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Rafał SMOLEC*
Mateusz BOR*
Wojciech KARPIUK*
Marek IDZIOR*
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DEVELOPMENT TRENDS OF HIGH PRESSURE COMMON-RAIL PUMPS

Due to systematic reduction of he permissible levels of harmful and toxic substances in the exhaust gases, particulary of which particulate matter appears to be unfavorable, there is a continuing need to improve the fuel injection parameters. One of the factors determining the correct fuel injection is the injection pressure, which strongly depends on the design of the common-rail pump. This article presents the latest common-rail pump solutions for automotive vehicles and prototype constructions in terms of improved system efficiency and reliability. The latest pump solutions utilize one pumping section and allows to inject pressure up to 3000 bar, while synchronizing the delivery phase with the fuel injection phase. In the further development of the injection systems, hybrid solutions are expected to form a combination of unit injector and common rail systems.

Keywords: common-rail, fuel pump, lubricity, emission

1. INTRODUCTION

Emissions standards, particularly in EU member states, constitute a basic factor in stimulating the development of combustion engines, with the aim of increasing the ratio of generated power to engine weight and improving their efficiency. Improving efficiency decreases fuel consumption, which contributes to the reduction of harmful emissions. Engine efficiency is mainly improved through better control over the combustion process and reduction of friction losses. Injection pumps of

* Poznan University of Technology, Faculty of Transport Engineering.

fuel supply systems play a significant role in optimizing the combustion process and reducing losses. The dominant type of fuel injection system, particularly in motor vehicles, is currently the common-rail system, which has pushed unit injector systems and distributor pumps from the market due to their inability to meet rigorous emissions standards. Common-rail systems make it possible to reach injection pressure up to 3000 bar, which contributes to minimizing the mean diameters of fuel droplets, thus improving self-ignition conditions. At the same time, this makes it possible to supply the large fuel dose required for achieving a maximum power exceeding 100 HP from one liter of the engine's displacement. The latest piezoelectric injectors are capable of dividing a fuel dose into up to 10 parts, which significantly contributes to reducing emissions and enables correct inter-operation with non-engine-based emissions purification systems.

Obtaining injection pressures on the order of 3000 bar and a large fuel dose is a big challenge for high-pressure pump designs. Despite the growth of pressure generated, it is important to limit power consumption by the pump as much as possible in order to reduce energy losses. For this reason, pump designs are constantly evolving, and the effect of designing work can be seen both in the shape of the body and the construction of the pump's internal mechanisms.

Ensuring the proper level of pump durability is also important from an operational perspective. Heightened forces occurring in the pump's drive system should not translate to an increase in wear in the cylinder and plunger precision friction pair or in the area of the cam and follower. Therefore, it is necessary to change pump design schemes applied until now and to apply materials characterized by elevated resistance to work under elevated friction conditions.

2. STRUCTURE OF COMMON RAIL SYSTEMS AND PUMPS

Modern injection systems of Diesel engines must ensure quiet operation, meet rigorous emissions standards and ensure low fuel consumption. Due to the beneficial functional parameters in currently manufactured designs, common-rail injection systems are applied. An undoubted advantage of common-rail over other systems on the market is that the fuel pumping process is independent of injection, meaning that pressure in the rail can be regulated regardless of the crankshaft's revolutions, and the pump's discharge is dynamically adapted to instant demand. Three basic elements can be distinguished in the architecture of the common-rail system (Fig. 1). These are:

- low-pressure system (feed pump, filter, fuel tank),
- high-pressure system (high-pressure pump, rail, high pressure lines, injectors),
- electronic control system (measuring and executive elements).

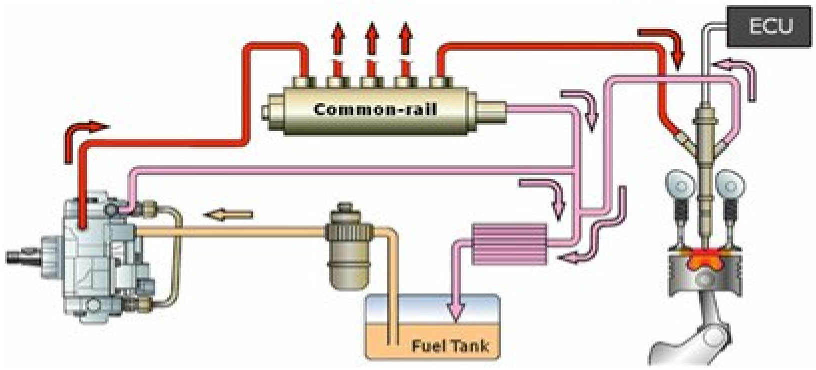

Fig. 1. Diagram of a common-rail system [Gunther 2014]

Many years of development, determined by the growing requirements of emissions standards and consumers' expectations, have led to the implementation of a series of solutions that improve the quality of the injection process. In the area of the pump and injector, the most important changes include:

- increasing fuel pumping and injection pressure,
- change of injectors' control elements,
- reduction of internal friction,
- multiplication of dose division.

With regard to injection systems, the particularly large role of high-pressure pumps should be accounted for. High-pressure pumps are currently positive displacement piston pumps. Such a construction, in combination with exceptionally low dimensional tolerance, allows for the achievement of high pressures, reaching up to 3000 bar. Solutions available on the market differ in the mechanism responsible for driving the piston and compressing fuel in the pumping section, however in every case, the following basic system can be distinguished: cam–piston unit [Karpiuk et al. 2014].

Depending on their design, injection pumps can be classified into pumps with a cam of interior or exterior profile (Fig. 2). The solution of an interior profile cam was applied by Denso and Delphi, however due to the small displacement of the pump section and large body diameter, it is not currently applied. Moreover, due to its larger diameter, this cam reaches a higher linear speed, which constitutes a significant barrier to the achievement of proper lubrication conditions of the cam and the roller cooperating with it. The pump's large dimensions also translate to an unfavorably large weight. Furthermore, it is easier to shape the profile of an exterior profile cam so as to achieve the highest possible injection pressure over as long a time as possible.

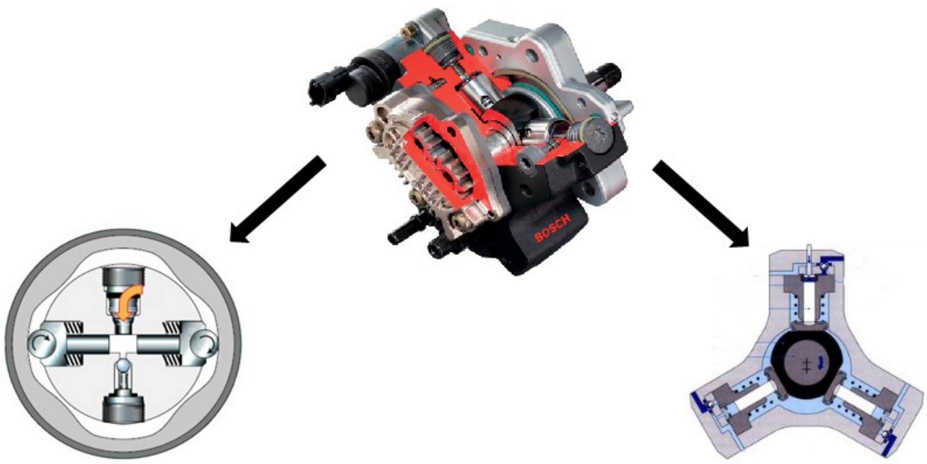

Fig. 2. Classification of common-rail pumps [Meyer 2003]

3. LATEST COMMON-RAIL INJECTION PUMP SOLUTIONS FROM THE PERSPECTIVE OF OPERATIONAL REQUIREMENTS

The engines of motor vehicles are currently very complicated mechatronic machines. They have been significantly modernized due to the introduction of emissions standards. Besides environmental requirements, it is also important to meet the expectations of the vehicle's driver with regard to dynamics and responsiveness. Electronically controlled fuel injection systems are particularly significant in the context of ensuring proper vehicle dynamics. At low loads, the pressure generated by the injection pump is relatively low, amounting to several hundred bar, which makes it possible to reduce energy losses related to pumping, however at high loads and revolutions, pressure must increase even several-fold in the shortest possible time in order to achieve full engine power. Figure 3 presents the pressure control strategy in the common-rail system of the engine applied in the BMW M550d vehicle. At idle gear speed, 770 rpm, the system's pressure amounts to 270 bar, but at the maximum dose of 85 mg/stroke and 4000 rpm, this pressure is 2300 bar. In order to adapt to such variable operating conditions, systems applied until now employ discharge regulation by means of a throttling valve as well as pressure regulation by means of a valve situated in the rail.

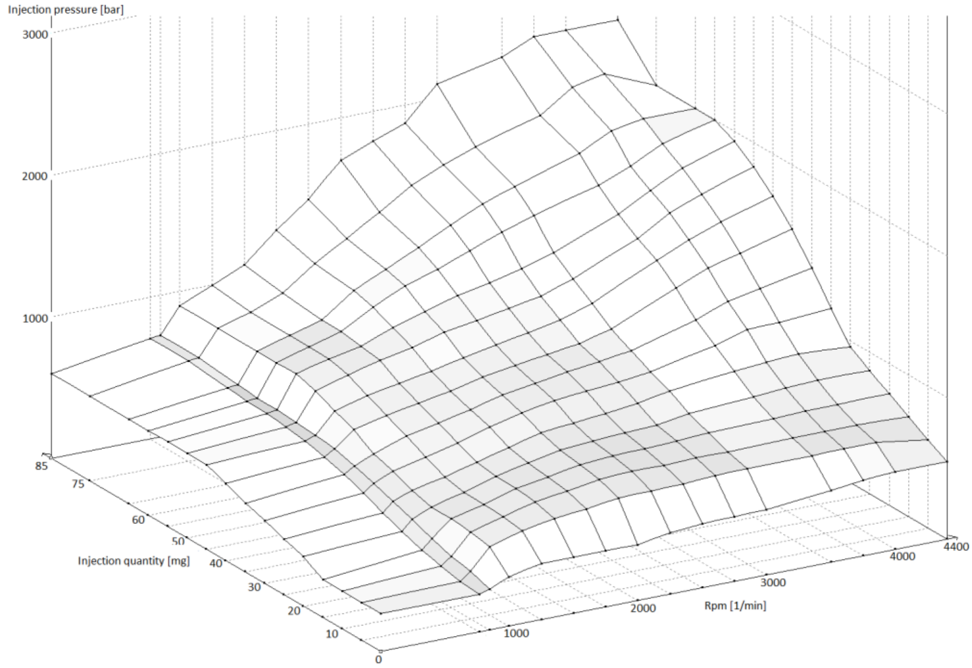

Fig. 3. Chart of pressure changes in the rail as a function of fuel dose and engine revolutions

Discharge regulation via throttling does not make real-time control possible and simultaneously increases losses related to filling of the section. This is why the application of a direct-action valve is proposed in the latest conceptual solutions. In traditional CR pump solutions, a discharge adjustment valve is installed in the body and controlled via pulse-width modulation (PWM). Depending on the desired discharge, pulse-width is increased or decreased, causing the valve to reduce or increase the cross-section of the fuel channel feeding the pumping section. The new concept calls for direct control of section filling in every work cycle. During the suction phase, the valve is open and makes it possible to fill the pumping section completely. After the piston passes through its extreme lower position, the valve is closed only when the requirement amount of fuel is found in the section. As the piston ascends in its stroke, excess fuel return to the feed conduit via the inlet channel (Fig. 4). The advantages of this solution should be sought, above all, in the possibility of shortening response time to the controller's command. It is possible to freely increase or decrease discharge in consecutive compression cycles, which, in combination with synchronization of the pump shaft's position with the crankshaft, can be applied to reduce harmful volumes harmful to the fuel rail (reduction of hydraulic phenomena). Furthermore, pumps performing two work cycles per section per shaft revolution are under high loads, both mechanical and thermal. Complete filling of a section improves the internal cooling of the pump's cylinder [Bor et al. 2017].

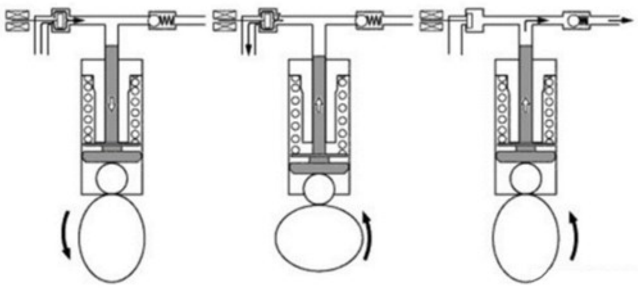

Fig. 4. Diagram of the operation of a section with a direct-action valve [Kędzia]

A common tendency observed in the design of pumps from leading manufacturers of common-rail systems is the pursuit of minimizing the number of pumping sections and creation of modular constructions. Modular pumps employ a common body with a replaceable shaft (cam ascent change) and replaceable pumping section for a single model. Such a design is dictated by the need to reduce production costs. The total cost of development and manufacturing per pump unit should not exceed EUR 100. For this reason, manufacturers strive to simplify and unify the design as much as possible. Limiting the number of pumping sections is intended to achieve two beneficial features:

- reduction of internal friction,
- synchronization of pumping phase with fuel injection phase.

Reducing internal friction in a pump's mechanisms increases its mechanical efficiency. In tri-sectional pumps applied until now, three precision friction pairs with follower elements were constantly in motion. The greatest friction forces are present in the piston – cylinder sliding surface and cam – piston areas. By reducing the number of sections, the number of friction nodes is reduced, and by increasing the number of cam lifts, the pump's discharge can be maintained at the desired level. Reduced pump dimensions are a side effect of reduction of the number of sections, which improves the conditions of the pump's enclosure. In addition, the application of a single section enables a more favorable piston guiding solution, which prevents damage in the drive mechanism (Denso system).

In a uni-sectional pump with two rises per shaft revolution, synchronization of the pumping and injection processes can be easily achieved. The pump is driven by the chain or belt of the timing gear mechanism. In earlier solutions, tri-sectional pumps were driven by the camshaft, so three pumping phases corresponded to four fuel injections. This solution causes fuel injection doses to differ between individual injections due to variable pressure in the rail. In the case where one fuel pumping cycle corresponds to every injection process, the doses dosed by the valve based on the set pressure and set opening time are very similar. Thanks to this, the amount of fuel that is injected into the cylinder can be more precisely estimated, leading to better control over the combustion process. Equalization of the dose for individual cylinders improves uniformity of the engine's operation, which, in certain cases, makes it possible to eliminate additional equalizing elements, thus ensuring more favorable operating conditions for the dual-mass flywheel.

Fuel lubricity has been a significant issue in common-rail pumps for many years. The lubricity of fuels with regard to common-rail pumps has been widely described by both independent research centers and manufacturers of fuel systems. In pumps currently in manufacture, lubrication takes place by employing fuel as the medium separating friction pairs (Fig. 5). Fuel is first supplied to the area of the cam mechanism, where it lubricates the piston drive unit and its surface, then it flows through the safety valve, and upon reaching the proper pressure, it flows through the discharge regulation valve, from where it flows to the pump's head. Due to the very high unit pressures in the system, any changes in fuel parameters lead to deterioration of inter-operation conditions, and in extreme cases, to detachment of the oil film and operation under dry friction. The improper operation of pumps and valves supplying fuel to the system also results in deterioration of lubrication, and in consequence, damage to the pump's precision elements. Damage to the pump's friction pairs often leads to destruction of the other fittings of the injection system, raising repair costs significantly. Furthermore, certain pumps are particularly exposed to damage caused by improper lubrication due to design flaws. One example is the CP4 pump, presented here, installed in the majority of common-rail systems from Bosch. The causes of damage are to be sought, above all, in the defective piston guide system, which does not protect it against rotation relative to the camshaft, and in effect, rolling friction in the roller-cam area is converted to sliding friction. Under sliding friction conditions, fuel lubricity is insufficient, which leads to the formation of abrasive micro-grains, which also damage injectors within a very short time. Over the course of production, the CP4 pump underwent 6 modernizations, and a special fuel filter replacement procedure was introduced in order to limit the risk of roller flipping. This problem is therefore very well known to manufacturers, so finding solutions that would limit unfavorable phenomena is important to the development of pumps [Meyer 2003].

Current measures intended to reduce pump wear due to reduced lubricity can be divided into two directions. Firstly, reduction of mechanisms' wear, particularly on the contact between the cam and piston, can be achieved through the application of hard materials. In particular, the cam's surface can be coated with DLC (Diamond Like Carbon). The hard surface that is formed counteracts wear even under conditions of insufficient fuel or its reduced lubricity. The second solution, planned to be implemented in the CP4 pump by Bosch, is to change the lubrication system to oil lubrication. Lubrication conditions achieved with the use of oil are significantly more favorable, lead to reduction of surface wear, and prevent damage to elements.

However, the application of oil lubrication brings with it the problem of fuel leakage from the pumping section into the drive mechanism. Therefore, it is important to reduce leakage, which raises the issue of proper section sealing. It seems that the best solution is to apply labyrinth sealing. Such a solution, according to Bosch, is to ensure fuel leakage no greater than 1 cm^3 per million work cycles, which will enable the application of lubrication with engine oil and significantly simplify the pump's design. Previously, Bosch made attempts to apply oil lubrication, however an inadequate sealing solution caused the engine oil to become diluted very rapidly, which significantly reduced the interval between oil changes.

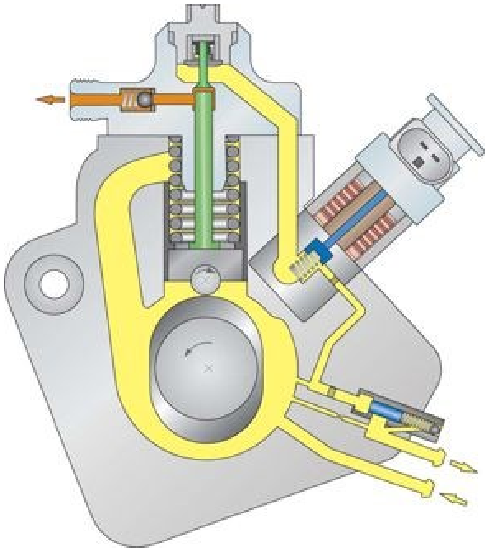

Fig. 5. Fuel circulation in the Bosch CP4 pump [Gunther 2014]

4. SUMMARY

Diesel engines, particularly in heavy duty vehicles, will continue to be commonly used due to the favorable energy density of the fuel. This is why it is important to continuously improve engine parts so that they meet the latest emissions standards. Fuel injection systems provide an opportunity to improve general efficiency, both by improving the injection process and reducing power consumption by devices. Increasing the pressure of fuel injection makes it possible to reduce the size of fuel droplets, which has a favorable impact on the process of solid particle formation. Increased injection pressure also makes it possible to supply a larger dose per work cycle, which translates to an increase of maximum power obtained from the given engine displacement. Reduction of the number of pump components has a considerable effect on increasing reliability, reducing pump weight and reducing internal losses through the reduction of the number of friction nodes. The application of new-generation control valves will considerably reduce the system's reaction time to load change, simultaneously providing the possibility of further energy loss reduction.

Hybrid systems are also found among the proposed solutions. Such systems are to be characterized by a combination of UIS and common-rail components, where utilization of both systems' advantages is to yield an injection system with a low number of components, simple installation in the engine head and low production costs. Delphi has proposed systems of this type for the latest line of low-volume engines from the Smart concern. The specifications of these systems are currently unknown and presented solutions have not been implemented yet.

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KIERUNKI ROZWOJU WYSOKOCIŚNIENIOWYCH POMP PALIWA TYPU COMMON-RAIL

Streszczenie

Ze względu na systematyczne obniżanie dopuszczalnych poziomów emisji substancji toksycznych i szkodliwych w gazach spalinowych, z których szczególnie ważne dla silników o zapłonie samoczynnym są cząstki stałe, istnieje potrzeba ciągłego polepszania warunków wtrysku paliwa. Jednym z czynników determinujących poprawne rozpylenie paliwa jest ciśnienie wtrysku, które jest bezpośrednio związane z konstrukcją pompy paliwa. W artykule zaprezentowano najnowsze proponowane rozwiązania pomp typu common-rail przeznaczonych do pojazdów samochodowych oraz rozwiązania prototypowe w aspekcie zwiększania sprawności oraz niezawodności układu. Najnowsze rozwiązania pomp common-rail wykorzystują jedną sekcję tłoczącą i pozwalają na osiągnięcie ciśnienia wtrysku do 3000 barów, umożliwiając jednocześnie synchronizację fazy tłoczenia z fazą wtrysku paliwa. Jako jeden z dalszych etapów rozwoju prognozuje się wykorzystanie układów hybrydowych, łączących zalety systemów typu common-rail oraz unit injector system.