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IDEA OF USE OF HYDRAULIC BOOSTER IN HIGH-PRESSURE FUEL PUMP WITH HYPOCYCLOID DRIVE

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Abstract

Common rail (CR) injection systems have been universally applied in passenger car engines for twenty years. Moreover, they are applied on a wide scale in trucks, machinery and stationary engines. They have many advantages such as very good fuel spraying due to high injection pressure, injection dose distribution to several smaller, or less heat generation compared to traditional systems. At the same time, the use of this type of system involves a number of problems. They are characterized, among other things, by the high cost of manufacturing and the high sensitivity to changes in the quality of the used fuel.

The most important component of the common rail injection system is the high-pressure injection pump. The authors propose a new, alternative pump design with the hypocycloid drive – the article presents the issue of using this type of pump. Further sections describe the design of a pump utilizing a hypocycloid mechanism; demonstrate beneficial functional features and present selected results of the assembly's dynamic simulation.

The pump is also characterized by the possibility of multiplying the piston's pitch while maintaining its diameter. It makes it possible to obtain much greater discharge per operating cycle. Taking into account the considerable quantity of fuel transferring by the pump, was also possible to propose an idea of use of hydraulic booster in such pump. In this field, the authors have presented schematic diagram of a pressure booster with a description of its operation.

Keywords: *high-pressure fuel pump, hypocycloid drive, hydraulic booster, common rail, simulation, combustion engines*

1. A hypocycloid drive in high-pressure fuel pump

The hypocycloidal transmission with interior tooting was already patented in the 19th century. Depending on the selected wheel diameters, it made it possible to obtain various curves resulting from its resultant motion. Its popularity was limited by design and economic aspects. At the time, these drives and engines did not transmit high powers or torques, and the lifetime of subassemblies was very limited. Therefore, the problem of optimizing the design of a system converting reciprocating motion to rotation was not as significant as it is today. Moreover, in reference to the traditional slider mechanism, manufacturing a hypocycloid transmission would be more expensive and more difficult due to the high requirements relating to its teeth.

For many years, designers have sought possibilities of applying a hypocycloid gear in combustion engines. This system would replace the slider-crank mechanism used until now. The absence of lateral forces acting on the guided element is a great advantage of hypocycloids because of the crank system. It is accepted that lateral forces make up approx. 10% of the axial force generated by the pressure in the cylinder. Significant lateral forces generate very high powers, and pressures, from one cylinder. Eliminating the effects of their action is a very large field of study for engineers concerned with combustion engine design [1, 2].

One example of a hypocycloid transmission is the Wiseman engine patented in 2001 (Fig. 1). As part of work performed at the company, an engine with 10, 20 and 30 HP was developed and an engine with approx. 1 HP was made and tested. The design was based on the classical slider-crank engine. The experiment's results showed power and efficiency parameters that were very similar to the base engine, however at the same time, high potential for optimization and improvement of indicators was observed.

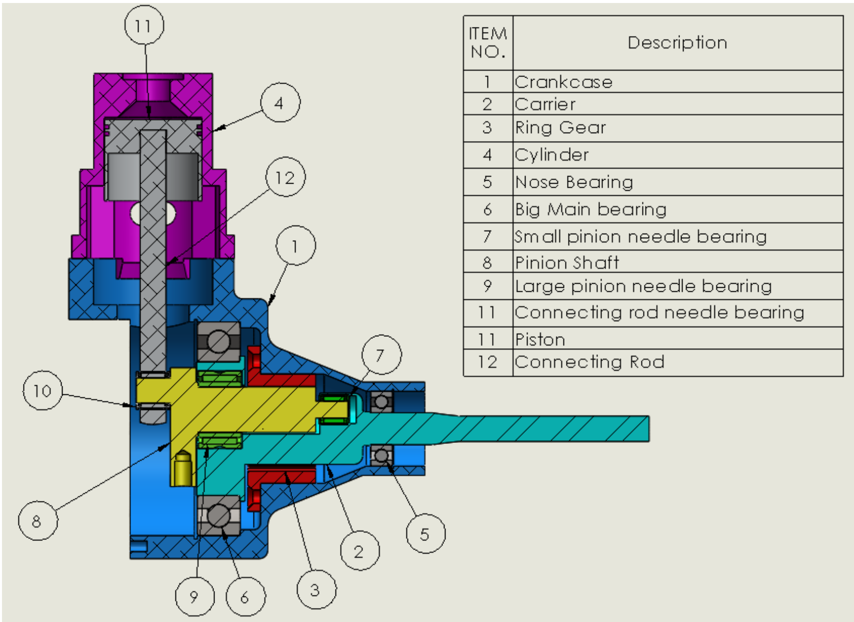

Fig. 1. Wiseman Engine Prototype Section View [3]

In addition, the engine's overall dimensions were limited significantly by using one of the hypocycloid's beneficial features, which is high pitch compared to the system's size [5]. Unfavourable efficiency and power parameters were obtained for the two-stroke engine, due to the large volume of the crankcase, resulting in low pressure. Numerous patent applications relating to designs utilizing a hypocycloid drive demonstrate the system's high potential and benefits of its application. Many attempts to implement the hypocycloid are being undertaken, in order to replace the aforementioned slider system or the cam drive. The hypocycloid can transmit power in two directions, which means it can be the system driving the working element and the power take-off (in the case of an engine – the piston), which is a significant advantage in comparison to the cam – pusher system.

2. Principle of operation of hypocycloid transmission

The hypocycloid transmission consists of two wheels – the larger wheel (R) has interior toothing and the smaller wheel (r) has exterior toothing. Torque is applied to the smaller wheel, making it turn, however the larger wheel cannot rotate around its axis. The smaller wheel moves over the circumference of the larger wheel, and any point on the smaller wheel's radius moves in a curve called the hypocycloid. To create the working drive of the pump, a hypocycloid transmission with a gear radius ratio of R/r = 2 was applied. This selection of wheels makes it possible to achieve resultant linear motion, as per Copernicus's Theorem: "Consider two circles of radii R and R/2 with the smaller one rolling inside the bigger circle without slipping. Any fixed point on the circumference of the small circle traces a straight line segment – a diameter of the big circle." Fig. 2 presents a diagram of the transmission, and the line on which the mechanism's sliding element moves is marked.

Analysis of the motion of the working element indicates that it performs movement in which the speed can be described using the sine function, similarly to a slider mechanism. The parametric equation determining the point's position as a function of angle of rotation can be defines as follows:

$$x(\alpha) = (R - r)\cos(\alpha) + r\cos\left(\frac{R-r}{r} \propto\right), \quad (1)$$

$$x(\alpha) = (R - r)\sin(\propto) - r sin\left(\frac{R-r}{r} \propto\right). \quad (2)$$

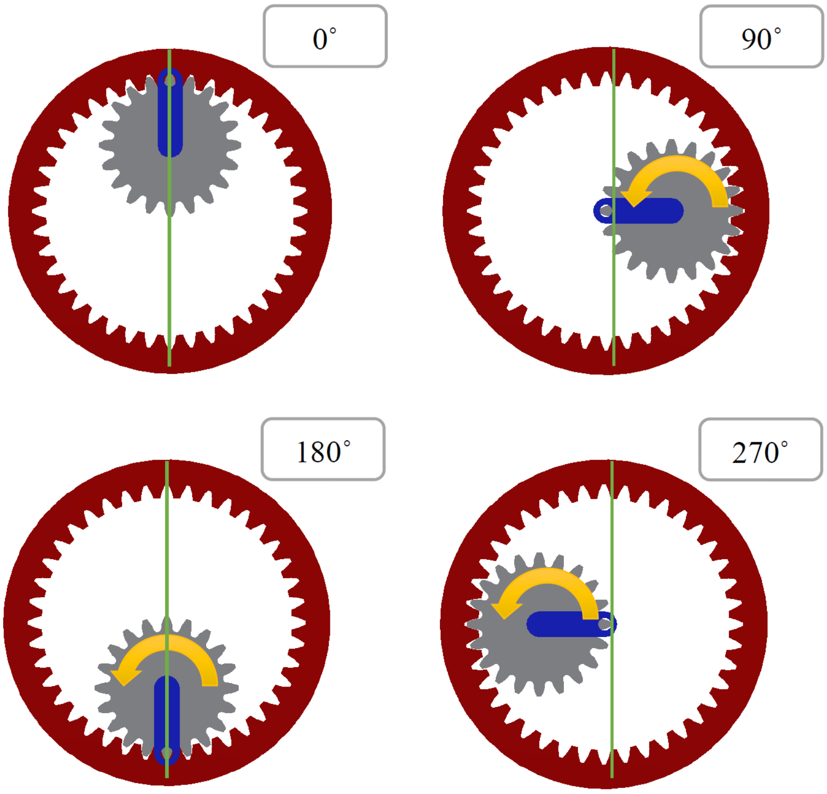

Fig. 2. Principle of operation of hypocycloid transmission

3. Selected operating parameters of pump with hypocycloid drive

High sensitivity to fuel quality as well as tendency for accelerated wear in the area of the drive due to lateral forces are main operational problems of pumps in common rail systems. The proposed solution of a pump with hypocycloid drive is free from these flaws and simultaneously makes it possible to utilize other beneficial features of the hypocycloid. Fig. 3 presents a concept cross-section of the designed pump, which was modelled using Autodesk Inventor software. The pump is driven by the main shaft (1), in which the countershaft (2) is mounted in a manner enabling their reciprocal rotation. A toothed wheel with exterior toothing is found on the countershaft and meshes with toothed wheel (3), which is immobile and bolted to the pump's body. The drive shaft has bearings on the exterior surface of wheel 3, bearing 4. A mandrel (9) is mounted eccentrically in the countershaft, and the plunger (8) along with the guide element is connected to this mandrel via bearing and positioned so that it can slide in the cylinder (7). Furthermore, the countershaft has a support (5) with bearings in the pump's body – bearing (6).

The presented pump design has been filed under the patent application P.418961, which also contains reservations concerning the further development of the design, such as the application of engineering ceramics or the introduction of gas into the chamber for the purpose of obtaining the implosion effect. Preliminary strength calculations have been conducted and confirmed the correctness of selected materials. Additional strength calculations using the finite element method were conducted using Femap software, running on the basis of the NX Nastran module. The countershaft is the element most under load in the system due to the complex state of flexural and torsional stresses. The authors created a model of the design in Autodesk Inventor software and conducted dynamic simulation of the assembly's operation on the basis of this model. Fig. 4 presents the progression of loading force acting on the pump piston in the dynamic simulation.

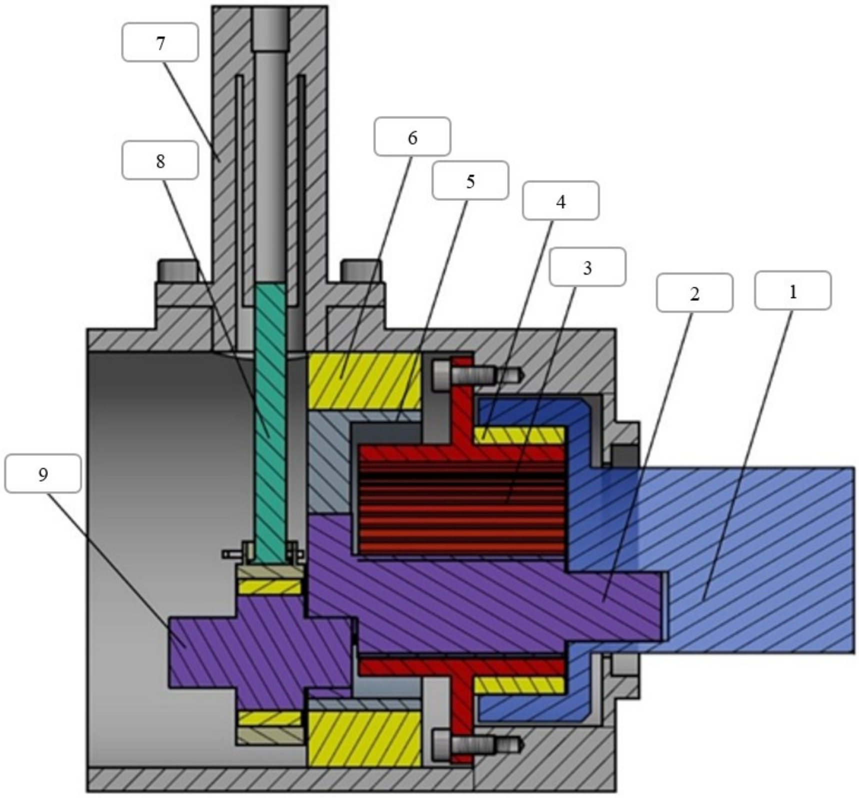

Fig. 3. Scheme of high-pressure pump with hypocycloid drive: 1 – main shaft, 2 – countershaft, 3 – toothed wheel with interior toothing, 4 – bearing of main shaft, 5 – support of countershaft, 6 – support bearing, 7 – cylinder of pumping section, 8 – piston (plunger) with guiding element, 9 – mandrel

Pressure was set to 1500 bar, and the 75% of the section's volume was filled with fuel. In effect, a force of 5300 N acting on the piston was obtained. The rapid growth of force to the maximum value during the compression phase is due to the fluid's low compressibility. When pressure reaches 1500 bar, the valve is opened and a batch of fuel is pumped outside of the system. The force progression is similar to the curves obtained for cam pumps with the same compression pressure and piston diameter, in terms of the value and profile of the curve. Decidedly greater values were achieved, however, for the piston's linear speed, which reaches a maximum of 3.14 m/s. This speed is directly proportional to angular speed and to the distance of the centre of rotation from the centre of the working element (in a cam system – eccentric, in a hypocycloid – distance of the mandrel's axis from the axis of the wheel with interior toothing). The relationship between angular speed and speed of reciprocating motion is defined by the formula:

$$V(\propto) = \omega r sin(\propto). \quad (3)$$

The increase of piston speed is linked to deterioration of the cylinder filling efficiency parameter due to elevated flow resistance, which is related to both elevated pumping resistance on conduits feeding the section and to the valve's design. For this reason, it seems advantageous to apply new-generation direct-action valves, which must be characterized by low flow resistance due to the two-way flow of compressed fluid. Due to the proportional dependency between speed and eccentricity, the hypocycloid system clearly benefits interoperating parts, particularly at low speeds. Increasing linear speed, according to lubrication theory, makes it possible to generate a layer of lubricating film in the piston-cylinder pair, which effectively separates the two interoperating elements. In relation to the absence of lateral forces, which cause chamfering of the piston, very beneficial parameters of interoperation between the side surfaces of the cylinder and piston (plunger), are obtained.

In order to determine power consumed by the pump, torque on the main shaft was determined. The value and progression of torque is presented in Fig. 5.

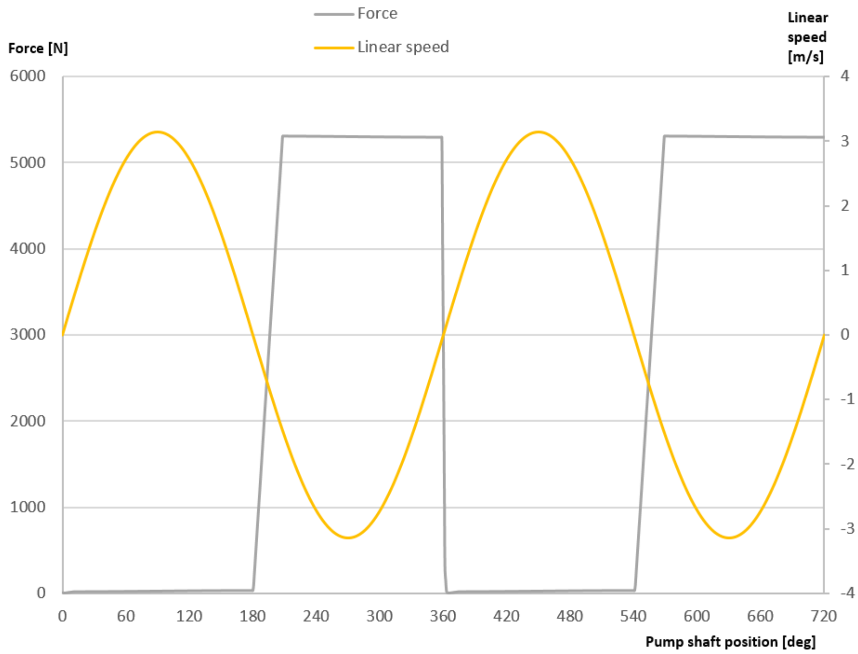

Fig. 4. Progression of force acting on the piston's face and piston's linear speed

The simulation accounted for friction losses between interoperating elements. The average torque required to drive the pump was calculated for the obtained curve. Based on this torque, knowing that the pump shaft was revolving at 1500 rpm, power consumption was determined to be 14.5 kW. This parameter seems unfavourable compared to conventional solutions; however, the fact that the discharge per shaft revolution is much higher, as demonstrated in the simulation, must be accounted for. It seems that it is much more representative to relate the volume of pumped fluid to the pump's power. Very similar indicators of both pumps' work were obtained as a result of comparing the given parameters (Tab. 1). Therefore, it is possible to achieve favourable working parameters of an engine using an injection pump with hypocycloid drive. Further optimization of the pump based on the results of workstation tests will go in the direction of reducing internal friction, which will additionally improve the entire system's efficiency.

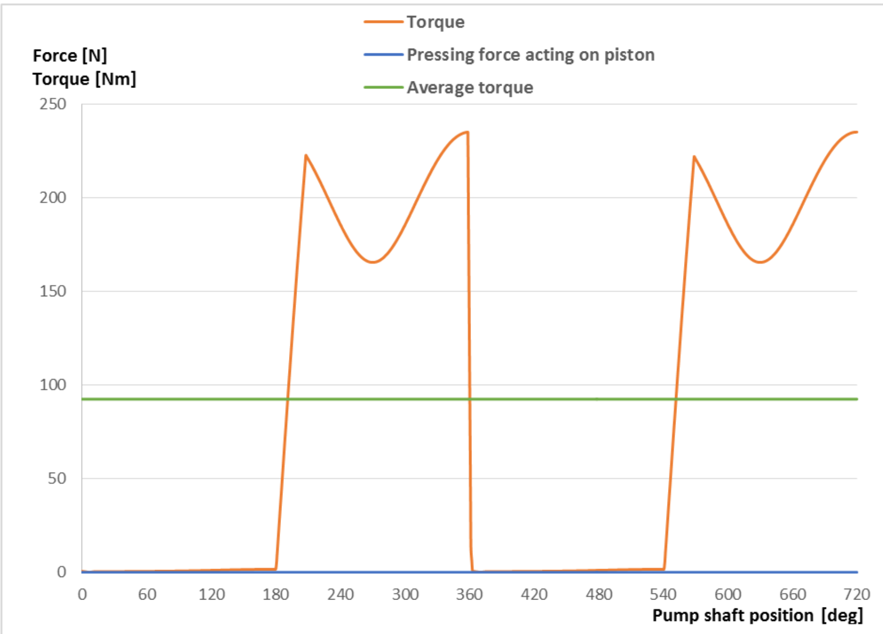

Fig. 5. Progression of pump's drive torque and lateral force acting on a piston and its linear speed

Tab. 1. Comparison between hypocycloid and CPL pump

	Bosch CPL	Hypocycloid pump
Input power [kW]	3.95	14.51
Unit discharge [m3]	0.3 (100% filling)	1.15 (75% filling)
Discharge to power ratio	0.076	0.079

Figure 5 also presents the progression of lateral force in the mandrel – working element pair. Low values within the range of 10-5 N were obtained due to the systems vibrations. In the cam solutions presented earlier, for a cam-plate friction coefficient of 0.01, this force reaches up to several hundred N. Reduction of this force also provides the possibility of applying cheaper materials, which work under elastohydrodynamic lubrication conditions in the mandrel – bearing pair of the working element, besides reducing the adverse impact on wear of elements. DLC (Diamond Like Carbon) coatings are currently applied to cams and pushers, which, due to their high hardness thanks to properties similar to diamond, is wear resistant. High production costs related to advanced technology and the need to employ additional machines are the disadvantages of applying such coatings. In addition, in the case of insufficient lubrication, the surface layer undergo abrasive wear, which leads to contact with the cam's core and seizing of interoperating pairs.

4. Hydraulic booster for hypocycloid pump – application proposal

One of the most important benefits of the pump's design is the high pitch of the working element, equal to the diameter of the large wheel's pitch circle diameter. In traditional CR pumps, the pitch of the working element is no greater than 7-8 [mm]. For the module under consideration, with a transmission ratio of 1 and 40 teeth, the pitch of the working element will be 40 [mm]. Multiplying the piston's pitch while maintaining its diameter makes it possible to obtain much greater discharge per work cycle. In practice, this solution leads to two benefits:

- the possibility of obtaining very small pump dimensions relative to discharge in comparison with conventional cam pumps
- the possibility of significantly reducing forces present in the pump mechanism by using high discharge to generate high pressures by means of a simple, mechanical hydraulic booster. Besides reducing the pump's overall dimensions, reducing forces will make it possible to apply cheaper (poorer) constructional materials.

The idea of a fuel pressure booster assumes the use of a high fuel quantity from hypocycloidal pump to achieve high fuel pressure, in accordance with Pascal's law. The force F exerted on the piston of the surface S at the preset pressure p is equal to the product of pressure and surface. It can therefore be concluded that for a system of two pistons connected through fluid, when the larger diameter piston exerts a certain force, then the pressure applied by the smaller piston must have a greater value in order to maintain the equilibrium within that system. It is therefore possible to multiply the pressure by changing the geometric ratio of both piston-cylinder assemblies forming such system. This feature is particularly advantageous due to the reduction of the force applied to the large piston, and this allows reducing the forces acting on the piston drive system.

The proposed booster as a supplement to the hypocycloid propulsion pump is shown in Fig. 6. The cylinder piston P1 is connected to the drive system and reciprocates inside cylinder C equipped with a valve Z1. As a consequence of the cylinder piston height, in the operating chamber OC1 – on the one side confined by the larger diameter piston LDP and front face of the cylinder piston P2 – pressure is generated causing the fuel flow through the channel C in the head piston P2 and the valve Z2. This results in the filling of the operating chamber OC2 – limited on one side by the head H with the control valve V3 and the smaller diameter of the piston SDP on the other. In addition, when the pressure equalization in the operating chambers OC1 and OC2 is reached, the valve V2 closes. Due to the difference in size of the front face of the larger diameter of the piston and the face of the smaller diameter of the piston, this results in greater force on the front face of the larger diameter of the piston. This in turn causes the piston head to rise to the upper position, which results in further fuel pumping in the head chamber until the control valve V3 is opened and the uppermost position of the cylinder piston reaches the cylinder piston. Then, as the cylinder piston falls down, the pressure in the operating chamber decreases causing the piston head to return to its lower position. When valve is exposed through the piston of the cylinder due to its return flow, the valve opens and the fuel is sucked into the operating chamber.

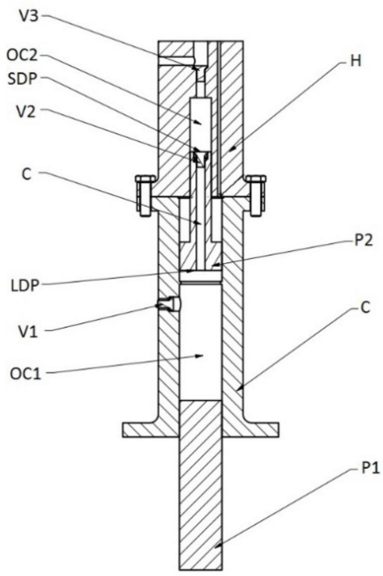

Fig. 6. Schematic diagram of a pressure booster

5. Summary

Injection systems have a significant role to play in improving Diesel engines operating parameters. Due to the high precision of injection process control, with high pressure of fuel compression, these systems are characterized by sensitivity to the quality of applied fuel due to the large forces acting on the system's elements. Numerous design solutions are susceptible to damage resulting from defective design of a given element, besides damage generated by fuel of insufficient quality. In the case of pump defects, leading to the creation of filings with diameters below several micrometres, other elements of the injection systems are also damaged very frequently, which increases repair costs significantly [4]. The modern CR pump should be characterized by resistance to improper fuel quality, high compression pressure and low power consumption [6].

The authors have proposed in their article a hypocycloid drive fuel pump. The benefits presented by the drive system are the advantages of the presented solution both in terms of durability and achieved environmental parameters. The pump uses a hypocycloid mechanism instead of a conventional cam to drive the pumping section, which is lubricated using a separate lubricating oil system. The high stroke of the piston relative to the overall dimensions of the pump optimizes the flow, contributing to the compact size and the reduction in the number of pumping sections even in multi-cylinder engines. This pump is part of the latest trends in the design of high-pressure injection systems. The lack of lateral force contributes to reducing the wear of the walls of pumping section. Due to the different design of the propulsion system, the problem of wear of the cam-piston knob caused by the resulting lateral force, also contributes to the complete damage to the pumps. In addition, the simulations showed that the torque curve does not deviate from the parameters of modern pumps. The large piston stroke of the pump gives the opportunity to create a system where the fuel tank is completely eliminated, which greatly simplifies the engine's layout and contributes to the reduction of harmful hydraulic volume. The direction of further work should be to optimize the flow of fuel in the canals and valve sections. Moreover, the authors have proposed for hypocycloid pump a hydraulic booster – by using such amplifier, it is possible to reduce forces present in the pump mechanism. Besides reducing the pump's overall dimensions, reducing forces will make it possible to apply cheaper (poorer) constructional materials.

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