozzle
2 Flatted-pintle nozzle (throttling pintle nozzle with flatted face)

ΔQ Difference in volumetric flow rate due to flatted face

Hole-type nozzles

Application

Hole-type nozzles are used on engines that operate according to the **D**irect-**I**njection process (DI). The position in which the nozzles are fitted is generally determined by the engine design. The injection orifices are set at a variety of angles according to the requirements of the combustion chamber (Fig. 1). Hole-type nozzles are divided into:

- Blind-hole nozzles
- Sac-less (vco) nozzles

Hole-type nozzles are also divided according to size into:

- *Type P* which have a needle diameter of 4 mm (blind-hole and sac-less (vco) nozzles).
- *Type S* which have a needle diameter of 5 or 6 mm (blind-hole nozzles for large engines).

In **C**ommon-**R**ail (CR) and **U**nit **I**njector (UI) fuel-injection systems, the hole-type nozzle is a single integrated unit. It combines, therefore, the functions of the nozzle holder.

The opening pressure of hole-type nozzles is in the range 150...350 bar.

1 Position of hole-type nozzle in combustion chamber

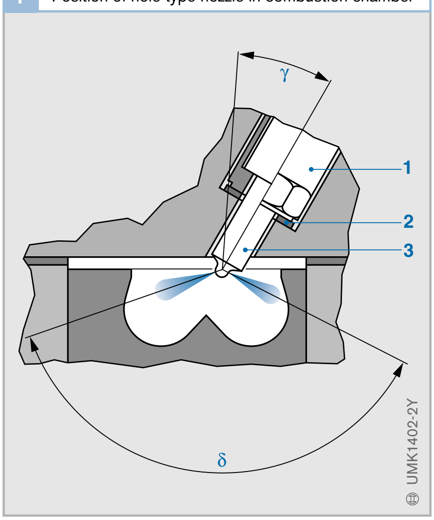


Fig. 1
1 Nozzle holder or injector
2 Sealing washer
3 Hole-type nozzle

γ Inclination
δ Jet cone angle

Design

The injection orifices (Fig. 2, 6) are located on the sheath of the nozzle cone (7). The number and diameter are dependent on:

- The required injected fuel quantity
- The shape of the combustion chamber
- The air vortex (whirl) inside of the combustion chamber

The diameter of the injection orifices is slightly larger at the inner end than at the outer end. This difference is defined by the port taper factor. The leading edges of the injection orifices may be rounded by using the hydro-erosion (HE) process. This involves the use of an HE fluid that contains abrasive particles which smooth off the edges at points where high flow velocities occur (leading edges of injection orifices). Hydro-erosion can be used both on blind-hole and sac-less (vco) nozzles. Its purpose is to:

- optimize the flow-resistance coefficient
- pre-empt erosion of edges caused by particles in the fuel, and/or
- tighten flow-rate tolerances

Nozzles have to be carefully designed to match the engine in which they are used. Nozzle design plays a decisive role in the following:

- Precise metering of injected fuel (injection duration and injected fuel quantity relative to degrees of crankshaft rotation).
- Fuel conditioning (number of jets, spray shape and atomization of fuel).
- Fuel dispersal inside the combustion chamber.
- Sealing the fuel-injection system against the combustion chamber.

The pressure chamber (10) is formed by **E**lectrochemical **M**achining (ECM). An electrode, through which an electrolyte solution is passed, is introduced into the pre-bored nozzle body. Material is then removed from the positively charged nozzle body (anodic dissolution).

Designs

Fuel in the volume below the nozzle-needle seat evaporates after combustion. This produces a large part of the engine's hydrocarbon emissions. For this reason, it is important to keep the dead volume, or "detrimental" volume, as small as possible.

In addition, the geometry of the needle seat and the shape of the nozzle cone have a decisive influence on the opening and closing characteristics of the nozzle. This, in turn, affects the soot and NO_x emissions produced by the engine.

The consideration of these various factors, in combination with the demands of the engine and the fuel-injection system, has resulted in a variety of nozzle designs.

There are two basic designs:

- Blind-hole nozzles
- Sac-less (vco) nozzles

Among the blind-hole nozzles, there are a number of variants.

Blind-hole nozzle

The injection orifices in the blind-hole nozzle (Fig. 2, 6) are arranged around a blind hole.

If the nozzle has a *rounded tip*, the injection orifices are drilled either mechanically or by electro-erosion, depending on the design.

In blind-hole nozzles with a *conical tip*, the injection orifices are generally created by electro-erosion.

Blind-hole nozzles may have a cylindrical or conical blind hole of varying dimensions.

Blind-hole nozzles with a cylindrical blind hole and rounded tip (Fig. 3), which consists of a cylindrical and a hemispherical section, offer a large amount of scope with regard to the number of holes, length of injection orifices, and spray-hole cone angle. The nozzle cone is hemispherical in shape, which – in combination with the shape of the blind hole – ensures that all the spray holes are of equal length.

2 Blind-hole nozzle

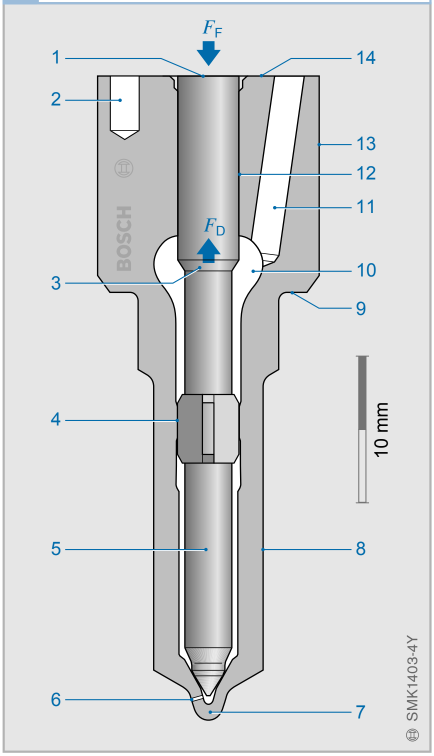


Fig. 2
1 Stroke-limiting shoulder
2 Fixing hole
3 Pressure shoulder
4 Secondary needle guide
5 Needle shaft
6 Injection orifice
7 Nozzle cone
8 Nozzle body
9 Nozzle-body shoulder
10 Pressure chamber
11 Inlet passage
12 Needle guide
13 Nozzle-body collar
14 Sealing face

F_F Spring force
F_D Force acting on pressure shoulder due to fuel pressure

3 Features of a nozzle cone with cylindrical blind hole and rounded tip

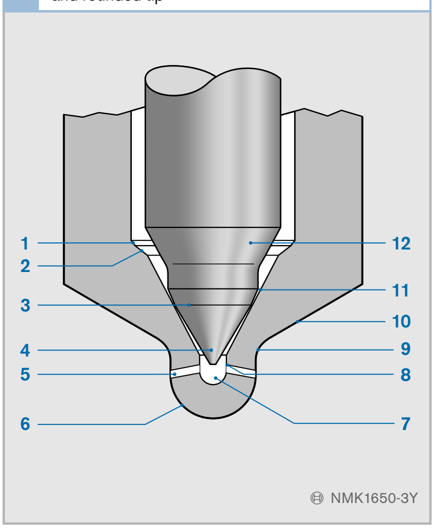


Fig. 3
1 Shoulder
2 Seat lead-in
3 Needle-seat face
4 Needle tip
5 Injection orifice
6 Rounded tip
7 Cylindrical blind hole (dead volume)
8 Injection orifice leading edge
9 Neck radius
10 Nozzle-cone taper
11 Nozzle-body seat face
12 Damping taper

The *blind-hole nozzle with a cylindrical blind hole and conical tip* (Fig. 4a) is only available for spray-hole lengths of 0.6 mm. The conical tip shape increases tip strength as a result of a greater wall thickness between the neck radius (3) and the nozzle body seat (4).

4 Nozzle cones

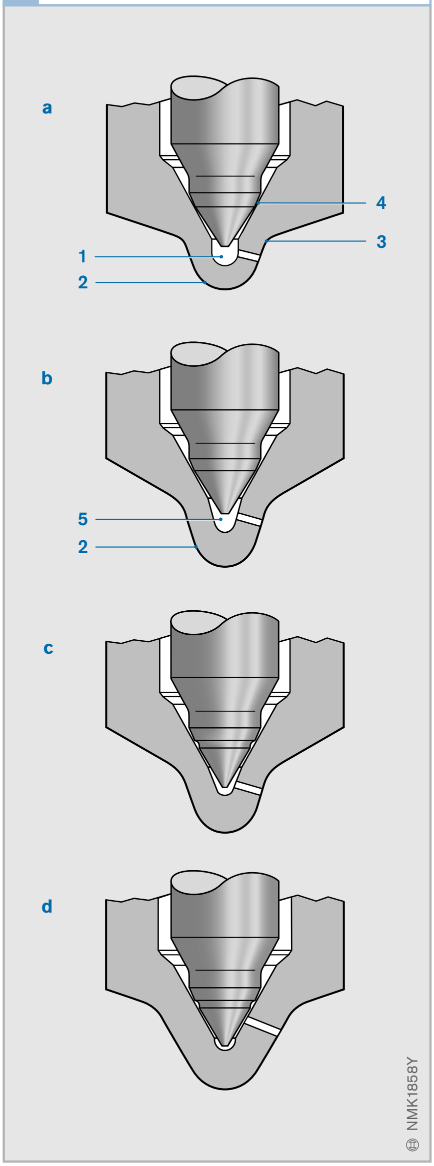


Fig. 4
- a Cylindrical blind hole and conical tip
- a Conical blind hole and conical tip
- c Micro-blind-hole
- d Sac-less (vco) nozzle

1. Cylindrical blind hole
2. Conical tip
3. Neck radius
4. Nozzle-body seat face
5. Conical blind hole

Blind-hole nozzles with conical blind holes and conical tip (Fig. 4b) have a smaller dead volume than nozzles with a cylindrical blind hole. The volume of the blind hole is between that of a sac-less (vco) nozzle and a blind-hole nozzle with a cylindrical blind hole. In order to obtain an even wall thickness throughout the tip, it is shaped conically to match the shape of the blind hole.

A further refinement of the blind-hole nozzle is the micro-blind-hole nozzle (Fig. 4c). Its blind-hole volume is around 30% smaller than that of a conventional blind-hole nozzle. This type of nozzle is particularly suited to use in common-rail systems, which operate with a relatively slow needle lift and, consequently, a comparatively long nozzle-seat restriction. The micro-blind-hole nozzle currently represents the best compromise between minimizing dead volume and even spray dispersal when the nozzle opens for common-rail systems.

Sac-less (vco) nozzles

In order to minimize dead volume – and therefore HC emissions – the injection orifice exits from the nozzle-body seat face. When the nozzle is closed, the nozzle needle more or less covers the injection orifice so that there is no direct connection between the blind hole and the combustion chamber (Fig. 4d). The blind-hole volume is considerably smaller than that of a blind-hole nozzle. Sac-less (vco) nozzles have a significantly lower stress capacity than blind-hole nozzles and can therefore only be produced with a spray-hole length of 1 mm. The nozzle tip has a conical shape. The injection orifices are generally produced by electro-erosion.

Special spray-hole geometries, secondary needle guides, and complex needle-tip geometries are used to further improve spray dispersal, and consequently mixture formation, on both blind-hole and sac-less (vco) nozzles.

Heat shield

The maximum temperature capacity of hole-type nozzles is around 300°C (heat resistance of material). Thermal-protection sleeves are available for operation in especially difficult conditions, and there are even cooled nozzles for large-scale engines.

Effect on emissions

Nozzle geometry has a direct effect on the engine's exhaust-gas emission characteristics.

- The *spray-hole geometry* (Fig. 5, 1) influences particulate and NO_x emissions.
- The *needle-seat geometry* (2) affects engine noise due to its effect on the pilot volume, i.e. the volume injected at the beginning of the injection process. The aim of optimizing spray-hole and seat geometry is to produce a durable nozzle capable of mass production to very tight dimensional tolerances.
- *Blind-hole geometry* (3) affects HC emissions, as previously mentioned. The designer can select and combine the various nozzle characteristics to obtain the optimum design for a particular engine and vehicle concerned.

For this reason, it is important that the nozzles are designed specifically for the vehicle, engine and fuel-injection system in which they are to be used. When servicing is required, it is equally important to use genuine OEM parts in order to ensure that engine performance is not impaired and exhaust-gas emissions are not increased.

Spray shapes

Basically, the shape of the injection jet for car engines is long and narrow because these engines produce a large degree of whirl inside of the combustion chamber. There is no whirl effect in commercial-vehicle engines. Therefore, the injection jet tends to be wider and shorter. Even where there is a large amount of whirl, the individual injection jets must not intermingle, otherwise fuel would be injected into areas where combustion has already taken place and, therefore, where there is a lack of air. This would result in the production of large amounts of soot.

Hole-type nozzles have up to six injection orifices in passenger cars and up to ten in commercial vehicles. The aim of future development will be to further increase the number of injection orifices and to reduce their bore size (< 0.12 mm) in order to obtain even finer dispersal of fuel.

5 Decisive areas of nozzle geometry

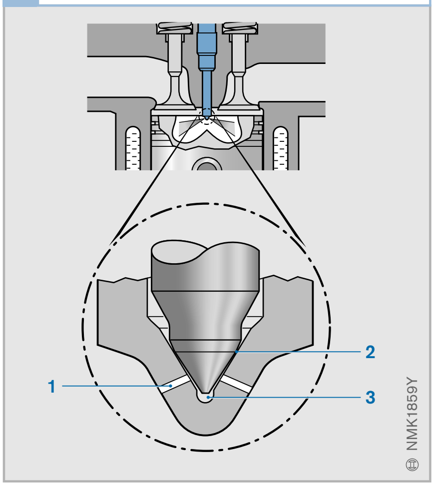
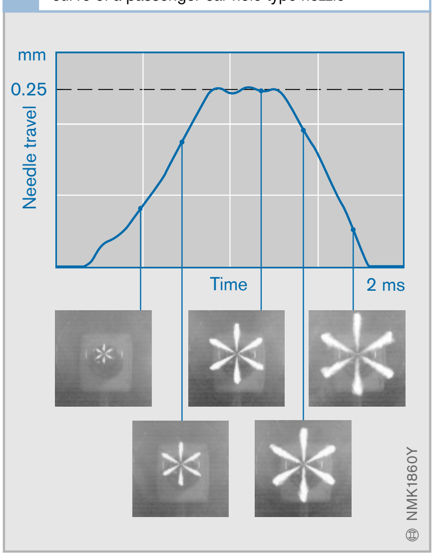


Fig. 5
1 Injection-orifice geometry
2 Seat geometry
3 Blind-hole geometry

6 High-speed photographs of rate-of-discharge curve of a passenger-car hole-type nozzle



Future development of the nozzle

In view of the rapid development of new, high-performance engines and fuel-injection systems with sophisticated functionality (e.g. multiple injection phases), continuous development of the nozzle is a necessity. In addition, there are number of aspects of nozzle design which offer scope for innovation and further improvement of diesel engine performance in the future. The most important aims are:

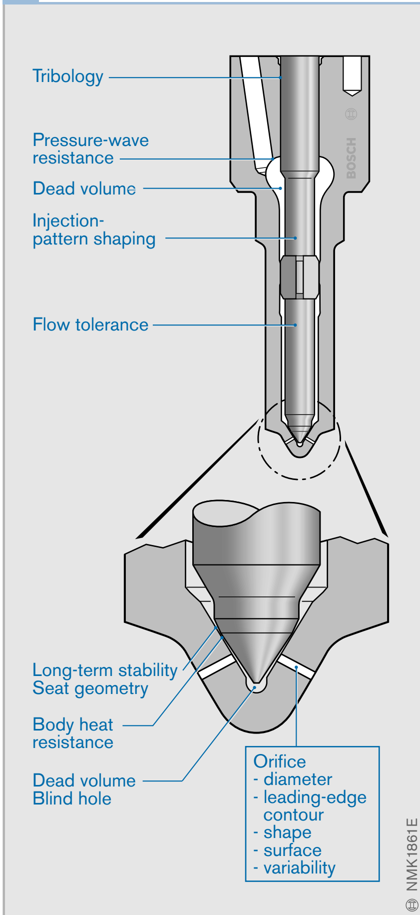
- Minimize untreated emissions to reduce or totally avoid the outlay for an expensive exhaust-gas treatment (e.g. particulate filter).
- Minimize fuel consumption.
- Optimize engine noise.

There various different areas on which attention can be focused in the future development of the nozzle (Fig. 1) and a corresponding variety of development tools (Fig. 2). New materials are also constantly being developed to offer improvements in durability. The use of multiple-injection phases also has consequences for the design of the nozzle.

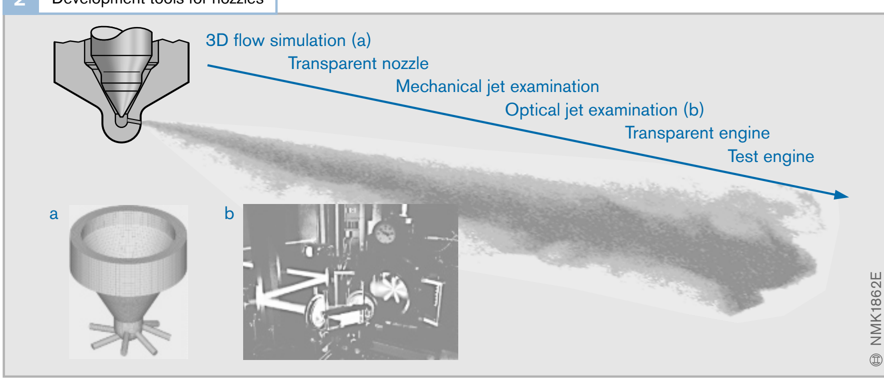
The use of other fuels (e.g. designer fuels) affects nozzle shape due to differences in viscosity or flow response.

Such changes will, in some cases, also demand new production processes, such as laser drilling for the injection orifices.

1 Main points of focus of nozzle development



2 Development tools for nozzles



High-precision technology

The image associated with diesel engines in many people's minds is more one of heavy-duty machinery than high-precision engineering. But modern diesel fuel-injection systems are made up of components that are manufactured to the highest degrees of accuracy and required to withstand enormous stresses.

The nozzle is the interface between the fuel-injection system and the engine. It has to open and close precisely and reliably for the entire life of the engine. When it is closed, it must not leak. This would increase fuel consumption, adversely affect exhaust-gas emissions, and might even cause engine damage.

To ensure that the nozzles seal reliably at the high pressures generated in modern fuel-injection systems such as the VR (VP44), CR, UPS and UIS designs (up to 2,050 bar), they have to be specially designed and very precisely manufactured. By way of illustration, here are some examples:

- To ensure that the sealing face of the nozzle body (1) provides a reliable seal, its has a dimensional tolerance of 0.001 mm (1 µm). That means it must be accurate to within approximately 4,000 metal atom layers!
- The nozzle-needle guide clearance (2) is 0.002...0.004 mm (2...4 µm). The dimensional tolerances are similarly less than 0.001 mm (1 µm).

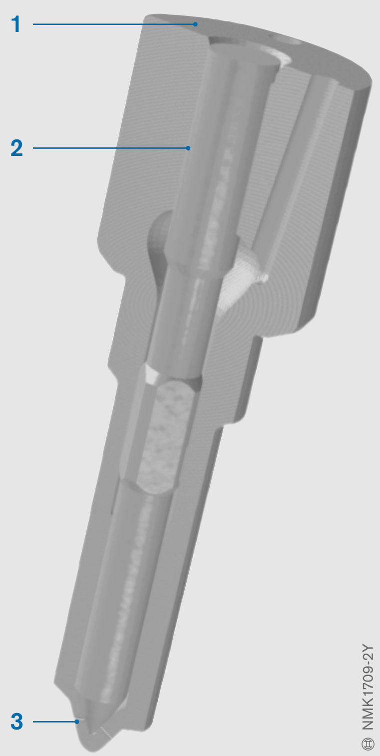
The injection orifices (3) in the nozzles are created by an electro-erosion machining process. This process erodes the metal by vaporization caused by the high temperature generated by the spark discharge between an electrode and the workpiece. Using high-precision electrodes and accurately configured parameters, extremely precise injection orifices with diameters of 0.12 mm can be produced. This means that the smallest injection orifice diameter is only twice the thickness of a human hair (0.06 mm). In order to obtain better injection characteristics, the leading edges of the nozzle injection orifices are rounded off by special abrasive fluids (hydro-erosion machining).

The minute tolerances demand the use of highly specialized and ultra-accurate measuring equipment such as:

- Optical 3D coordinate measuring machine for measuring the injection orifices, or
- Laser interferometers for checking the smoothness of the nozzle sealing faces.

The manufacture of diesel fuel-injection components is thus "high-volume, high-technology".

A matter of high-precision



1 Nozzle-body sealing face
2 Guide clearance between nozzle needle and nozzle body
3 Injection orifice