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Analiza sistemov za neposredno vbrizgavanje goriva v sodobne hitrotekoče dizelske motorje

An Analysis of Fuel-Injection Systems for Advanced High-Speed Diesel Engines

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Razvoj hitrotekočih dizelskih motorjev se je začel v Evropi pred 22 leti. Največje težave pri razvoju so bile povezane z opremo za visokotlačno vbrizgavanje goriva. Doseči je treba visoke tlake vbrizgavanja, pravilen potek tlaka vbrizgavanja, možnost znižanja hrupa zgorevanja in seveda tudi zmanjšanja količine škodljivih snovi v izpušnih plinih. Značilnosti, primerjave tehničnih karakteristik ter predvidevanja za razvoj vbrizgalnih sistemov v prihodnosti so prikazane v tem prispevku.

(Ključne besede: motorji dizelski, motorji hitrohodni, vbrizgavanje goriva, vbrizgavanje direktno)

The development of the high-speed Diesel engines began in Europe 22 years ago. Since this time major technical problems have been encountered with the fuel system and its components. Different technical requirements have been met simultaneously: very high injection pressures, suitable pressure-to-time distribution, sophisticated injection timing control, reduced combustion noise and very stringent exhaust emission standards. General features, a comparison between some of the most advanced fuel-injection systems, and guidelines for the future are presented in the paper.

(Keywords: Diesel engines, high speed engines, fuel injection, direct injection)

0 UVOD

Že v začetku 20. stoletja smo bili tehnično zmožni izdelati počasne dizelske motorje z neposrednim vbrizgavanjem goriva.

Dizelski motorji z neposrednim vbrizgavanjem dosežejo v primerjavi z vsemi drugimi motorji z notranjim zgorevanjem največji izkoristek.

Razvoj sistemov za vbrizgavanje je v začetku tridesetih let omogočil doseganje tlakov vbrizgavanj goriva okoli 700 bar. S tako visokim tlakom vbrizgavanja goriva smo bili v stanju izdelati dizelske motorje, ki so se vrteli z 2000 do 2500 vrtljaji v minuti. Začela se je izdelava 4-taktnih dizelskih motorjev z neposrednim vbrizgavanjem, in sicer za pogon tovornih vozil in za nevozne potrebe. Motorji so se izkazali kot zelo zanesljivi, tako da so bila v naslednjih 20 letih praktično vsa tovorna vozila v zahodni Evropi opremljena s takšnimi motorji. Omejeno število vrtljajev in potrebni presežek zraka sta omejevala specifično moč motorja.

Z dvotaktnimi in s štiri-taktnimi tlačno polnjenimi motorji je bilo tehnično mogoče povečati specifično moč motorjev. Pri dvotaktnih motorjih je bilo potrebno nadaljnje povečanje tlaka za

0 INTRODUCTION

At the beginning of the 20th century engineers were capable of making low-speed Diesel engines with direct fuel injection.

It is well known that this type of the internal combustion engine has the highest thermal efficiency.

Fuel-injection systems of the 30s were capable of working at pressures of about 700 bar. As a result, faster – 2000 to 2500 rpm — four-stroke Diesel engines with direct fuel injection were produced for stationary applications as well as for driving commercial vehicles. The engines were quite reliable and replaced most of the power units in Western Europe over the next 20 years. A relatively low engine speed and large amounts of air needed for combustion, however, prevented any increase in the specific power of Diesel engines.

Advanced two-stroke and four-stroke supercharged engines brought the advantage of a higher specific output power for the engine. Fuel-injection systems with higher operating pressures were developed for up- to-date two-stroke engines vbrizgavanje, kar so v Ameriki dosegli z vbrizgovalnim sistemom "Unit-Injector" (sistem združene tlačilke in šobe za vbrizgavanje goriva). Za velike nevozne motorje smo imeli na voljo zanesljiva turbopuhala že v začetku štiridesetih let, za manjše motorje za pogon tovornih vozil pa so se učinkovita in zanesljiva turbopuhala pojavila šele ob koncu šestdesetih let.

Za pogon osebnih avtomobilov in lahkih tovornjakov uporabljamo lahke, hitrotekoče motorje z večjim številom vrtljajev. Konec štiridesetih let so bili razviti prvi hitrotekoči dizelski motorji s predkomoro. Temu ustrezne zahteve za sistem vbrizgavanja niso bile velike, toda specifična moč motorjev je bila s takim sistemom zelo omejena. Tudi uporaba turbopuhala na takšnih motorjih je bila zaradi velike toplotne obremenitve bata omejena na srednje vrednosti specifične moči. Poraba goriva je bila majhna pri nizkih obremenitvah, z uvedbo tlačne polnitve pa je bila poraba goriva dizelskega motorja s predkomoro samo še neznatno manjša od sodobnega bencinskega motorja ([1] do [3]).

1 LASTNOSTI, KI JIH ZAHTEVAMO OD SODOBNIH VBRIZGALNIH SISTEMOV

Da bi hitrotekoči dizelski motor mogel tekmovati s sodobnim bencinskim motorjem, mora imeti naslednje lastnosti:

- enako moč kakor bencinski motor;
- nizko raven hrupa, ki je primerljiva tisti pri bencinskem motorju;
- lahek in takojšnji zagon motorja pri temperaturah okolice do -40°C;
- dolgo življenjsko doba trajanja motorja v primerjavi z bencinskim motorjem pri enaki obremenitvi;
- doseganje največje moči motorja vsaj pri 4000 min^{-1};
- največje število vrtljajev vsaj 5200 min^{-1};
- nizko raven vibracij;
- majhne stroške izdelave - največ 10% nad ceno bencinskega motorja s primerljivo močjo in ob približno enakem številu izdelanih enot;
- preprosto zanesljivost in vzdrževanje;
- nizko raven vseh škodljivih in zakonsko preverjenih sestavin v izpušnih plinih.

Da bi lahko vsem opisanim zahtevam ugodili, postavljamo zelo velike zahteve za sistem vbrizgavanja goriva. Predvsem je treba vbrizgati velike količine goriva v zelo kratkem času (velika moč motorja in veliko število vrtljajev). To gorivo je treba vbrizgati skozi zelo majhne luknjice v šobi, da se doseže izrazita razpršitev vbrizganega goriva. Zato potrebujemo visoke tlake vbrizgavanja. Najvišji tlaki vbrizgavanja vse do 2500 bar imajo prednost. Prednost tlakov vbrizgavanja, ki presegajo 2000 bar ni več zelo velika. Toda samo zagotavljanje visokih tlakov vbrizgavanja še ne zadošča.

Zahteve, ki jih mora izpolniti celotni sistem vbrizgavanja so:

and unit injectors were developed in the USA for this reason. Large stationary engines were equipped with relatively modern turbochargers in the 40s, whereas small and reliable turbochargers for high-speed engines were not available until the end of the 60s.

Passenger cars and light trucks need light, high-speed engines. The first high-speed pre-chamber diesel engines were available at the end of the 40s. There was no special technical demand for adequate fuel-injection systems, but the engine's specific rated output was limited. The thermal load of the engine piston was also a limiting factor that prevented the use of the turbochargers and the development of a higher specific engine power. Specific fuel consumption was relatively low at low engine loads, however, at higher engine loads and with a turbocharged prechamber Diesel engine almost the same fuel consumption as by a modern petrol engine was achieved ([1] to [3]).

1 REQUIREMENTS FOR A MODERN FUEL-INJECTION SYSTEM

A modern, high-speed Diesel engine can compete with a modern petrol engine if it fulfils the following requirements:

- it must develop the same power output;
- the noise level must not exceed the level of a comparable petrol engine;
- reliable start-up must be ensured at very low ambient temperatures of about -40 °C;
- the longevity of the engine must be higher than a petrol engine under the same operating conditions;
- the rated engine speed must exceed 4000 *rpm*;
- the maximum engine speed must be at least 5200 *rpm.*
- the level of the engine's mechanical vibrations must be kept low;
- production costs of a Diesel engine must be low; they can only exceed the cost of a comparable petrol engine for the same production volume by a maximum of 10%;
- the engine must be reliable and the maintenance must be simple;
- the exhaust gases must be clean; all regulated polutants must be within the prescribed limits.

Very high standards are required of a fuel-injection system (FIS) in order to fulfil all the above-mentioned requirements. Large quantities of fuel need to be injected in a relatively short time to ensure a high engine output at higher engine speeds. Fuel must be injected through tiny nozzle holes to obtain intensive atomization; very high pressures are required and pressures of up to 2500 bar can be achieved in modern fuel systems. The advantage of the extremely high injection pressure deminishes when 2000 bar is exceeded. Some extra conditions concerning optimum injection must therefore be fulfiled.

The following requirements must be taken into account with a new injection system:

- visok povprečni tlak vbrizgavanja;
- visoki tlaki ob koncu postopka vbrizgavanja;
- zelo visoki gradient znižanja tlaka ob koncu vbrizgavanja;
- krmiljenje tlakov vbrizgavanja v skladu s potrebami motorja;
- časovni potek tlaka vbrizgavanja, ki se zvišuje proti koncu vbrizgavanja;
- vžig dela goriva preden so večje količine goriva vbrizgane v zgorevalni prostor motorja (predvbrizg goriva);
- krmiljenje začetka vbrizgavanja, ki je odvisno od temperature motorja, srednjega efektivnega tlaka (obremenitve motorja), števila vrtljajev motorja in certifikacijskim (emisijskim) zahtevam vozila;
- enakomerna porazdelitev goriva po vseh valjih;
- spremenljiv prerez luknjic vbrizgovalne šobe brez dušenja curka (za zdaj še ni doseženo z nobenim sistemom). Večkratno delno vbrizgavanje goriva z dobro razporeditvijo goriva po prostoru bi imelo podoben učinek;
- celotno trajanje vbrizga pri polni obremenitvi motorja naj ne bi preseglo 25° zasuka ročične gredi;
- dosegljivost emisijskih predpisov “Euro 4”;
- majhen mehanično-hidravlični hrup sistema za vbrizgavanje;
- zelo majhne kavitacijske poškodbe v sistemu;
- velika mehanična zanesljivost sistema;
- preproste zahteve po opremljenosti servisnih postaj;
- dimenzije vbrizgalne šobe, ki omogočajo gradnjo v valjevo glavo s po štirimi ventili;
- majhni stroški izdelave in vgradnje;
- majhni stroški vzdrževanja (servisa);
- možnost prilagodljive konstrukcije motorja;
- mogoča velika specifična moč motorja.

Pri tem so pomembne tudi mehanske zahteve, ki jih mora izpolnjevati šoba za vbrizgavanje goriva:

- konstrukcija šobe mora omogočati in trajno zdržati tlake vbrizgavanja nad 2200 bar;
- pri majhnih zračnostih (natančno prileganje) med iglo in vrtino šobe ne sme priti pri vgradnji do škodljivih deformacij, ki bi lahko preprečile prosto gibanje igle v šobi;
- vrtina - vodilo igle šobe mora biti čim daljša, obenem pa ne sme segati v področje šobe s previsoko temperaturo;
- razdalja med vrtino za dovod goriva pod tlakom v spodnji del šobe in vodilno vrtino igle šobe mora biti čim večja, da se izognemo prevelikim mehanskim napetostim in deformacijam v okrovu šobe;
- vrtina za dovod goriva v spodnji del šobe in vodilna vrtina igle šobe ne smejo biti vzporedne;

- very high mean injection pressure;
- very high injection pressure decrease in the final sequence of the fuel delivery;
- very high gradients of presure decrease at the end of the fuel-injection process;
- suitable control of the injection pressure history according to the requirements of the engine;
- adequate pressure-time pattern that must increase throughout most of the injection process;
- ignition of a small portion of the injected fuel prior to the injection of the major part of the fuel into the engine combustion chamber (pre-injection);
- control of the start of fuel injection depending on the engine temperature, speed, load and the exhaust emission requirements of the vehicle;
- uniform fuel distribution in all engine cylinders;
- adjustable area of the fuel-nozzle holes without excessive choking effects — this has not yet been developed. Multiple sequential fuel injection during the same engine working cycle with optimum fuel spray distribution within the combustion chamber might have a similar effect;
- duration of the fuel injection at the engine’s rated operating conditions should not exceed a 25 ^{0} crank angle;
- implementation of the “Euro 4” exhaust emission standards;
- low mechanically and hydraulically born noise generated by the FIS;
- negligible damage to the FIS due to cavitation;
- high mechanical reliability of the FIS;
- relatively low requirements for special equipment in service stations;
- restricted dimensions of the FIS can lead to easy installation even in multi-valve cylinder head;
- low production and installation costs;
- low maintenance (service) costs;
- flexible engine design;
- high specific engine power.

In addition to the very high mechanical and strength standards that need to be taken into account when advanced FISs are considered. The following requirements are also crucial:

- the fuel-injection nozzle must operate continuously and reliably at 2200 bar;
- the extremely small clearance between the injector needle and its leading surface (bore) must, under no circumstances, be affected by the mechanical deformations caused during the installation of the injector holder;
- the supporting-leading surface of the needle must be as long as possible and must be removed from the bottom – the thermally highly loaded area;
- the high-pressure fuel-inlet borehole in the injector body (holder) must be moved away from the needle leading bore to prevent excess mechanical deformations;
- both high-pressure channels mentioned in the point above must not run parallel;

- tesnilka vbrizgalne šobe ne sme povzročiti dodatnih sil in napetosti, ki bi povzročile deformacijo vrtine šobe pri vgradnji;
- sila udarca pri nasedu igle šobe na sedež mora biti omejena;
- zaobliti je treba notranje robove luknjic na vrtinah šobe.

Že iz samih zahtev vidimo, da vsega, kar bi radi dosegli z novimi konstrukcijam ni mogoče doseči brez kompromisov.

Visoki tlaki vbrizganja omogočajo skrajšani čas vbrizgavanja pri isti izmeri luknjic šobe. Na tak način je mogoče vbrizgati gorivo kasneje in obenem lahko znižamo emisijo dušikovih oksidov (NO_X) motorja. S kasnejšim vbrizgom so tudi tlaki zgorevanja nižji, kar dopušča uporabo višjega kompresijskega razmerja in s tem tudi boljše pogoje za delovanje motorja pri nizkih temperaturah okolice.

Vsi novi sistemi so zgrajeni z upoštevanjem kompromisnih rešitev, ki so bolj ali manj uspešne. Pri tem uporabljamo dandanes sisteme s prostorninskim krmiljenjem količine vbrizganega goriva (najbolj enakomerna porazdelitev goriva po vseh valjih) in časovnim krmiljenjem količine vbrizganega goriva.

Z zaokroženimi vtočnimi vrtinami luknjic z notranje strani šobe, ki ustrezajo kalibriranemu (primerjalnemu) uporu pretoka goriva je mogoče doseči izboljšano enakomernost razporeditve goriva med valji tudi pri sistemih s časovnim krmiljenjem količine goriva.

2 PREDSTAVITEV SODOBNIH SISTEMOV ZA VBRIZGAVANJE GORIVA

V novih, sodobnih hitrotekočih dizelskih motorjih imamo dandanes vgrajene naslednje vbrizgalne sisteme:

Visokotlačna porazdelilna (distribucijska) tlačilka

Visokotlačna distribucijska tlačilka za gorivo, kombinirana z dvostopenjskim odpiranjem šobe, je prikazana na sliki 1a in b. Ta sistem je uporabljen pri sodobnih vozilih znamk VW, Seat, Audi, Škoda, DB, Rover in Renault.

Z novimi izboljšanimi konstrukcijskimi rešitvami je bilo mogoče doseči tlake (izmerjeni pri tlačilki) 1300 bar in z dinamičnim procesom nihanj v visokotlačni cevi za gorivo med tlačilko in šobo tudi tlake do 1600 bar. Časovni potek tlaka vbrizgavanja pri tem sistemu ni posebej ugoden. Prostorninsko krmiljenje količine goriva omogoča enakomerno porazdelitev vbrizganega goriva po vseh valjih. Ta sistem ima prednosti pri predelavi starejšega motorja z deljenim zgorevalnim prostorom. Stroški opisanega sistema so večinoma majhni. Z dvostopenjsko vbrizgalno šobo je mogoče doseči nizko raven hrupa zgorevanja. Zaradi dolgih cevi med tlačilko in šobo morajo biti tlaki za odpiranje v šobi sorazmerno nizki (pri prvi stopnji ~200, pri drugi pa ~350 bar). Tlak vbrizgavanja ni optimalen za vse pogoje delovanja motorja (po celotni

- the sealing (element) under the injector body must not provoke additional deformations during the assembly procedure;
- the impact force at the injector needle closure must be limited;
- the intake edges of the injector spray holes must be carefully rounded.

It can be concluded from the above-mentioned requirements that compromises are necessary in the design of new FISs.

A high injection pressure means a shorter duration of the fuel injection if the geometry of the nozzle holes remains unchanged. It is therefore possible to delay the injection sequence and simultanously reduce the NO_X content in the exhaust gasses. In addition, lower peak combustion pressures are obtained and higher engine compression ratios – for more economic engine operation at lower ambient temperatures – can be used.

All newly developed FISs involve compromises. Today, two types of FIS are in use to control the injected fuel per cycle: volumetic control of the injected fuel, which ensures uniform fuel distribution in all engine cylinders, and time-controlled fuel distribution.

The intake radius at the fuel-injector holes can be adjusted and used for the mass-calibration of the particular fuel injectors to obtain a more uniform distribution of the fuel in particular engine cylinders even if a FIS with time control of the injected fuel is applied.

2 DESCRIPTION OF SOME ADVANCED FISs

The following FISs can be found in new high-speed Diesel engines:

High-pressure fuel distributor pump

A high-pressure distributor pump combined with a two-stage fuel injector is schematically presented in Fig. 1a and b and is used by several car manufacturers: VW, Seat, Audi, Škoda, DB, Rover, and Renault.

New design solutions in the above-mentioned FIS have led to maximum operating pressures of about 1300 bar (measured at the fuel pump outlet) and maximum dynamic pressures up to 1600 bar. The shape of the pressure-time history of the fuel injection is not ideal. Volumetric control of the injected fuel means a very uniform distribution of the fuel in the engine cylinders. This FIS can also be easily adapted to a traditionally designed indirect injection pre-chamber engine. The costs for the above-mentioned FIS are low. A two-stage injection greatly reduces the combustion noise. Relatively long fuel lines between the high-pressure pump and the injectors require a relatively low opening pressure of the needle: 200 bar for the first stage delovni karakteristiki motorja). Vrtilni moment je zaradi tega pri nizkih vrtljajih motorja nižji v primerjavi z vrednostmi, ki jih dosegamo s sodobnimi sistemi vbrizgavanja. Z omenjenim sistemom lahko dosežemo specifično (litrsko) moč motorja 45 kW/dm^3 delovne prostornine valja. Doseganje te vrednosti je seveda odvisno tudi od mehanične vzdržljivosti motorja za določen namen uporabe.

Sistem tlačilke s šobo

a) Z mehaničnim pogonom

Obstajata izvedbi bodisi s kombiniranim dvostopenjskim odpiranjem igle v šobi (Steyr [3] in Lucas [4]), (sl. 2, 3), ali pa izvedba, ki je kombinirana z dinamično pripravo za predvbrizg goriva (Bosch, sl. 4). Steyerjev Unit–Injector je opremljen s prostorninskim krmiljenjem vbrizgane količine goriva, ki uravnava začetek vbrizgavanja samo v odvisnosti od obremenitve motorja. Za popolno krmiljenje začetka vbrizga je potrebna dodatna naprava, ki obrača os nihajnega vzvoda in zato poveča stroške sistema na raven sistema s solenoidnim (elektromagnetni krmilni ventil) krmiljenjem.

Steyrjev sistem omogoča doseganje tlakov do 2000 bar z ugodnim časovnim potekom tlaka vbrizgavanja. S stalnim merjenjem lege bata tlačilke obstaja razmeroma zanesljiva povratna informacija - podatek za računalnik o prostornini vbrizganega goriva. Konstrukcija je zelo prilagojena zmanjšanju deformacije pri vgradnji in omogoča zelo veliko zanesljivost delovanja tudi pri zelo visokih obremenitvah motorja.

Časovni gradient znižanja tlaka na koncu vbrizgavanja je razmeroma ugoden in znaša $50 \cdot 10^6$ bar/s, diagram 1. Še bolj strmo znižanje tlaka bi bilo dobrodošlo, toda pojavila bi se nevarnost poškodb sistema zaradi kavitacije. Tlak vbrizgavanja določajo: oblika odmikalne krivulje, elastičnost mehaničnega pogona in količina goriva med tlačilko in vbrizgalno šobo sistema. Rezultat je sicer dober, toda povečani tlak goriva v področju vrtljajev motorja med 800 in 1500 min^{-1} bi tam še dodatno zvečal vrtilni moment. Z opisanim sistemom se dandanes lahko doseže specifična moč motorja 62 kW/dm^3 delovne prostornine motorja. Pri tem moramo seveda upoštevati mehanično vzdržljivost motorja za določen način uporabe. Predpisi o emisiji izpušnih plinov - stopnja "Euro 3" so dosegljivi. Za doseganje stopnje "Euro 4 " je potrebna oprema skupaj s sodobnim samočistilnim filtrom za delce v izpušnih plinih, ki pa za zdaj še ni razvita.

Tlačilke s šobo Bosch in Lucas vodi elektronsko krmiljeni ventil: uravnava trenutek začetka vbrizgovanja in časovno prirejeno količino vbrizganega goriva. Bat tlačilke ima veliko tesnilno površino, kar omogoča doseganje višjih tlakov

and approximately 350 bar for the second stage. Pressure distribution is not adjusted for all engine running conditions: peak engine torque is relatively small at lower engine speeds when compared to the engines with other advanced FISs. A specific engine output of 45 kW/dm^3 of the engine working displacement can be achieved, as a general consequence of the engine design.

Unit-Injector

a) Mechanically driven unit-injector

Two general systems can be found today: one with the combined two-stage needle lift (two-stage injection – Steyr [3] and Lucas [4]), Fig.2 and 3, and a unit-injector with a mechanically actuated two-stage pre-injection – Bosch, Fig.4. Steyr's unit-injector applies volumetric control of the injected fuel and controls the start of the injection sequence as function of the engine load only. A separate suplementary unit should be introduced to enable perfect control of the fuel-injection process. Production costs would be substantially increased and would be comparable to the costs of the electronically controlled unit-injector with a solenoid valve.

With the Steyr unit-injector operational pressures of up to 2000 bar can be obtained and the time-pressure history is appropriate as well. Continuous inspection of the plunger position gives reliable feedback information on the quantity of the injected fuel. The design of the FIS is reliable, eliminates most of the possible deformations provoked by the installation and ensures safe and continuous engine operation, even at very high engine loads.

The gradient of the pressure release (GPR) at the end of the fuel-injection event is suitable when using the above FIS and amounts to $50 \cdot 10^6$ bar/s, diagram 1. A still steeper GPR would be an advantage, but it could probably introduce certain problems and damage the FIS. The pressure history is determined by the shape of the cam of the mechanically driven unit-injector and the quantity of pressurized fuel between the fuel pump and the injector nozzle. The injection characteristic is generally appropriate, but still higher injection pressures in the lower engine-speed range between 800 and 1500 rpm would increase the engine torque. Today, a specific power of 62 kW/dm^3 engine displacement can be achieved with the presented FIS. High mechanical stresses and its achievable reliability must be taken into account when such an extreme engine output is considered. The "Euro 3" exhaust emission standards can also be achieved with this FIS. The introduction of an extra self-cleaning exhaust particulate trap, which has not been developed yet, is required to fulfil the forthcoming "Euro 4" Diesel exhaust emission standards.

Bosch and Lucas unit-injectors are equipped with an electronic solenoid control: the start of the injection as well as the time-dependent quantity of the injected fuel are controlled. The pumping element (plunger) has a relatively large sealing surface:

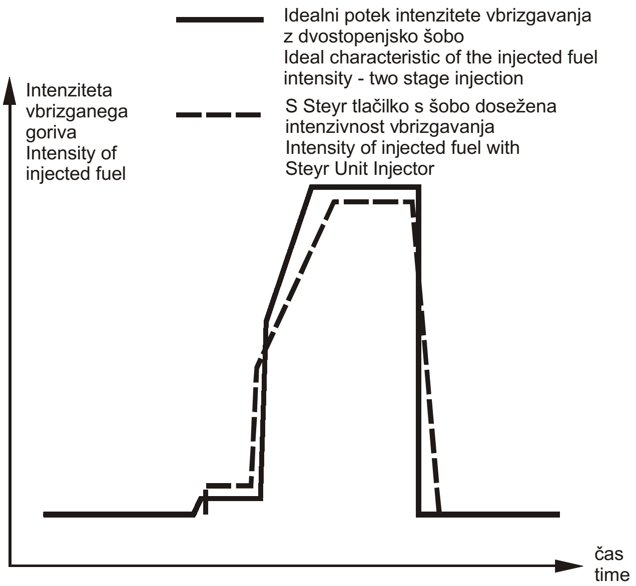


Diagram 1. *Primerjava idealnega poteka intenzitete vbrizgavanja goriva in poteka s Steyr-jevo tlačilko s šobo pri polni obremenitvi motorja. Ostale različice omogočajo podobno karakteristiko vbrizgovanja*
Diagram 1. *Comparison between the ideal intensity of the fuel distribution and the time–dependant fuel distribution of the Steyr Unit–Injector. Similar characteristic can be obtained by the application of other Unit–Injectors*

vbrizga - približno 2.200 bar. Mehanični deli solenoidnega krmilnega ventila in velike tesnilne površine bata obenem povečujejo občutljivost sistema na premalo očiščeno gorivo. Poleg tega je potrebna zelo selektivna vgradnja, da bi dosegli enakomerno porazdelitev goriva po valjih. Z opisanim sistemom se lahko doseže specifična moč motorja 60 kW/dm^3 delovne prostornine valja, pri tem pa moramo upoštevati mehansko vzdržljivost in namembnost motorja. Predpisi o emisijah stopnje "Euro 3" so dosegljivi. Za stopnjo "Euro 4" je potrebna oprema skupaj s sodobnim samočistilnim filtrom za delce v izpušnih plinih, ki pa še ni na voljo izdelovalcem motorjev: Ta sistem je uporabljen za hitrotekoče motorje pri vozilih znamke VW, Seat, Audi, Škoda in Rover. Opisani sistem za vbrizgavanje ni veliko dražji od sistema z običajno porazdelilno tlačilko za gorivo, ki je kombiniran z dvostopenjskim odpiranjem igle v šobi.

Sistem ima velike prednosti pred porazdelilno tlačilko, toda potrebna je prilagojena konstrukcija motorja, ki zahteva povečane stroške razvoja. Tudi višina motorja se s tlačilko s šobo nekoliko poveča. Razen tega do sedaj znane izvedbe tlačilk s šobo s svojimi izmerami ne dopuščajo vgraditve tlačilke s šobo v motorje s štirimi ventili v glavi vsakega valja.

b) Sistem združene tlačilke in šobe s hidravličnim pogonom

Tlačilka s šobo s hidravličnim pogonom in z dodatnim hidravličnim ojačevalnikom je prikazan na sliki 5. To je najmlajši - najnovejši koncept za vbrizgavanje goriva v dizelske motorje. Razvoj tega

very high injection pressures of approximately 2200 bar can therefore be achieved. However, excessive high-pressure surfaces and the mechanical parts are sensitive to unsatisfactorily cleaned fuel. In addtion, a very high degree of selection of the described FIS elements is required to ensure uniform fuel distribution for all engine cylinders. A specific engine power up to 60 kW/dm^3 engine displacement can be obtained, however, the application of the appropriate engine should certainly be taken into the consideration. The "Euro 3" exhaust emission standards can be met with the described FIS, however "Euro 4" can only be achieved by the application of a modern – so far not yet developed – self-cleaning exhaust particulate trap. The "Bosch" unit-injector is applied by the engine manufacturers: VW, Seat, Audi, Škoda and Rover. It is not much more expensive than a conventional FIS with a distribution pump combined with a two-stage needle lift.

There are many advantages of the presented high-pressure unit-injectior FIS, however, a substantial redesign of an already existing engine is required to replace a conventional FIS, and as a consequence the development costs are increased. The overall engine height is also increased by the FIS. Available up-to-date unit-injector FIS designs with their overall dimensions are not compatible with multi-valve cylinder-head technology.

b) Hydraulically operated Unit-injector (HOUI)

A HOUI with a supplementary hydraulically operated intensifier is the newest and the most advanced concept of fuel injection for modern Diesel engines. The system was invented by John Beck from sistema je pričel Američan John Beck iz Kalifornije. Sistem sedaj izdelujejo v podjetjih Caterpillar [8] in Siemens-USA. Uporablja se predvsem za motorje, ki se vrtijo do 3500 min^{-1}. S tem sistemom še ni bil rešen problem hrupa zgorevanja. Specifična moč motorjev je omejena na približno 30 kW/dm^3 delovne prostornine motorja. Vgrajen je predvsem v ameriške motorje za lahka tovorna vozila. Za hidravlični pogon tlačilke se uporablja srednji tlak iz skupne napajalne cevi. To je pravzaprav obenem tudi vrsta sistema za vbrizgavanje s skupnim visokotlačnim vodom in skupno visokotlačno tlačilko goriva, ki je kombinirana s tlačilko s šobo: gorivni sistem vbrizgavanja s skupnim zbiralnikom - vodom, iz katerega se napajajo posamezne enote. Omenjeni sistem ne omogoča izrazitega predvbrizga. Zvišanje tlaka, ki ga dosežemo s sedanjimi konstrukcijskimi izvedbami, je premajhno za doseganje visokih tlakov vbrizgavanja in ne omogoča doseganja večjih specifičnih moči motorja. Potek tlaka vbrizgavanja ne ustreza zahtevam zakonov zgorevanja. Za pogon osebnih vozil je težko doseči emisijsko stopnjo "Euro 2" celo z majhnimi specifičnimi močmi motorja. Pri vgradnji v vozila s skupno maso nad 3500 kg lahko zadostimo zahtevam ustreznih emisijskih predpisov. V nasprotju s sistemom s skupnim vodom so tlaki goriva v skupnem zbiralniku nizki, zato je potrebna le nizkotlačna tlačilka za gorivo. Igla šobe je, podobno kakor pri tlačilki s šobo, izpostavljena visokim tlakom samo v času vbrizgavanja.

Sistem je preprost in ne zahteva izjemno zahtevne tehnološke opreme. Vzdrževanje je preprosto. Navkljub sedaj pretežno negativnim rezultatom menimo, da temu načinu vbrizgavanja pripada prihodnost. Tudi Cummins v ZDA dela v razvoju na modificirani konstrukciji, ki deluje po opisanem načelu. Ta sistem lahko tudi opišemo z besedami: "Ameriška pot v tehniki".

Sistem za vbrizgavanje s skupnim visokotlačnim vodom in skupno visokotlačno tlačilko goriva (SViT - Common–Rail) ([6] in [7])

Po tem načelu je začel delati prof. Eichelberg na ETH v Zürichu v začetku tridesetih let, raziskovalno delo pa so nadaljevale kar štiri generacije strokovnjakov na omenjeni ustanovi.

Z razvojem moderne elektronike, z moderno tehnologijo obdelave in z ustreznimi merilnimi instrumenti je postal razvoj omenjene opreme za vbrizgavanje tudi industrijsko pomemben.

Bosch je pripeljal ta sistem do industrijske uporabe in izdelave.

Sistem uporablja osrednjo tlačilko, ki pošilja gorivo v skupni zbiralnik za vse valje motorja (sl. 6). S konstrukcijo je možno doseči tlake vbrizgavanja do 1400 bar, toda z izjemno visokim časovnim gradientom znižanja tlaka ob koncu vbrizgavanja. Tlaki vbrizganja niso tako visoki kakor pri tlačilki s šobo, toda izredno

California and is manufacturated by Caterpillar [8] and Siemens in the USA. It is generally applied for the engines running up to 3500 rpm and not exceeding 30 kW/dm^3 cylinder displacement. Combustion-born noise has not been eliminated by this FIS yet. It has been applied for light commercial vehicles in the US. Fuel with moderate pressure from a common-rail is applied for hydraulic operation of the high-pressure system. It is in fact a type of Common-Rail system combined with a unity-injector: the Common-Rail, as the first stage, feeds particular uniti-injectors of particular engine cylinders. Intensive pre-injection of the fuel cannot be achieved with this system. The pressure gradient of the existing design solutions is too moderate and does not lead to very high injection pressures and consequently to a high engine-specific power. The pressure-time injection characteristic does not fit the requirements for optimum combustion. The "Euro 2" emission standards can hardly be met with the above-mentioned FIS despite the relatively low specific power of the engine. If the engine is used to drive a vehicle weighing over 3500 kg, appropriate emission standards can be met. Pressure in the feeding common-rail is relatively low; an ordinary pressure pump is therefore required to operate the first phase of the described system. The injector needle is exposed to very high pressures, however, as with the other unit-injector FISs this is only during the fuel-injection period.

The described FIS is simple and does not require extremely demanding technology. Maintenance of the FIS is also simple. The author of the system considers this system to be the prevailing FIS for the future, although the existing results are not very promising. Cummins, of the USA, makes efforts to develop a new design of the modified hydraulically operated FIS. This system was marketed with the slogan "The American Way of Engineering".

Common–Rail FIS ([6] and [7])

This FIS was first examined by Prof. Eichelberg from ETH Zuerich at the beginning of the 30; four generations of experts continued his work at the same institution over the next decades.

The common-rail system became suitable for industrial applications with the development of modern technology, electronics and advanced measurement techniques.

Bosch was the first to introduce the Common-Rail (CR) system into mass production.

A central high-pressure pump feeds the fuel into a common-rail for all engine cylinders, Fig.6. Injection pressures up to 1400 bar can be achieved today with a modern CR FIS; an extremely steep gradient of GPR can be obtained at the end of the injection period. Peak pressures are far below the pres-

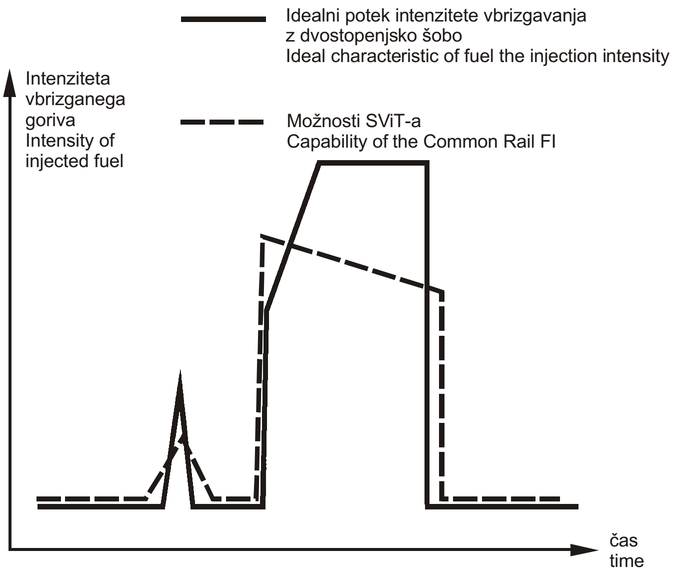


Diagram 2. *Primerjava idealnega časovnega poteka intenzitete vbrizgavanja z ustrezno karakteristiko SViT sistema pri polni obremenitvi motorja*

Diagram 2. *Comparison between the ideal time-dependant distribution of the fuel and the appropriate characteristic obtained with the Common–Rail at the engine full load*

visok gradient znižanja tlaka ob koncu vbrizga delno nadomesti to pomanjkljivost.

Za uspešno delovanje sistema so potrebne štiri zelo kakovostne in skrbno prilagojene komponente s selektivno vgradnjo. Pri teh delih prihaja v primerjavi z drugimi sistemi do večje nenadzorovane izgube goriva zaradi iztekanja skozi špranje. Elektronski krmilni sistem nima nobenega podatka, ki bi predstavljal (meril) dejanski tok goriva skozi šobo. Ta pomanjkljivost dodatno otežuje enakomerno porazdelitev goriva po vseh valjih motorja in dodatno podraži sistem zaradi potrebnega selektivnega sestavljanje komponent za doseganje enakomernejše porazdelitve goriva po vsakem valju. Visoki tlak, ki vlada v skupnem zbiralniku, stalno deluje na sedež igle v vbrizgalni šobi. S tem faktorjem je povezano tudi tveganje, da bi gorivo pri poškodovanem sedežu igle skozi špranjo lahko nenadzorovano iztekalo v valj in v najkrajšem času uničilo motor.

Vbrizgalni sistem SViT potrebuje visokotlačno tlačilko, zelo zahtevni zbiralnik ter zelo zahtevno elektronsko krmiljenje šob za vbrizgovanje. Stroški izdelave so večji kakor pri drugih sistemih. Rezultati zgorevanja in dosegljiva največja specifična moč motorja so zelo podobni vrednostim, ki jih dosežemo s tlačilko s šobo.

Ob vseh zgoraj navedenih pomanjkljivostih pa ima sistem SViT štiri velike prednosti:

- Vbrizgalna šoba ima pri SViT-u razmeroma majhen premer in jo lahko vgradimo v motor s po štirimi ventili na valjevo glavo.
- Sistem SViT je lahko integrirati v obstoječe konstrukcije motorjev brez velikih sprememb.
- Proces optimiranja opisanega vbrizgovalnega sistema za neki motor je razmeroma kratek, ker lahko pomembne parametre vbrizgavanja zelo hitro

sures obtained with the UIs, but a very high gradient (GPR) at the closure of the injector needle almost compensates for this disadvantage.

Successful operation of the CR FIS requires four perfectly mutually tuned and selected components and a very careful installation. Uncontrolled leakage is typical for a CR in comparison with other modern FISs. There are no suitable input data available for the electronic control system that could measure the injected quantity of the fuel. This disadvantage affects uniform delivery of the fuel for all engine cylinders and increases the costs of the described components due to higher selection of the required components. High pressure in the CR acts continuously on the injection needle; there is a risk of uncontrolled fuel leakage through the needle seat and, in the worst case, complete failure of the engine.

A CR requires a high-pressure fuel pump, a relatively complicated common container – rail, and highly demanding electronic control for the particular engine injectors. Total manufacturing costs are higher in comparison with the other FISs. The quality of the combustion and the highest developed engine-specific output is in the range of the other advanced UI FISs.

In spite of the above- mentioned disadvantages, the CR system offers four big advantages:

- The fuel injector is small enough to be easily built in a multi-valve cylinder head.
- No special redesign of an old engine is required to introduce a CR system.
- The optimisation process of a new engine with the CR is relatively simple and short; injection parameters, especially the optimum injection

spremenimo. Predvsem lahko hitro prilagodimo optimalni tlak vbrizgavanja zahtevam motorja.

- SViT ponuja teoretično možnost večkratnega vbrizgavanja goriva v istem delovnem ciklu motorja. Z uspešnim načinom večkratnega vbrizgavanja z zelo pozno zadnjo fazo vbrizga, ki jo kombiniramo s filtrom za delce v izpušnih plinih, obstaja možnost uporabe samočistilnega filtra za delce. Na tak način je bilo že mogoče znižati raven vseh škodljivih in zakonsko predpisanih komponent v izpušnih plinih na raven predpisa "Euro 4".

Z zelo poznim dodatnim vbrizganjem se lahko poveča temperatura izpušnih plinov, ne da bi vplivali na zahtevano moč motorja. Z uporabo sistema SViT so dokazali, da je to dejansko mogoče doseči. Pri sistemu vbrizgavanja s SViT ne moremo spremeniti tlaka vbrizgavanja v posameznih fazah deljenega vbrizga in v istem delovnem krogu motorja. Zaradi enakega - visokega tlaka vbrizgavanja, ki se nadaljuje po glavnem vbrizgavanju tudi v zadnjo fazo dodatnega vbrizga goriva ter zaradi bistveno manjše gostote ostankov zgorevanja v valju (globoko v fazi ekspanzije), pride zaradi

pressure, can be altered and adjusted very quickly according to the demands of the engine.

- CR provides the advantage of multiple fuel injection during the same engine working process. Interaction of the very late (last) phase of the multiple fuel injection together with the exhaust particulate trap leads to a practical solution for a self-cleaning particulate trap. This was proved (in research) to be a realistic possibility to ful fill the requirements of the "Euro 4" exhaust emission standards.

Very late fuel injection increases the exhaust temperature without influencing the output power of the engine. However it has not yet been possible to alternate the injection pressure of particular phases of a single multiple fuel-injection process. As the result of the very high injection pressures in the late phase expansion and therefore a substantially higher penetration of the fuel through the lower density cylinder content there is always the possibility of a direct wetting of the cylin-

Preglednica 1. *Primerjava sedanjih sistemov za neposredno vbrizgavanje v hitrotekoče dizelske motorje. Vrednotenje je opravljeno na temelju informacij, dostopnih avtorju. Z nadaljnjim razvojem lahko pričakujemo spremembe. Najboljše vrednosti so tiskane poudarjeno.*
Table 1. *Comparison of diverese advanced FIS for high–speed DI Diesel engines. Evaluation is based on the available informations and data. With the future development change of data is to be expected. The best results and values are marked bold.*

	ZAHTEVE ZA SISTEM VBRIZGAVANJA GORIVA REQUIREMENTS FOR ADVANCED FIS Nepristranska ocena stopnje popolnosti posameznih tehničnih karakteristik sistemov za vbrizgavanje goriva Impartial evaluation of completion of particular FIS characteristic	Visokotlačna distribucijska tlačilka goriva High pressure distributor fuel pump	Steyr-jeva enotna tlačilka s šobo Steyr Unit Injector	Enotna tlačilka s šobo -Unit Injector s solenoidno regulacijo Lucas - Bosch UI with the solenoid control	Unit Injector s hidravličnim pogonom Hydraulically operated UI	Tlačilka s skupnim vodom Common Rail
1	Visok srednji tlak vbrizgavanja Very high mean injection pressure	65%	95%	**100%**	70%	75%
2	Visok tlak na koncu vbrizgalnega procesa High pressure at the end of injection period	40%	95%	**100%**	50%	65%
3	Zelo visok tlak na koncu vbrizgavanja Very high injection pressure gradient at the end of injection	30%	50%	45%	30%	**100%**
4	Krmiljenje tlaka vbrizgavanja po potrebi motorja Control of the injection pressure according to the engine requirements	40%	70%	65%	**100%**	**100%**
5	Kakovost poteka tlaka vbrizgavanja, ki narašča proti koncu vbrizgavanja Quality of the progressive injection - pressure characteristic towards the end of injection	60%	**90%**	85%	40%	65%
6	Predvbrizg goriva Multi - stage fuel injection	Dvostopenjski two - stage	Dvostopenjski two - stage	Dvostopenjski-Pilot vbrizg two - stage - Pilot	0	Pilot vbrizg Pilot injection
7	Krmiljenje začetka vbrizgavanja Control of the begin of fuel injection	**100%**	50% **-100%**	**100%**	**100%**	**100%**
8	Enakomerna porazdelitev goriva po vseh valjih motorja Uniform fuel distribution for all cylinders	95%	95%	90%	85%	90%
9	Spremenljiv presek luknjic šobe brez dušenja curka Variable injection nozzle flow area without excessive pressure losses	0	0	0	0	0
10	Kratko skupno trajanje vbrizga Short duration of the complete fuel injection	65%	90%	**100%**	70%	80%
11	Dosegljivost emisijskuih standardov "Euro 4" danes Actual implementation of the exhaust emission standards "Euro 4" today	ni možno not possible	ni možno not possible	ni možno not possible	ni možno not possible	**možno? possible?**
12	Hrup sistema za vbrizgavanje goriva Noise of the FIS	40%	60%	60%	**30%**	50%
13	Nevarnost kavitacijske poškodbe sistema Danger of the cavitation damages on the FIS	30%	**10%**	35%	10%	20%
14	Mehanična zanesljivost sistema Mechanical reliability of the FIS	50%	**90%**	70%	**90%**	30%
15	Višina zahtev na opremo za servis Requirements for maintenance of the FIS	80%	**20%**	70%	40%	120%
16	Možnost vgraditve v glave s po 4-mi ventili na valj Possibility for installation of the FIS into a multi - valve cylinder head	**možno possible**	ni možno not possible	ni možno not possible	ni možno not possible	**možno possible**
17	Stroški izdelave in montaže Production and instalation costs	100%	80%-100%	110%	75%	180%
18	Stroški servisa Maintenance	100%	**30%**	110%	50%	200%
19	Konstrukcijske zahteve motorja Special design requirements for the FIS (engine)	**manjše lower**	velike large	večje larger	**manjše minor**	**manjše minor**
20	Dosegljiva specifična moč motorja v KW/l Maximum achievable specific engine power (in kW/dm^3 engine swept volume)	45	**62**	60	30	52

prodornosti curka goriva do neposrednega brizganja goriva na steno valja. To seveda zelo hitro pokvari mazanje valja do te mere, da lahko pride celo do težjih poškodb motorja. Pot za veliko zmanjšanje emisije delcev in s tem posredno tudi NO_X je z zgornjim opisom sistemov za vbrizgavanje dokazana. Potrebno je še dosti razvojnega dela, ki nas bo pripeljalo do uspešnega trženja omenjenega izdelka.

Tudi z drugimi prej opisanimi sodobnimi sistemi obstajajo teoretične možnosti za uporabo samočistilnega filtra, toda samo z uporabo SViT-a je dosedaj uspelo doseči emisijske zahteve, ki jih podajajo bodoči predpisi stopnje "Euro 4" .

3 SKLEP

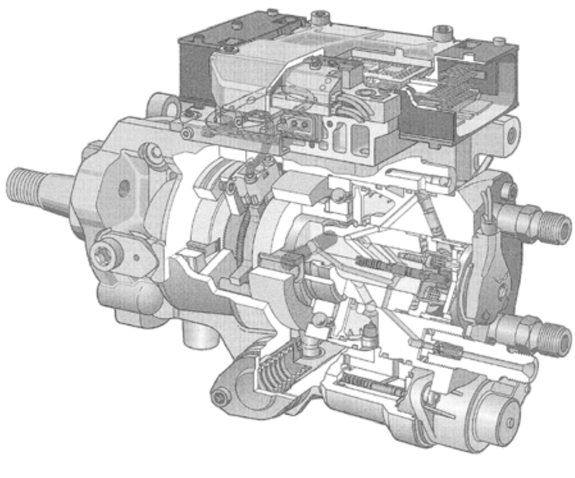
Kakor je razvidno iz preglednice 1 so opisani vbrizgalni sistemi prve generacije za vbrizgavanje goriva za hitrotekoče dizelske motorje še nepopolni. Toda doseženi rezultati omogočajo izdelavo homologiranih visokokakovostnih dizelskih motorjev. S sodobnimi dizelskimi motorji dandanes dosežemo v primerjavi z bencinskim motorji še nekoliko manjše specifične moči motorjev. Največji za 50% večji moment teh motorjev dosežemo že pri 1600 do 3000 min^{-1}. Motor je zato prožen in z njim se vozne sposobnosti na vozilu z enako skupno maso izboljšajo. Upajmo da bo naslednja generacija vbrizgalnih sistemov, na katerih poteka pospešen razvoj, dajala še boljše rezultate.

der wall. Lubrication quality is affected and serious engine damage can occur. Nevertheless, this is the way to achieve very low emissions of particulates and NO_X. A lot of research and development work needs to be done so that a commercially successful product will be available.

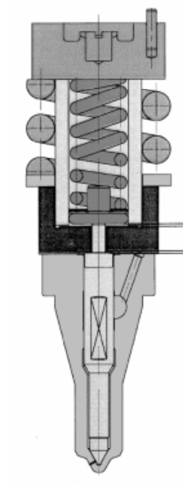
There are also some theoretical solutions available for the efficient operation of a self-cleaning particulate filter with the other advanced, high-pressure FISs. But CR has so far been, the only one to overcome the very stringent "Euro 4" exhaust emission standards.

3 CONCLUSION

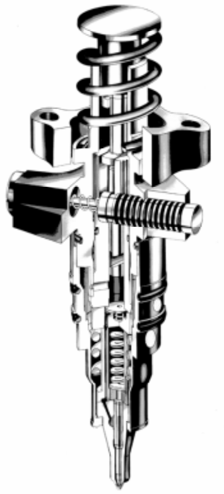
There are some blank spaces in Table 1, where a comparison of different features for the first generation of different advanced FISs is made. However, modern and environmentally suitable engines can be produced today with such a FIS. The rated power of modern Diesel engines is still slightly less than the power of a comparable modern petrol engine. The maximum (50% higher) engine torque can be obtained in the engine speed range from 1600 to 3000 rpm. A very elastic engine torque characteristic can therefore positively affect the driving attributes of a vehicle. We hope to obtain still better results with the next generation of the advanced FISs.



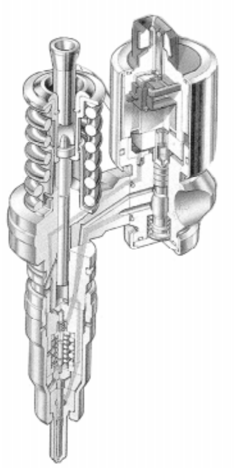
Sl. 1a. *Visokotlačna razdelilna tlačilka za gorivo*
Fig. 1a. *High pressure fuel distribution pump*



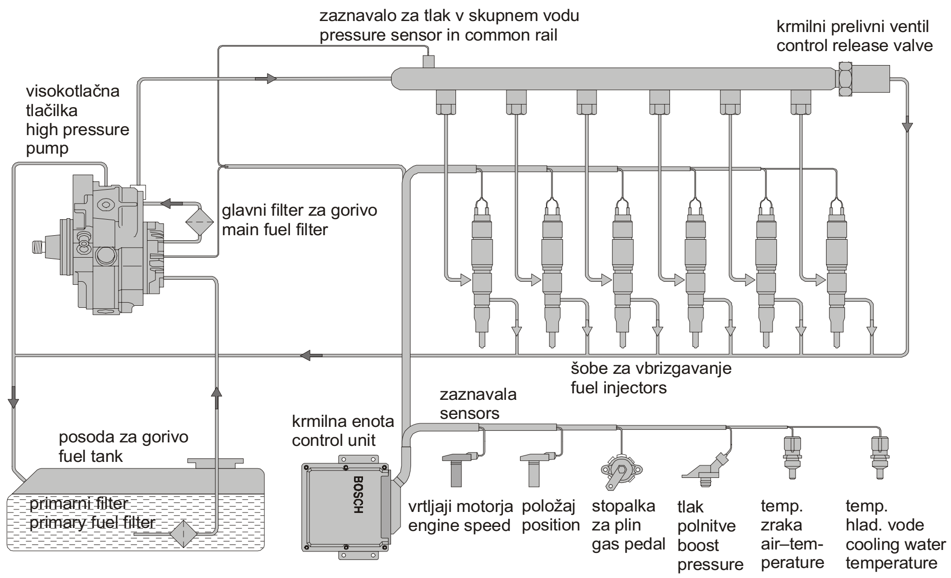
Sl. 1b. *Sistem za dvostopenjsko odpiranje šobe pri združeni tlačilki s šobo Steyr in Lucas*
Fig. 1b. *Two-stage fuel injection by Steyr and Lucas Unit Injectors*



Sl. 2. *Steyr-jeva naprava za vbrizgavanje goriva z združeno tlačilko s šobo*
Fig. 2. *Steyr's Unit Injector*



Sl. 3. *Lucas-ov sistem združene tlačilke s šobo s časovnim krmiljenjem količine in dvostopenjskim vbrizgavanjem goriva*
Fig. 3. *Unit Injector Lucas with the time control of the injected fuel and with the two-stage injection*



Sl. 4. *Shematični prikaz naprave za visokotlačno vbrizgovanje goriva s skupnim vodom*
Fig. 4. *Schematic outline of the Common rail fuel injection system*

4 LITERATURA
4 REFERENCES

[1] Shahed, S.M. (1998) Turbo 2000 - Turbocharging solutions for the next century, *Engine Technology Int.*, May, 1998.

[2] Ashley, S. (1998) Diesel cars come clean, *Mechanical Engineering*, Vol.119, No.8, 1998.

[3] Dolenc, A. (1995) Fuel system for the future high speed DI Diesel engines and the suitable electronic control, uvodno vabljeno predavanje, *Koferenca IAT'95*, Radenci, 1995.

[4] Osenga M. (1998) CAT gears up for next generation fuel systems, *Diesel Prograss Int.Edition*, Volume XVIII, No.9-10, 1998.

[5] Glassey, S.F., et al (1993) HUEI - A new direction for Diesel engine fuel systems", *Int. SAE Congress and Exhibition*, Detroit, March, 1993, Paper No. 930270, pp. 1 - 11.

[6] Osuka I., et al (1994) Benefits of new fuel injection system technology on cold startability of Diesel engines - Improvement of cold startability and white smoke reduction by means of multy injection with common rail fuel system (ECD-U2), *Int. SAE Congress And Exhibition*, Detroit, 1994, Paper No. 940586, pp. 7-17.

[7] Stumpp, G., et al. (1996) Common rail - An attractive fuel injection system for passenger car DI Diesel engines, *Int. SAE Congress and Exhibition*, Detroit, February, 1996, Paper No. 960870, pp. 183 - 191.

[8] Greeves, G., et al. (1993) Contribution of EUI-200 and quiescent combustion system towards US94 emissions, *Int. SAE Congress and Exhibition*, Detroit, March, 1993, Paper No. 930274, pp. 69 - 87.

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