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ПРОФЕССИОНАЛЬНЫЕ СТАТЬИ

PROFESSIONAL PAPERS

DIESEL FUEL FILTRATION PROBLEMS WITH MODERN COMMON RAIL INJECTION SYSTEMS

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Summary:

Modern diesel fuel injection systems called ”common rail systems” have been increasingly developing over the past two years. Along with the development of such systems it has been, at the same time, necessary to follow the development of ancillary systems used for their proper and efficient operation. This paper provides a detailed presentation of the *latest generation of common rail systems operating at high pressure together with problems regarding diesel fuel filtration.*

Key words: common rail systems, pumps, maintenance, fuel filtration, diesel fuel, filters.

Introduction

Modern common rail systems designed for diesel fuel injection represent the main type of fuel distribution in diesel engines. The traditional conception of fuel injection with in-line or rotational piston pumps that operates at low working pressures is gradually abandoned due to high environmental requirements being introduced in industrial developed countries. Additionally, with imposition of very strict regulations with regard to environmental issues, manufactures of diesel fuel injection systems have to adapt to both the regulations and laws and the market itself.

Lately, on the global market of common rail system manufacturers, there have been several companies supplying the global automotive industry (passenger, freight, special purpose army vehicles, diesel-electric generators sets, etc).

Among the global suppliers of common rail systems, the major ones are: Cummins, Denso, Delphi, Bosch, Heinzmann, Ganser, Liebherr, Mercedes, Mitshubishi, MTU (Motoren Turbinen und Union-Germany), Perkins, Rollce Royse, Siemens, etc.

Denso, Delphi, Bosch and Siemens are the manufacturers of fuel injection systems designed primarily for passenger, light commercial and freight vehicles, while Cummins, HeinzmannPerkins, Mitshubishi, Rollce Royce, Ganser, Liebherr are primarily oriented to high-horsepower engines for heavy freight vehicles, off-road vehicles, navy, railways, etc.

Some manufacturers of modern common rail (CR) systems, such as Denso, have been continuously developing new designs, thus giving a new task to other manufacturers. Since the end of the first quarter of 2016, Denso has been planning the start-up of its latest common rail system design operating at 3000 bars (Hydac, 2015b).

Fuel injection systems operating at high working pressures require clean fuel with as few contaminants as possible, such as solid particles and water. The function of new fuel filtration systems is to maintain the quality of fuel at the required cleanliness level.

Development of CR systems and gas emission regulations

Many well-known international manufacturers of diesel engines and diesel engine components have been involved in design and development of CR systems. Among them are: Cummins, Denso, Delphi, Bosch (Fiat), Heinzmann, Ganser, Liebherr, Siemens and others. Since 1995, when the Japanese Denso introduced the first CR systems into commercial production (Denso, 2016), (240 landmarks of Japanese automotive technology, 2016), other international manufacturers have joined the race.

Some manufacturers have developed CR system generation operating at 2000 – 2500 bars, for low-horsepower engines (passenger vehicles and light commercial vehicles). The major ones of them are: Denso, Bosch and Delphi.

Back in 2002, Denso launched systems operating at 1800 bar working pressure, then in 2008, systems operating at 2000 bars, and finally in 2013 systems operating at 2500 bars appeared on the market (Denso, 2016).

Bosch develops their CR system designs in cooperation with the FIAT development centre who was among of the first ones to initiate the development of modern CR systems. Due to some difficulties, FIAT integrated with Bosch to start mutual development of fuel injection systems (Petruzzelli, 2013), (Robert Bosch GmbH, 2010). In 1997, Bosch developed a system operating at 1350 bar working pressure (Robert Bosch GmbH, 2009), in 1999 the working pressure was increased to 1400 bars (Robert Bosch GmbH, 2009), in 2001 to 1600 bars (Robert Bosch GmbH, 2009), (Robert Bosch GmbH, 2011a), and in 2007 with a new pump and injector generation the working pressure was increased to 2000 bars (Robert Bosch GmbH, 2009), (Robert Bosch GmbH, 2014). At the beginning of 2015, Bosch increased the working pressure to 2500 bars (Robert Bosch GmbH, 2011b) for passenger cars and light commercial vehicles, and to 2700 bars for heavy freight vehicles (Robert Bosch GmbH, 2015).

Delphi – the leading American manufacturer of CR systems was following the development of CR systems by other international manufacturers, to launch, at the end of the ‘90s, its own series of CR systems operating at 1400 bars, which resulted in the latest generations that operate at 2000 up to 2700 bars (Delphi France SAS, 2007), (Knight et al, 2012), (Meek et al, 2014).

Based on the above mentioned, we can conclude that the majority of international manufacturers have developed the latest generation of CR systems operating at 2000-2700 bar working pressures, except for Denso and Delphi who have developed CR system designs operating at 3000 bars, which are currently being tested by engine manufacturers. We can emphasize that the latest CR system designs operating at 2500 bars, comparing to 2000 bars, show higher efficiency in fuel consumption up to 3%, decrease in solid particles in exhaust gasses even up to 50%, as well as decrease in nitrogen oxides from exhaust gasses up to 8% comparing to previous generation operating at up to 2000 bars (Denso, 2016). By increasing the working pressure in CR systems to higher levels, lower emissions of harmful compounds are obtained (primarily NOx) as well as lower soot emissions, i.e. solid particles in exhaust gasses. This is very important in respect to environmental regulations, laws and standards being currently in force and new regulations that will be even more stringent (new Euro 7 standard regarding gas emissions has been announced).

In the European Union, passenger cars and light commercial vehicles produce about 15% of the total quantity of CO_2 emissions, while heavy road vehicles produce about 20% of CO_2 emissions (European Comission, 2007), (http://ec.europa.eu, 2016).

There was sudden increase in relative CO_2 emission obtained from combustion of fossil fuels in road traffic, from 21% of the total quantity in 1990 up to 28% in 2004 (European Comission, 2007), (Mulvey, 2007), (Suellentrop, 2007). Although there were considerable improvements in engine manufacturing technologies during the past few years – especially regarding fuel consumption efficiency, which reflects in lower CO_2 emissions – they were insufficient regarding neutralization of the effect of increased traffic. EU – 25 directive relating to reduction of total gas emissions resulted in the reduction of the greenhouse effect by nearly 5% between 1990 and 2004; however, CO_2 emission from road traffic increased by 26% (European Comission, 2007).

Currently, hydrocarbons emission (HC), nitrogen oxides (NOx), nonmethane hydrocarbons (NMHC), carbon monoxide (CO) and particulate matter (PM) emissions, have been regulated by particular European norms for the majority of vehicle types, including cars, trucks, trains, tractors and similar engines, but excluding marine engines and airplanes. Different standards apply to each type of vehicles.

Newly produced models of vehicles have to fulfil current and planned standards. EU Regulative No. 443/2009 prescribes an average CO_2 target emission for new passenger cars at the level of 130 g/km, which was to be implemented in phases between 2012 and 2015. From 2015 to 2021, target emission is only 95 g/km and it will apply from 2021. For light commercial vehicles CO_2 emission will be 175 g/km starting from 2017, and 147 g/km from 2020 (International Council on Clean Transportation, 2014).

According to the EU norms, allowed quantity of emissions of air pollutants is defined according to the emission standards relating to certain groups of vehicles classified according to their size and purpose. The emission standards for motor vehicles are classified in the following categories: passenger vehicles, light commercial vehicles (several categories depending on transport capacity), trucks and busses, large freight vehicles and off-road vehicles (agricultural, construction, mining and other vehicles).

Passenger vehicles and light commercial vehicles are the most used vehicles in road transport, so the following tables show the European emission standards for passenger and light commercial vehicles powered by diesel engines.

Table 1 – European emission standards for passenger cars (Category M), g/km*
Таблица 1 – Европейские стандарты выхлопных газов для легковых автомобилей (категория M), г/км*
Табела 1 – Европски емисиони стандарди за путничка возила (категорија M), g/km*

Tier	Date	CO	THC	NMHC	NOx	HC+NOx	PM	P[km]
Euro 1♣	July 1992	2.72 (3.16)	-	-	-	0.97 (1.13)	0.14 (0.18)	-
Euro 2	January 1996	1.0	-	-	-	0.7	0.08	-
Euro 3	January 2000	0.64	-	-	0.5	0.56	0.05	-
Euro 4	January 2005	0.5	-	-	0.25	0.3	0.025	-
Euro 5a	September 2009	0.5	-	-	0.18	0.23	0.005	-
Euro 5b	September 2011	0.5	-	-	0.18	0.23	0.005	$6x10^{11}$
Euro 6	September 2014	0.5	-	-	0.08	0.17	0.005	$6x10^{11}$
* Before Euro 5, passenger vehicles>2500 kg were type approved as light commercial vehicles N_1-I ♣ Values in parentheses are conformity of production (COP) limits								

For light commercial (transport) vehicles from N_1-I category, the allowed level of some particles according to the Euro standards is the same as in the previous Table relating to passenger vehicles. It can be seen from the notes in Table 1, where passenger vehicles up to Euro 5 norm are classified as light commercial vehicles.

Table 2 – European emission standards for light commercial vehicles 1305–1760 kg (Category N_1-II), g/km
Таблица 2 – Европейские стандарты выхлопных газов для легких коммерческих автомобилей 1305 -1760 кг (категория N_1-II), г/км
Табела 2 – Европски емисиони стандарди за лака комерцијална возила 1305–1760 kg (категорија $Н_1$-II), g/km

Tier	Date	CO	THC	NMHC	NOx	HC+NOx	PM	P[km]
Euro 1	October 1994	5.17	-	-	-	1.4	0.19	-
Euro 2	January 1998	1.25	-	-	-	1.0	0.12	-
Euro 3	January 2001	0.8	-	-	0.65	0.72	0.07	-
Euro 4	January 2006	0.63	-	-	0.33	0.39	0.04	-
Euro 5a	September 2010	0.63	-	-	0.235	0.295	0.005	-
Euro 5b	September 2011	0.63	-	-	0.235	0.295	0.005	$6x10^{11}$
Euro 6	September 2015	0.63	-	-	0.105	0.195	0.005	$6x10^{11}$

Table 3 – European emission standards for light commercial vehicles >1760 kg max 3500 kg. (Category N_1-III & N_2), g/km
Таблица 3 – Европейские стандарты выхлопных газов для легких коммерческих автомобилей >1760 кг макс. 3500 кг. (категория $Н_1$-III & $Н_2$), г/км
Табела 3 – Европски емисиони стандарди за лака комерцијална возила >1760 kg макс. 3500 kg (категорија $Н_1$-III & $Н_2$), g/km

Tier	Date	CO	THC	NMHC	NOx	HC+NOx	PM	P[km]
Euro 1	October 1994	6.9	-	-	-	1.7	0.25	-
Euro 2	January 1998	1.5	-	-	-	1.2	0.17	-
Euro 3	January 2001	0.95	-	-	0.78	0.86	0.1	-
Euro 4	January 2006	0.74	-	-	0.39	0.46	0.06	-
Euro 5a	September 2010	0.74	-	-	0.28	0.35	0.005	-
Euro 5b	September 2011	0.74	-	-	0.28	0.35	0.005	$6x10^{11}$
Euro 6	September 2015	0.74	-	-	0.125	0.215	0.005	$6x10^{11}$

After Euro 2, EU regulations introduced different emission limits for petrol and diesel engines. Diesel engines have more stringent CO_2 standards but are allowed higher NOx emissions.

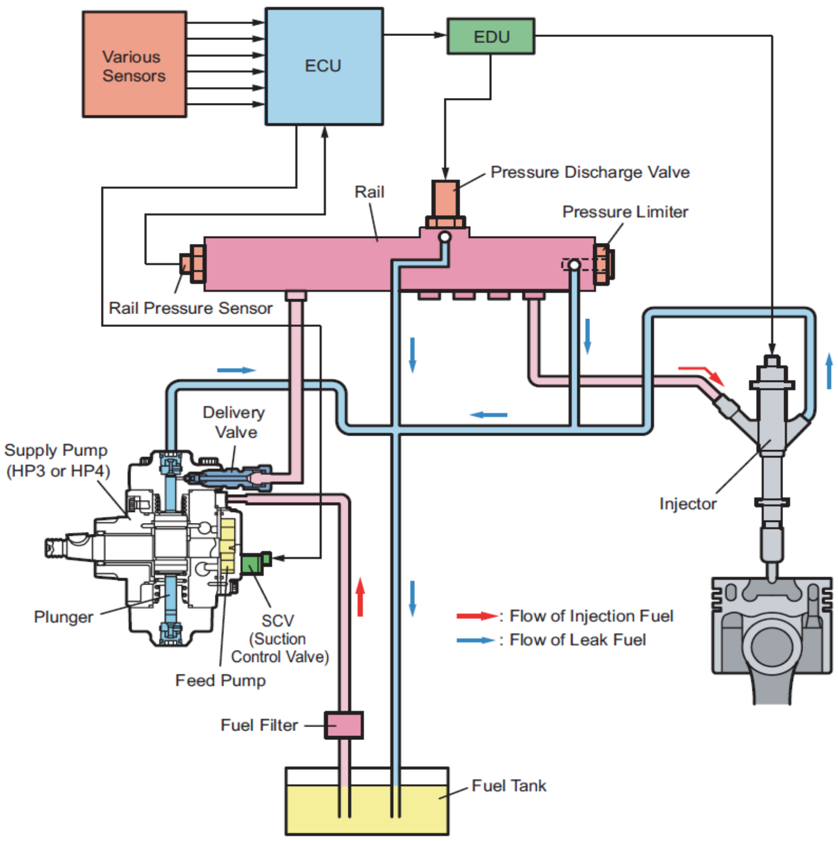
The above presented Tables 1, 2 and 3 show that diesel-powered vehicles with direct injection are subjected to limited emissions of 0.005 g/km according to Euro 5 and Euro 6 norms that were introduced in 2010-2014, depending on the type of vehicle (passenger or light commercial vehicles of certain transport capacity) (Macaudière & Matthess, 2013), (Emission Standards European Union, 2015), (The European Parliament and the Council of the European Union, 2007).

Based on European norms and standards, the majority of manufacturers of direct injection diesel engines have decided on development of engines with minimum emission of harmful substances. In order to achieve that, leading manufacturers of diesel injection systems are trying to improve the existing direct injection systems by developing new designs of injection systems and their accompanying components such as filtration systems, which enable their efficient and reliable operation. Additionally, development of new common rail systems is aimed towards gradual abandoning of Diesel Particulate Filters (DPF), which in the exhaust section of the system cause certain problems during the engine exploitation due to accumulation of soot particles.

Modern CR systems

Figure 1 shows a Denso fuel injection system of older generation. The system consists of the driving part of the system, where two pumps have been connected to the same drive shaft.

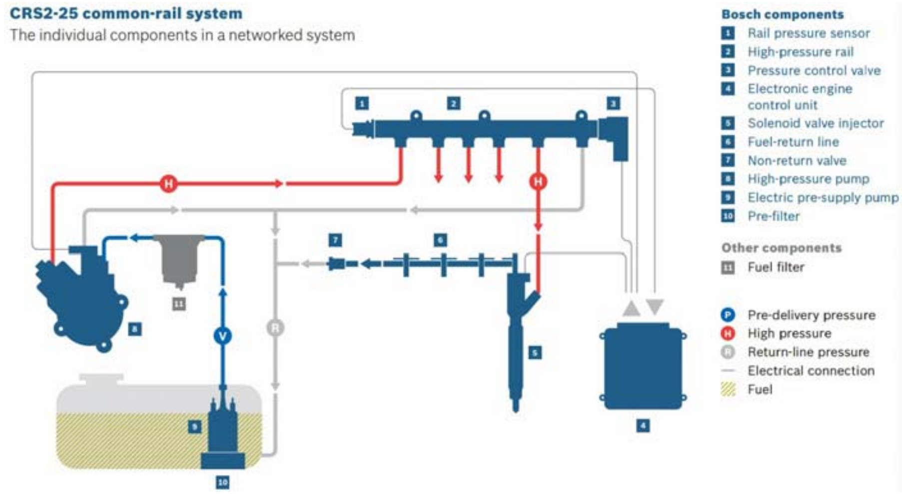
The first pump (SCV) is the supply pump that supplies fuel from the tank up to the distribution pump which distributes the fuel further into the system through the delivery valve up to the high-pressure accumulation reservoir. From the accumulation reservoir, the fuel under high pressure (approx. 2000 bars), is distributed up to the injector that contains electronically controlled valves controlled by an electronic control unit (ECU and EDU). The excessive fuel that appears during the injector operation or because of transgression of the preset pressure of the accumulation reservoir will be returned through the return lines directly into the reservoir.



Picture 1 – CR system example (Denso, 2007)
Рис. 1 – Пример системы common rail (Denso, 2007)
Слика 1 – Пример једног common rail система (Denso, 2007)

Modern generation of CR systems, manufactured by Bosch and Rolls Royce, are shown in Figures 2 and 3. Bosch modern injectors CRS3-27 are built around fast-switching piezo injectors that always inject the optimum amount of fuel into the cylinders for clean and economical combustion.

The CRI3-27 piezo injectors lead the way in multiple injection technology due to their capability for smallest pilot injection quantities, fast injection sequences, and low injection quantity drift over system lifetime.

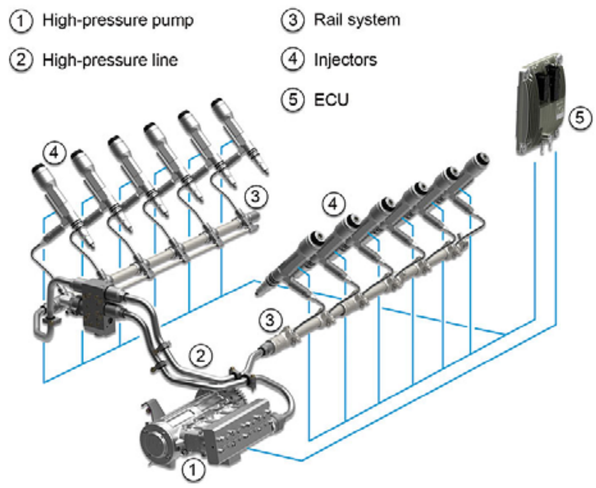


Picture 2 – Example of a modern CR system (Robert Bosch CRS 3-27, 2015)
Рис. 2 – Пример современной системы Bosch common rail (Robert Bosch CRS 3-27, 2015)
Слика 2 – Пример савременог Bosch common rail система (Robert Bosch CRS 3-27*, 2015)*

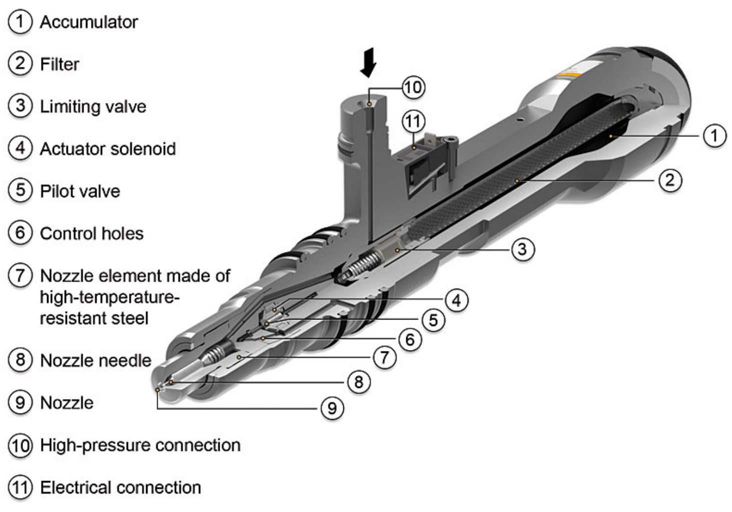
Because the piezo actuator is integrated into the injector body, the injectors are slim and require much optimized packaging than their solenoid valve counterparts. Due to their robust piezo principle, the injectors are compatible with various fuel qualities for various fuel qualities. The piezo actuator generates approximately ten times the force of solenoid valves. Therefore, the piezo injector is less sensitive against particle contaminated fuel.

Rolls Royce CR system with fuel accumulator injectors (see Figure 3*).* Because of its performance capabilities, the CR system has established itself as standard equipment on car diesel engines in the course of the last few years. The version of the system as described is also well suited for use in small capacity industrial engines. In the case of engines with larger cylinder capacities, however, the conventional CR system is now revealing its limitations, since these require a relatively large quantity of fuel to be injected into the cylinder for each ignition stroke. This produces pressure pulsations in the CR system's fuel reservoir that can interfere with the subsequent injection sequences. Since 2000, MTU has used an advanced version of the common rail system for the Series 4000 and 8000 engine, and since 2004 for the Series 4000 as well, in which the fuel injectors have an integrated fuel reservoir (see Figure 4). This permits the fuel lines between the injectors and the CR to have a relatively small cross section.

During an injection sequence, all that happens is that the pressure in the injector's own fuel reservoir drops slightly. This prevents pressure fluctuations in the common rail system and, therefore, a momentary undersupply or oversupply of fuel to the injectors.



Picture 3 – Example of a modern MTU Rolls Royce CR system (Kech, 2014)
Рис. 3 – Пример современной системы MTU Rolls Royce common rail (Kech, 2014)
Слика 3 – Пример савременог MTU Rolls Royce common rail система (Kech, 2014)

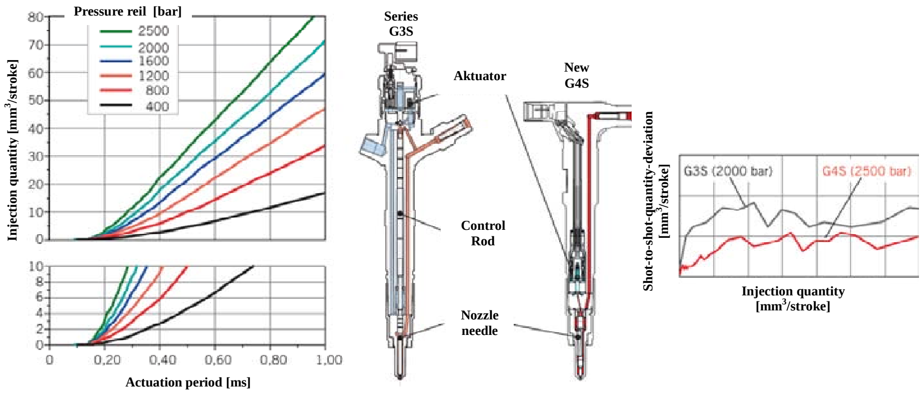


Picture 4 – Injector with the integrated fuel reservoir (Kech, 2014)
Рис. 4 – Форсунка со встроенным топливным аккумулятором (Kech, 2014)
Слика 4 – Ињектор са интегрисаним акумулатором горива (Kech, 2014)

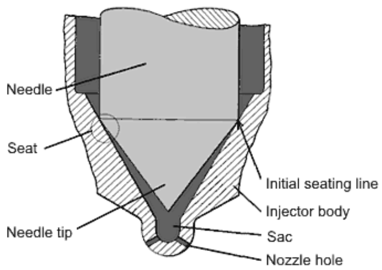
Modern injectors of the last generation, operating at 2000-2500 bars, have 100 – 200 μm nozzles at the injector discharge line for the purpose of producing an optimum fuel spray and mist out of the minimum fuel quantity, which again creates a problem regarding the quality and cleanliness of the fuel.

Figure 5 shows a new generation injector G4S produced by Denso, which, comparing to earlier injector types, performs a faster injection cycle along with smaller fuel consumption.

Modern injectors have contact surface clearances between the needle and the seat of 2-5 μm, so that care must be taken that the working fluid is clean. Figure 6 shows the cross section of the injection part of the injector and the needle; the needle moves up and down performing the distribution of fuel into the nozzle part of the injector.

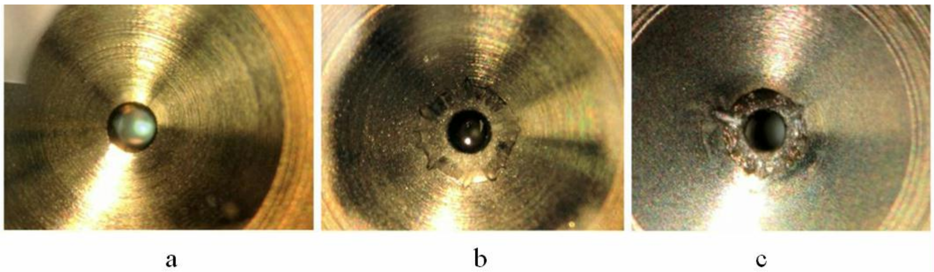


Picture 5 – Comparison of the old (G3S – 2000 bar) and the new (G4S – 2500 bar) injector generation (Matsumoto et al, 2013)
Рис. 5 – Сопоставление старых образцов форсунок (Г3С – 2000 бар) с новыми (Г4С – 2500 бар) (Matsumoto et al, 2013)
Слика 5 – Поређење инјектора старије (Г3С – 2000 бар) и новије генерације (Г4С – 2500 бар) (Matsumoto et al, 2013)



Picture 6 – Cross sectional view of the top of the fuel injector
Рис. 6 – Изображение поперечного сечения наконечника форсунки
Слика 6 – Приказ пресека вршног дела инјектора

Figure 7a shows the nozzle part of the injector when it is new, Figure 7b shows it during the exploitation and Figure 7c shows it after it has been damaged due to improper maintenance and fuel filtration.



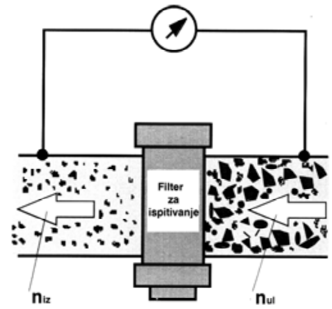
Picture 7 – Look of the damaged nozzle (Common rail Injectors FAQ – triplet diesel injection – Waco, 2011)
Рис. 7 – Изображение поврежденного сопла форсунки (Common rail Injectors FAQ – triplet diesel injection – Waco, 2011)
Слика 7 – Приказ изгледа оштећене млазнице (Common rail Injectors FAQ – triplet diesel injection – Waco, 2011)

Based on all of the above mentioned regarding the fuel distribution system presented in Figure 1, we may conclude that all CR systems represent small hydraulic systems. If we take a more detailed look, the system contains positive displacement pumps of the same design as in a hydraulic system. The design of the SCV supply pump consists mainly of different designs of gear or vane pumps, while in the supply section radial-piston pumps are used. One of the good features of supply pumps is their ability to achieve high working pressures, which particularly relates to radial-piston pumps. However, operation of pumps at high working pressures requires the use of fluid of a specific level of cleanliness, in our case diesel fuel. Diesel fuel as working fluid must fulfil certain requirements regarding lubrication features as well as regarding the minimum content of contaminants. Contaminants mostly present in the fuel are solid particles and water. Designers of hydraulic systems have already noticed these issues in hydraulic components of older generations (primarily with pumps, but also with other hydraulic components sensitive to the presence of contaminants). Modern hydraulic systems in transport vehicles such as CR fuel injection systems also require so-called working fluid ”treatment” regarding the necessary level of fuel filtration and water separation, the same as with the aforementioned hydraulic systems.

Fuel filtration issues with CR systems

The majority of the manufacturers of filtration media supply the market with filter elements that enable fuel filtration up to the cleanliness level of 4 $\mu m_{(c)}$ with 95% water separation degree; however, they do not mention solid particles separation levels.

Solid particles separation levels, or better, filtration efficiency, is defined by the beta factor (β_x) – meaning the relation between the number of particles of size (x) in oil, before and after filtration. Figure 8 shows a filter with the number of particles at the filter entrance and exit.



Picture 8 – Filter separation of solid particles (Jocanović, 2015)
Рис. 8 – Фильтрирование твердых частиц (Jocanović, 2015)
Слика 8 – Издвајање чврстих честица помоћу филтера (Jocanović, 2015)

As an example, we have shown a simple simulation of filter elements operation with the beta factor 100 and 99% solid particles filtration degree.

If we suppose that the filter presented in Figure 8 requires 4 $\mu m_{(c)}$ filter element, i.e. the filter separates particles of 4 $\mu m_{(c)}$ and bigger, it means that the filter efficiency regarding solid particle separation is equal to the beta factor $\beta 4$. If the filter element is marked with β_4 = 100 and if at the filter entrance there is the following number of particles (quantities of particles taken as an example):

n_{ul} = 1000 of solid particles equal to or bigger than 4 $\mu m_{(c)}$ in 1 ml of oil sample,

then the following number of particles will appear at the filter exit:

n_{iz} = 10 of solid particles equal to or bigger than 4 $\mu m_{(c)}$ in 1 ml of oil sample,

then the efficiency of separation of 4 $\mu m_{(c)}$-sized particles is equal to:

$$\beta_x = \frac{n_{ul} \geq x(\mu m)}{n_{iz} \geq x(\mu m)},$$

i.e. for the previous example:

$$\beta_4 = \frac{1000}{10} = 100\,.$$

The beta factor is defined by filter manufactures, and it can be defined for other particle sizes of 4, 6, 14... $\mu m_{(c)}$, regardless of their specified filtration degree.

The solid particle filtration degree is defined in relation to the measured value of the beta factor (β_x) in percentage relation:

$$S = 100 - \frac{100}{\beta_x}[\%]\,.$$

Based on the β_x factor and the solid particle separation degree, their comparative review can be performed as shown in Table 4.

Table 4 – Comparison of βx and the adequate solid particles separation degree
Таблица 4 – Сравнение β_x фактора с соответствующей степенью выявленных твердых частиц
Табела 4 – Поређење β_x фактора и одговарајућег степена издвајања чврстих честица

$\beta_x$factor	Solid particles separation degree[%]
20	95
75	98.66
100	99
200	99.5
500	99.8
1000	99.9

Based on the previously shown example, we can conclude (taught by experience and work with modern hydraulic systems where the pumps and small clearance systems (like servo systems) operate with 2 – 5 μm clearances), that we can draw a parallel between hydraulic and modern CR systems. In order to have modern injection systems operating smoothly and without damage in the form of wear of the pump and injector working components, lately, the filter manufacturers have understood the issues and started producing filters that will be used for fuel filtration in this case. All major filters manufacturers (Hydac, Parker, Pall, Fleetguard, etc.)

have already started the production of filters that should satisfy the fuel cleanliness requirements according to standards imposed by CR system pump and injector manufacturers. According to Table 5, the manufacturers of fuel filters for common rail systems require certain levels of fuel cleanliness regarding the allowed quantity of solid particles according to ISO 4406/99. According to this standard, in 1 ml of fuel, the allowed quantity of 4, 6 and 14 μm-sized solid particles is observed (ACEA, 2013).

Table 5 –The required purity class fuel according to the requirements of manufacturers of CR systems (Hydac, 2015a)
Таблица 5 – Класс чистоты топлива, в соответствии с требованиями производителя системы common rail (Hydac, 2015a)
Табела 5 – Класе чистоће горива према захтевима произвођача common rail система (Hydac, 2015a)

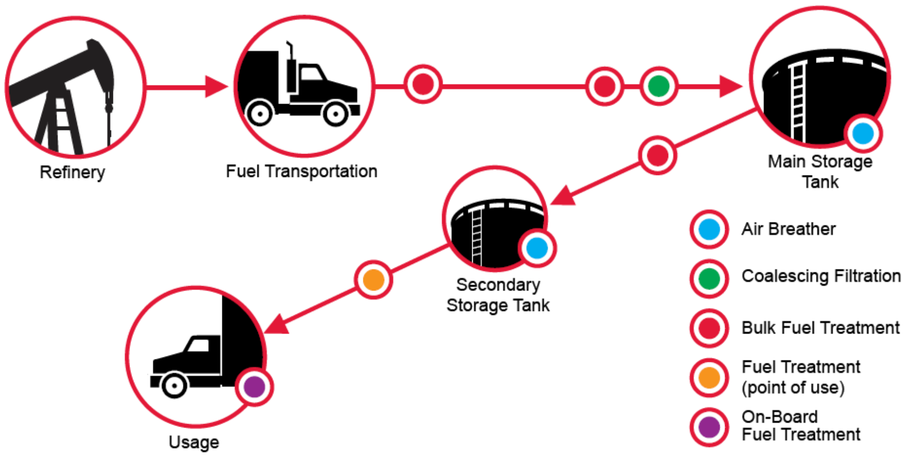
Organization	Particulate ISO 4406	Water
Bosch	11/8/6 at injector	< 200 ppm
CAT	18/16/13 at storage	200 ppm
CUMMINS	18/16/13 at storage 15/13/10 at vehicle tank 12/9/6 at injector	< 200 ppm
Worldwide Fuel Charter	18/16/13	No free emulsified, dissolved < 200 ppm

With regard to the Worldwide Fuel Charter adopted in 2013 (ACEA, 2013), Table 5 shows that fuel cleanliness criteria have been made more stringent by CR system manufacturers even by 6 or 7 times since then. Modern injectors cannot operate with 18/16/13 fuel cleanliness levels when for a proper operation cleanliness levels 11/8/6 are required. Table 6 shows a practical example of comparison of these two cleanliness classes with the number of particles present in the fuel sample.

Table 6 –Comparison of classes of fuel cleanliness according to ISO 4406/99 standard
Таблица 6 – Сравнительная таблица классов чистоты топлива, в соответствии со стандартами ИСО 4406/99
Табела 6 – Упоредна табела класа чистоће горива према ИСО 4406/99 стандарду

ISO 4406: 1999 Hydraulic Fluid Power Solid Contamination Code		
ISO Code	Number of Particles per 1 ml of Fluid	
	More Than	Up To and Including
At storage		
18	1300	2500
16	320	640
13	40	80
At injector		
11	10	20
8	1.3	2.5
6	0.32	0.64

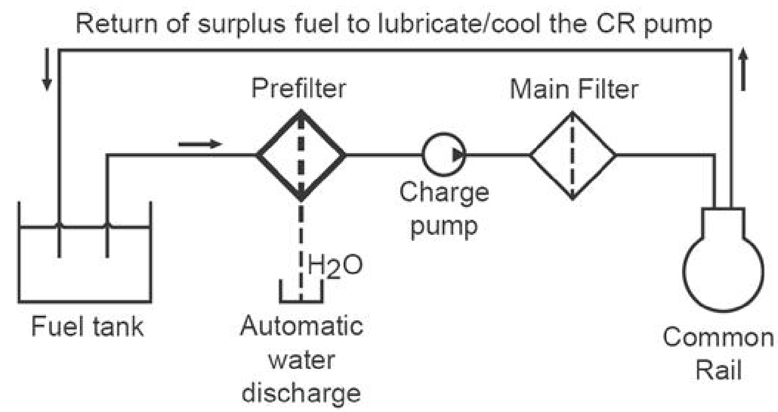
Comparison of two different fuel cleanliness classes shows that the need for fuel cleanliness in injectors is much bigger comparing to the number of particles present in fuel distributor tanks. Cleanliness level 11, related to 4 $\mu m_{(c)}$-sized particles, is by 130 times cleaner comparing to level 18, while cleanliness level 8, related to 6 $\mu m_{(c)}$-sized particles, is even by 246 times cleaner comparing to level 16 than the fuel being stored in fuel distributor storage tanks. From the above presented example, we can conclude that the need for new filtration technologies for new types of CR systems is much bigger comparing to older generations. Some filter manufacturers, such as Hydac, are leading other manufacturers who have already started developing certain filtration units for fuel used in modern diesel engines. According to their studies, it is necessary, at each step of the fuel transport, to provide a corresponding filtration level in order to satisfy the required fuel cleanliness level regarding the presence of particles and water as contaminants. Figure 9 shows all fuel filtration levels for the purpose of maintaining the required fuel cleanliness level.



Picture 9 – Fuel filtration treatment locations from refineries to the final consumer (Hydac, 2015b)
Рис. 9 – Уровни фильтрирования топлива от нефтеперабатывающего завода до конечного пользователя (Hydac, 2015b)
Слика 9 – Нивои филтрирања горива од рафинерије до крајњег потрошача (Hydac, 2015b)

In America and some European countries, fuels coming out of refineries are already being treated in this way. What we must specially take care of is fuel filtration performed right in vehicles, which is called "Onboard Fuel Treatment". This method of filtration includes pre-filtration and final filtration. The pre-filtration process is performed by the filtration unit designed in two parts. One part is designed for rough separation of water by warming-up of fuel and fine separation of water by the filtration medium, while the second part of the filtration medium performs the filtration of solid particles. Such filter units are commonly installed in the pipeline between the fuel tank and the supply pump.

The second filtration part relates to the so-called main – final filters that are installed in a location between the supply pump and the high pressure pump. Main - final filters provide high level of fuel cleanliness with a solid particles separation level of 99.9 % and the beta factor βx=1000. The aim of the filtration procedure is to provide proper operation of high pressure pumps and sensitive parts of the CR system, i.e. the injectors themselves. Figure 10 shows a modern system, consisting of the fuel tank, the pre-filter whose task is to separate water and bigger particles in the system, the supply pumps, the main – final filter, the CR system and the return line through which the fluid overflow returns. The overflow fluid serves for lubrication and cooling of the distribution – the radial piston pump.



Picture 10 – Fuel filtration system with pre-filtration and main-filtration (Hydac, 2015b)
Рис. 10 – Система фильтрирования топлива с предварительным и главным фильтром *(Hydac, 2015b)*
Слика 10 – Систем за филтрирање горива са претфилтером и главним филтером (Hydac, 2015b)

Fuel pre-filtration units

Figure 11 shows a modern solution of the filtration unit for fuel prefiltration.

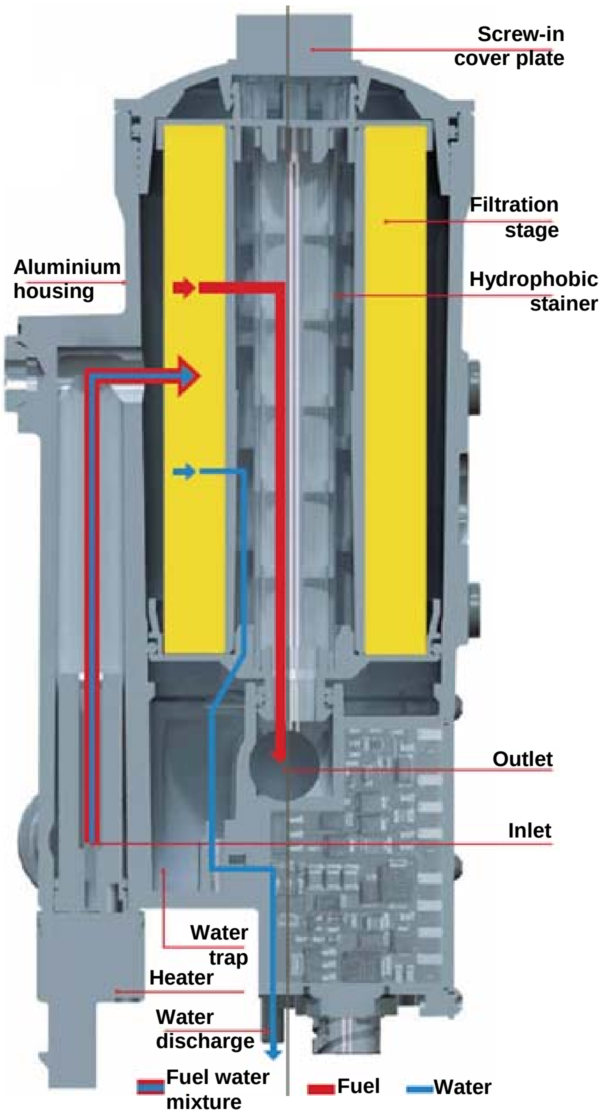
It consists of an aluminium housing containing the following parts:

- Filter element – a synthetic medium having excellent hydrophobic features for water and solid particles separation;
- Heating unit – for heating of fuel at the start-up and during the operation in order to provide optimum water separation;
- Water presence detection sensor – for signalling the presence of water in fuel.

Different water separation media operate under different principles. *Hydrophobic barrier media*, such as silicone treated cellulose, reject water and causes it to bead up on the upstream surface. As the beads become larger, they run down the face of the element into a cup under the force of gravity. *Hydrophilic depth coalescing media*, such as glass micro-fibre, have high affinity for water. The water in the fuel associates with the glass fibres and over time as more water enters from the upstream side, massive droplets are formed. The water moves through the filter with the fuel and on the downstream side, falls out of the fuel flow into a collection cup.

Increased use of surface active fuel additives and fuel components such as biodiesel have rendered conventional separating media less effective and filter manufacturers have needed to develop new approaches such as composite media and ultra-high surface area coalescing media (Stanfel, 2009), (Pangestu & Stanfel, 2009), (Bessee & Hutzler, 2009). Methods of quantifying fuel/water separation performance have also been affected (Stone et al, 2009).

Fuel filters can also contain additional features such as fuel heaters, thermal diverter valves, de-aerators, water-in-fuel sensors, and filter change indicators.



Picture 11 – Cross section of the pre-filter (Hydac, 2012)
Рис. 11 – Поперечное сечение устройства для предварительного фильтрирования (Hydac, 2012)
Слика 11 – Пресек уређаја за претфилтрацију горива (Hydac, 2012)

A fuel preheater helps to minimize the accumulation of wax crystals that can form in the fuel as it cools to low temperatures. Common heating methods use electric heaters, engine coolant or recirculated fuel.

The filter medium is designed in several combinations of synthetic medium, of which the most efficient combination is glass/synthetic, which removes solid particles, in the pre-filtration process, to the level of 6 $\mu m_{(c)}$, and water with an efficiency of 95% (Schroeder Industries, 2016).

Filter elements for main – final filtration

This group of filter elements was used for fuel filtration in CR systems before. However, due to the presence of water in modern diesel fuels (resulting form addition of biodiesel which is hydroscopic) it became nearly impossible to filter the fuel in the mixture of particles and water that were saturating the filter elements very quickly. Accordingly, old filter elements did not have to achieve a high level of separation of solid particles, with the beta factor within the range of 100 – 200 and the efficiency level of 99 – 99.5%.

However, new CR systems operate at very high pressures amounting to 2000-2500 bars, with even 3000 bars in the future, so that the working fluid – diesel fuel in our case, must have the maximum fluid cleanliness. For this reason, the idea about pre-filtration was born, leaving the final filtration to be performed with filters of a higher level of separation of solid particles and water.

For this reason, it will be necessary to use high separation filter elements that will be able to satisfy very high criteria, especially regarding the separation level of solid particles required for 11/8/6 fuel cleanliness standard. In order to achieve this, a CR system will use, as the main – final filter element, the filter elements of high separation levels 99.8 to 99.9%, or the beta factor $\beta x = 500$ up to $\beta x = 1000$. That this topic is not new and was considered before, prove the research described in the paper by von Stockhausen (von Stockhausen et al, 2009). These research works, however, were done for the systems operating at lower working pressures and with slightly bigger clearances in injectors.

Modern CR systems equipment, which is required to solve problems related to filtering quality, is very expensive. If we know that the passenger car injector can have a price range from a couple of hundreds to a couple of thousands of Euros, (high pressure pumps prices can be even higher), then the filtering problem cannot be ignored. Activities like diagnostics, adjustments, reparation or replacement of CR system components (such as injectors, pump, pressure regulation valves, flow regulation valves, ECU, etc.) must be carried out by qualified personnel.

Conclusions

Passenger cars, off-road vehicles, freight vehicles, disel-electric generator sets and others are subject to the heaviest exploitation conditions. In order to provide proper and efficient operation of the injection CR system, as well as of the engine itself, which, of course, produces effects on the vehicle exploitation features, it will be necessary to provide high quality diesel fuel. Modern CR systems have subsystems which monitor engine and CR system condition and exploitation performances. Based on collected data, central computer controls engine operation, in order to reduce emission of harmful gases and to achieve better fuel economy (Cummins Engines, 2016).

This paper presents some of the currently used CR systems, as well as some that will be used in the future and require high cleanliness fuel regarding the presence of contaminants, i.e. solid particles and water. We have specified current requirements of manufacturers of CR systems equipment regarding the fuel cleanliness and allowed water presence. Additionally, we have compared the allowed levels determined by manufacturers with the old Worldwide Fuel Charter levels, and based on the comparison, we have defined the necessary levels of the efficiency degrees for both pre-filtration and the main – final filter elements, in order to determine sufficient quality levels for both current and future CR systems.

Also, modern CR systems that are being used in the vehicle engines subject to Euro 5 and 6 norms regarding exhaust gas quality, require the diesel fuel cleanliness class to be minimum 12/9/6, or better according to ISO 4406/99 standard regulating the presence of solid particles. It means that fuel should be filtered through the top quality filtration media providing the fuel cleanliness level in injectors in respect of solid particles not bigger than 4 $\mu m_{(c)}$, or even smaller with the solid particle separation level being minimum 99.9% and the beta factor of the filter $\beta x \geq 1000$.

However, modern multi-purpose filters commonly used in modern diesel engines do not satisfy the required quality level and are not designed to provide the sufficient and required fuel quality level for modern CR systems and injectors.

With the application of modern solutions for pre-filtration and final filtration, the required quality level of fuel can be achieved for modern fuel injection systems.

The advantages of pre-filtration systems to be used in vehicles are as follows:

- the possibility of automatic water separation;

- the possibility of installation of fuel heaters and installation of sensors for water presence detection;
- high flexibility regarding the position of installation in relation to the entrance and exit of fuel;
- continuous water separation during the whole exploitation life of the filter element;
- economical and reliable operation of the filter element, easily replaceable;
- easy detection of the presence of other contaminants in fuel (metal, other deposits, etc.) that can be detected visually and sent to analysis;
- water filtration with an efficiency level of >95%;
- separation of solid particles up to the size of 6 $\mu m_{(c)}$.

Filter elements for main – final filtration have completely different concept – they are mainly intended for separation of solid particles from fuel with the minimum quantity of residual water from the pre-filtration process.

This filter group is produced in different designs (replaceable elements with housing or more commonly, spin-on design) with the following characteristics:

- easy to install and uninstall;
- absolute fluid filtration (declared level of contaminant separation degree);
- fuel filtration of particles of 4 μm(c) and smaller;
- solid particles separation level equal to or higher than 99.9% with $\beta_x \geq 1000$.

It is only this method of filtration that can provide quality and safe operation of modern CR systems and diesel engines, preventing high costs of maintenance that could occur as a consequence of poor or insufficient quality of diesel fuel, which is commonly manifested in the form of frequent defects in the pumps and CR system injectors. In addition to its reliability in exploitation, the aim is to achieve the engine operation with the lowest possible emission of harmful matter, which the manufacturers of engines and injection systems have to satisfy.

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ПРОБЛЕМЫ ФИЛЬТРИРОВАНИЯ ДИЗЕЛЬНОГО ТОПЛИВА В СОВРЕМЕННОЙ СИСТЕМЕ ВПРЫСКА COMMON RAIL

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ОБЛАСТЬ: машиностроение
ВИД СТАТЬИ: профессиональная статья
ЯЗЫК СТАТЬИ: английский

Резюме:

За последние годы заметно возросло развитие современных систем впрыска дизельного топлива, под названием „common rail“. Наряду с развитием данных систем необходимо одновременно следить за соответстующим развитием вспомогательных систем, которые обеспечивают их правильную и эффективную работу.

В данной статье подробно описаны последние поколения common rail систем, которые работают под высоким давлением, а также обсуждаются вопросы фильтрирования дизельного топлива, и подчеркнута проблема загрязнения окружающей среды от промышленного топлива.

Ключевые слова: common rail системы, технологические процессы фильтрирования, дизельное топливо, обслуживание, насосы, фильтры.

ПРОБЛЕМ ФИЛТРИРАЊА ДИЗЕЛ-ГОРИВА КОД САВРЕМЕНИХ COMMON RAIL СИСТЕМА УБРИЗГАВАЊА

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ОБЛАСТ: машинство
ВРСТА ЧЛАНКА: стручничланак
ЈЕЗИК ЧЛАНКА: енглески

Сажетак:

Савремени системи за убризгавање дизел горива, под називом „common rail” последњих неколико година се нагло развијају. Упоредо са развојем ових система потребно је истовремено пратити и одређени развој помоћних система који се користе за њихов правилан и ефикасан рад. У раду је детаљно описана последња генерација common rail система који раде са високим радним притисцима. Наведен је и проблем филтрирања дизел-горива и издвајања непожељних контаминаната у погонском гориву.

Кључне речи: common rail системи, технолошки процеси филтрирања, дизел-горива, одржавање, пумпе, филтери.

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