

Concept of a pump for diesel engines fuel supply using hypocycloid drive

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Abstract. Detailed analysis of modern injection pumps used for diesel engines fuel supply shows that for the most part these structures are far from ideal. Therefore authors of the article proposed a completely novel injection pump construction, which uses hypocyclic gears to drive the piston. The purpose of this article is to present this construction. In relation to existing, classic solutions using a cam drive, the construction of the hypocycloid pump is characterized by the minimization of lateral forces at the interface between the piston and the cylinder of the pump section – this aspect is proven in the article. It is also possible to separate the pressing function from the lubrication function in the pump. In addition – the high stroke of the piston in relation to the dimensions of the pump has a positive effect on the output, enabling reduction of the number of pumping sections even in multi-cylinder engines. In the opinion of the authors, this pump is part of the latest trends related to the construction of high-pressure injection systems.

1. Introduction

A consequence of the pursuit to continually reduce fuel consumption, the toxicity of exhaust emission and quieter operation of diesel engines is a steady increase in requirements concerning primarily their injection systems. These requirements can be complied with injection systems providing very good fuel atomization, very precise fuel dosage and proper shaping of the course of injection and allowing multiple fuel injection. A system that satisfies the above mentioned requirements is the common rail fuel injection system (CR), in which, unlike other injection systems, the fuel is under constant high pressure in the common rail. The CR supply system is composed of three main systems: the low-pressure area (contains the elements of fuel supply), the high-pressure area (includes the high-pressure pump, fuel common rail, injectors with high-pressure fuel pipes), and EDC (Electronic Diesel Control) with executing elements.

The high-pressure pump, whose design and operation is the subject of this article, is one of the most important component of the injection system of the CR type. The purpose of the pump is to generate a suitable high pressure of the fuel in the common rail in each of the engine operating points and in as failure-free way as possible throughout the whole period of vehicle use. The high-pressure pump is driven directly from the engine by a transmission giving a constant ratio (usually 1 to 2 or 2 to 3), namely a chain transmission, a toothed-belt transmission, toothed-wheeled transmission or by means of a connection via the clutch. The power required to drive the pump increases in proportion to fuel pressure set in the common rail and the angular velocity. The increase in demand of power results from the occurring losses generated in the high pressure system caused in particular by the following



increase: the leak off dose, the demand for fuel pressure controlling the work of injectors and the fuel stream hitting the flow-way through the control valve. The power absorbed by the pump under the conditions of nominal characteristics fluctuates within 4 kW, having an overall efficiency at the level of 90%. The maximum fuel pressure generated by the pump ranges from 130 MPa (in the pumps of the older type) to over 250 MPa (in the latest solutions).

Despite numerous undeniable advantages which characterize common rail injection pumps, one should state that they are not devoid of many disadvantages. There are a number of structural and operational problems we deal with in common rail systems. Due to the complexity of the problem, the authors have systematized damage to CR pumps currently present on the market (fig. 1) through detailed and reliable analysis.

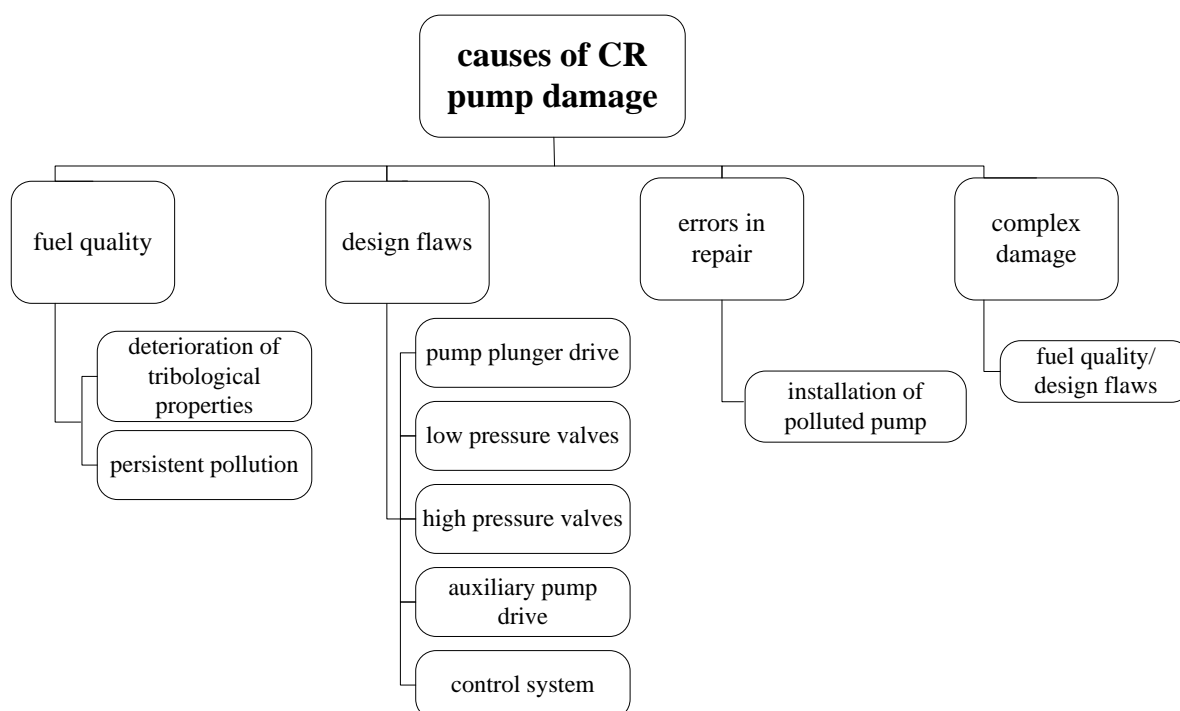


Figure 1. Causes of common rail pump damage.

In the authors' opinion, two problems among those listed required in-depth analysis. The first significant cause of damage in high-pressure pumps is reduced fuel quality. Additionally, fuel quality can be divided into primary and secondary quality. Primary quality is the quality of fuel pumped into the vehicle's fuel tank from the dispenser at the fuel station. Secondary quality is the quality of fuel supplied directly into the high-pressure part of the fuel system (after passing through the low-pressure pump and fuel filter). Several quality parameters are significant to proper pump operation, including water content, content of impurities, lubricity and viscosity. Excessive water content leads to corrosion of the fuel system and rust, or permanent inclusions that lead to faster clogging of the fuel filter, and in consequence, also penetrate into the work area of moving pump parts (between precision pairs T-C, pistons of control valves, valve faces), leading to intensification of abrasive erosion. Analogous phenomena occur when pollution content is too high.

Besides improper fuel quality, design flaws have a marked influence on the reliability of injection pumps. The most common flaws concern the pump piston drive. Such problems are related to, among other things, improper distribution of forces in the section piston – driveshaft system, which arises from the use of camshafts to drive pistons in most cases. This may cause accelerated wear in the area of the drive due to lateral forces. Design flaws result in, among other things: cracking of plates in the Bosch CP1 pump, rotation of the pushrod's roller in the Bosch CP4 pump, and excessive abrasion of

the cam ring in Delphi designs. Damage to low- and high-pressure valves responsible for ensuring that pump parts are properly lubricated are encountered equally often.

A detailed assessment of the subject matter of using CR pumps, the most important aspects of which have been briefly presented below, shows the need to present a completely different design concept of a high-pressure pump. In relation to this, the authors proposed a series of design changes, the most important of which concerns the method of driving the pump and involves the application of a hypocycloid transmission.

2. Pump characteristics

This section presents the most important characteristics relating to the hypocycloid pump. The authors focused on three features: discussion of hypocycloid drive and its basic features, discussion on the possibility of using ceramic materials in pump, and consideration on the possibility of applying the gas desorption effect.

2.1. Hypocycloid pump drive

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 circumference moves in a curve called the hypocycloid. It may have different shapes depending on the selection of the ratio of wheel diameters. In the considered case, a transmission with gear radius ratio $R/r = 2$ was applied. This made it possible to obtain the resultant linear motion – from 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." Figure 2 presents a diagram of the transmission, and the line on which the mechanism's sliding element moves is marked.

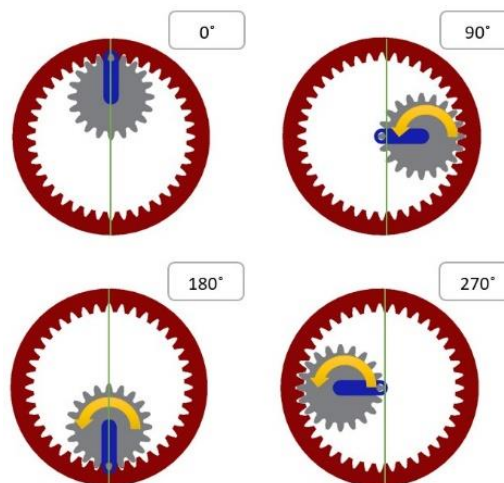


Figure 2. Principle of operation of hypocycloid transmission.

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 defined as follows:

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

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

The above drive concept was used in the pump's design. Several variants were prepared in this regard – figure 3 presents the simplest of them, based on a single pumping section. An assessment of this solution is the focus further in the article.

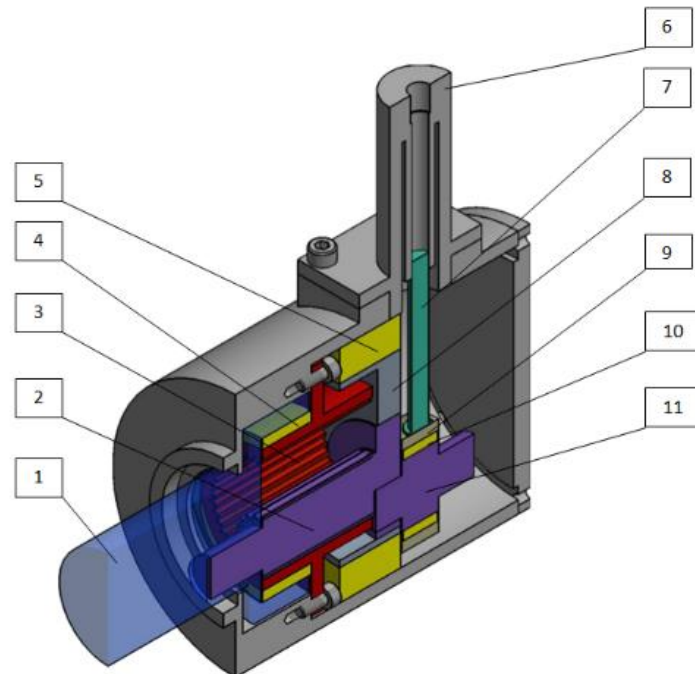


Figure 3. Model of pump with hypocycloid drive: 1 – main shaft, 2 – countershaft, 3 – gear with interior toothing, 4 – main shaft bearing, 5 – support bearing, 6 – cylinder of pumping section, 7 – piston with guiding element, 8 – countershaft support, 9 – mount, 10 – bearing, 11 – mandrel.

The innovative pump drive was realized by means of 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), via bearing (4). A mandrel (11) is mounted eccentrically in the countershaft, and the piston (7) along with the guide element is connected to this mandrel via bearing and positioned so that it can slide in the cylinder (6). Furthermore, the countershaft has a support (8) with bearings in the pump's body - bearing (5).

The above pump model was created in the Autodesk Inventor environment, thanks to which it was possible to perform dynamic simulation of the subassembly. In order to show the characteristics of a hypocycloid pump, the selected relationships were presented on the basis of a comparison with a classic cam drive. The first of the comparisons refers to the movement of the pistons in reference to the angle of shaft rotation in the pumps – figure 4. Analyzing both curves we can notice that they are characterized by a sinusoidal course. In each case, the start position of the piston was the top death center position, but for each type of drive it was at a different distance from the axis of the drive shaft. The position of the piston at the same point of rotation of the driving shaft is different for each of the pumps. In the case of a hypocycloid drive, the displacement of the piston from the top death center position (0° SA) to the bottom death center position (180° SA) is 40 mm. For a classic drive system, the displacement of the piston is equal to 7.8 mm. This means that both types of drives will be characterized by different linear speed of the piston.

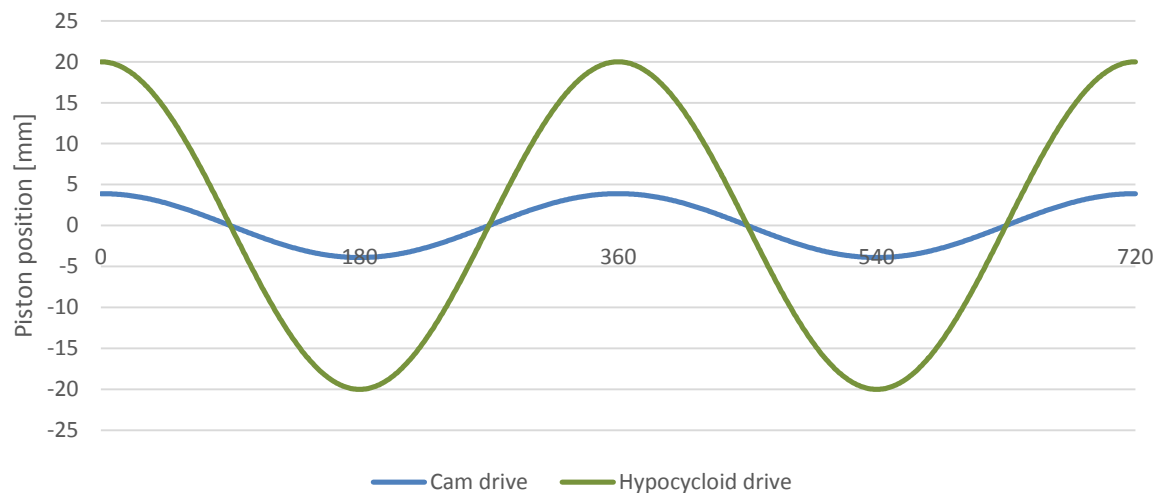


Figure 4. Comparison of the piston position in reference to the angle of the shaft rotation in the cam-driven pumps and the pumps fitted with the hypocycloidal drive.

Velocity is a vector value, so it should be assumed that in the case when it takes values less than zero, the vector's rotation is directed towards the bottom dead center position and consequently, when it takes positive values it has a return towards the top death center position. The initial velocity value for both types of drive is equal to zero, which results from the piston located at the top dead center at the start of the simulation. Additionally, the simulation allows to obtain the maximum piston velocities and accelerations. Therefore, the maximum piston velocity for the hypocycloidal drive is 3.14 m/s i.e. it is several times higher compared to the piston velocity in the cam drive system (0.61 m/s). The maximum values of piston acceleration were determined using the obtained curves of this parameter. For the cam-driven pump, the maximum piston acceleration is 96.23 m/s^2 , and for the pump based on the hypocycloidal drive, the acceleration is 493 m/s^2 .

The simulation also made it possible to compare the torque curve (Figure 5) on the drive shaft. When comparing two types of drives, the torque value can be one of the key elements that demonstrate the superiority of one drive over the other.

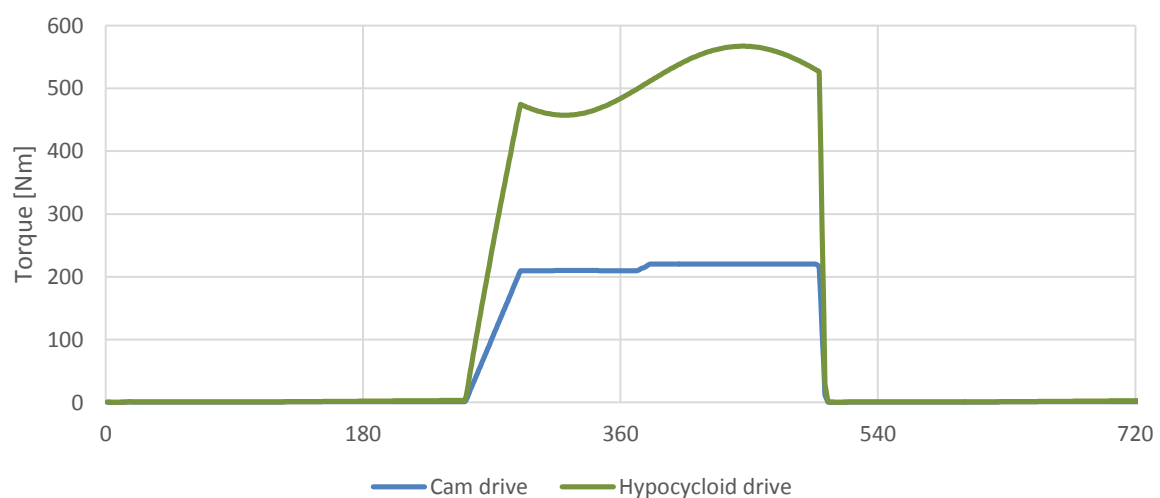


Figure 5. Comparison of the torques on the driving shaft of the cam-driven pump and the pump fitted with the hypocycloidal drive.

The torque results obtained for both cases vary widely, particularly in terms of the differences in the values of the obtained torques. For a conventional drive pump, the torque reached in the pumping phase is almost constant. It achieves a constant value of approximately 210 Nm for the position from 180° SA to 270° SA, then increases to 220 Nm after exceeding 270° SA and remains at the same level until the end of the pumping phase. In the case of a pump with a hypocycloidal drive, the value of the moment in the pumping phase changes. In the initial pumping phase, as in the case of a cam drive pump, we can observe a rapid increase in the moment associated with the compressibility of the fuel. Then the torque value decreases slightly to start to increase and reach its maximum for the position when the shaft has fully rotated. The maximum torque value achieved by a hypocycloidal drive pump is 567 Nm. The torque value changes, most likely due to the change in the distance of the piston fitting point relative to the axis of the drive shaft caused by the action of the hypocycloidal drives.

Modeling of parts' motion demonstrated that force at piston-cylinder contact was completely eliminated in practice. This is a decided advantage over classical systems driven by camshafts, in which the value of the lateral force, for a 0.01 value of the friction coefficient between the plate and cam, reaches up to several hundred newtons (fig. 6). Such values cause so-called snaking of the piston, which may lead to increased wear of the cylinder's side surface and reduce the tightness of the pumping section. Lower wear of parts, but also the possibility of applying cheaper materials for the piston and cylinder, are the result of the force reduction arising from the application of the hypocycloid mechanism.

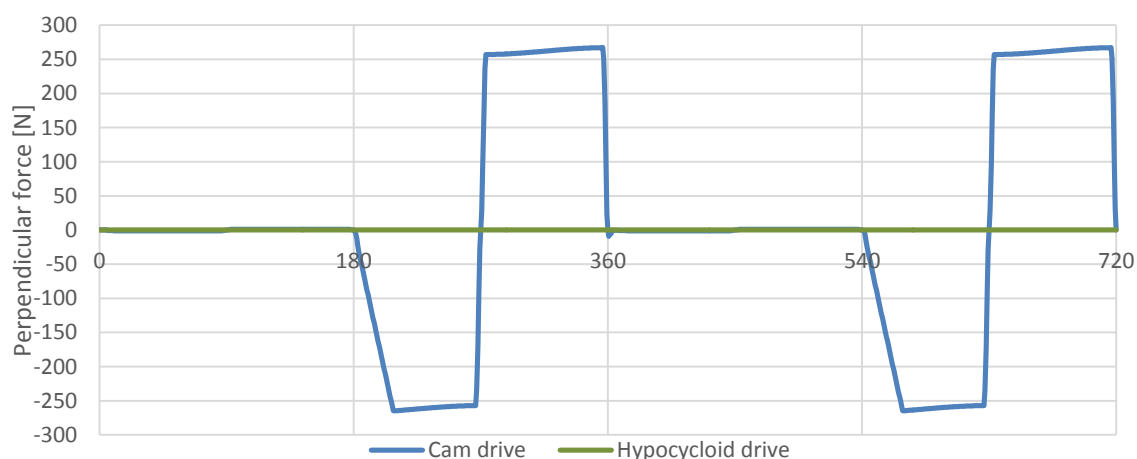


Figure 6. Comparison of force acting on piston perpendicularly to its axis in pumps with camshaft and hypocycloid drive.

As mentioned, the need to maintain high fuel pressure is a significant problem in modern high-pressure pump designs. To eliminate this problem, the creators of the pump decided to separate the pumping function from the functions of lubrication and cooling of the pump's parts – this task was realized by separating the pumping section from the pump's drive. At the same time, the possibility of lubricating the drive system with motor or transmission oil was provided. Such a modification should have a beneficial influence on the lifetime of inter-operating parts, mainly in the area of slide bearings and the gears applied in the solution. This solution makes it possible to pump fuels of varying properties (lubricity, density, viscosity) with respect to conventional diesel oil.

2.2. Possibility of applying ceramics

The minimization of lateral forces affords the possibility of applying ceramic engineering materials as inter-operating surfaces of the piston and cylinder. Ceramic materials are currently interesting as substitutes for the metals traditionally used for engineering applications. This part of paper focuses on a comparison of ceramic materials: corundum (alumina, Al_2O_3) and silicon carbide (solid-state

sintered) – SSiC with bearing alloy steel 100Cr6, i.e. the material used to make pistons and cylinders of pumps in common rail injection systems. A characteristic feature of ceramic materials is their high hardness and the resistance to abrasion that comes with it. They also have good tribological properties – these characteristics are very beneficial from the perspective of parts in the pumping section. On the other hand, ceramic materials have a tendency to undergo brittle cracking due to their limited capacity for plastic deformations, hence their lower impact resistance – in contrast to metals. This is due to the structure of ceramics – covalent bonds are directional. Moreover, ceramics contain defects like cracks, pores and voids, and specimens are destroyed within the elastic strain range [1]. These structural discontinuities contribute to reduced tensile strength and cracking under the action of tensile stresses, lower than assumed on the basis of interatomic bonds. The voids mentioned above then expand, which leads to reduced load-carrying capacity [2]. Therefore, ceramics are characterized by greater compressive strength compared to tensile strength ($R_C \cong 15 \cdot R_m$) [2]. During pumping of fuel, the main type of loads acting on the precision pair are compressive – therefore, it is beneficial to apply engineering ceramics in the pistons of sectional pumps but also in drive rollers (present e.g. in the CP4 pump between the drive cam and sectional piston), since these elements carry compressive loads due to the nature of their work.

Using specialized software (Autodesk Inventor 2017), a model of the pump's piston was built, based on one of the most popular CR pumps available on the market, i.e. the Bosch CP3 pump. With the application of the finite element method and a specialized numerical environment (Nastran in Cad), analysis involving a comparison of ceramic materials and bearing steel was performed. In this regard, analysis of time-variable piston load was conducted from the perspective of the stresses, strains and displacements that occurred – the part of subjected to the highest possible pressure (end of compression stroke) occurring in the CP3 pump, i.e. 180 MPa. The interactions of the cylinder and head on the piston were omitted in considerations. Pressure load was applied to the piston's top surface while the bottom surface of the stem end was fixed in place. Analysis was performed for three materials – example results are presented in figure 7.

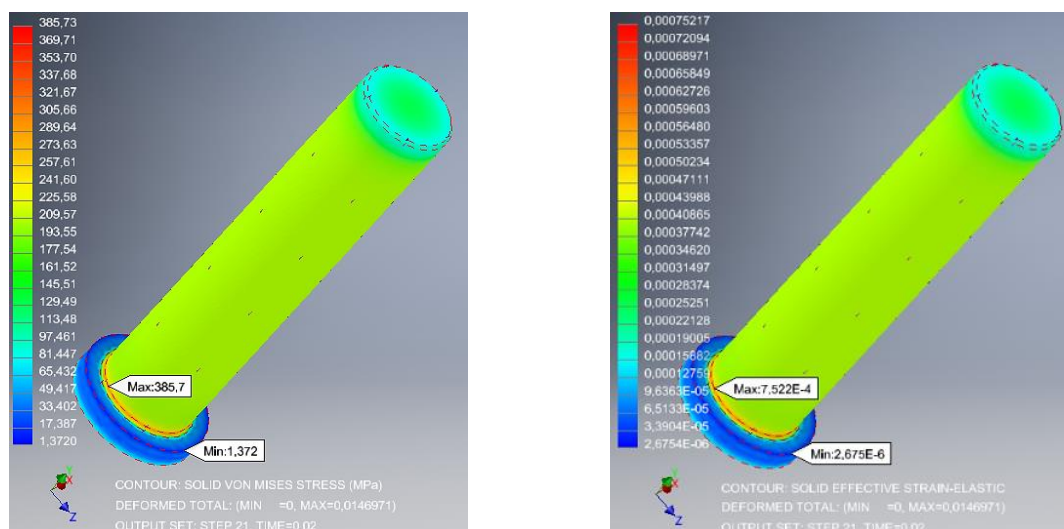


Figure 7. Distribution of reduced Huber-von Mises stresses [MPa] at the instant of occurrence of the highest pumping pressure (left side) and distribution of [-] strains – example results for part made of sintered silicon carbide SSiC.

The maximum stress results show (tab. 1) that their concentration in all variants of the element fell within the area of geometry change. It is worth briefly analyzing the case of bearing steel here. The lowest maximum reduced stress was obtained in this case, since metals are characterized by

Table 1. Results of the analysis.

	100Cr6	Al ₂ O ₃	SSiC
max. red. Huber-von Mises stresses [MPa]	372.8	373.4	385.7
max. strain [-]	0.001539	0.000852	0.000752

an elastic and plastic range, in contrast to ceramics. However, similarly as in the case of other materials, the concentration of the highest stresses and strains occurs near the transition of the piston's geometry to its stem end (area marked in blue – fig. 5). However, in this case, reduced stresses exceed the value of critical stresses calculated analytically according to dependency (3):

$$\sigma_{dop} = (0,55 \div 0,65)R_e \quad (3)$$

$$\sigma_{red} < \sigma_{dop} \quad (4)$$

It can be accepted that for compression, the R_e parameter has similar values determined on the basis of a tensile test. A yield point of 400 MPa was determined in analysis for 100Cr6 steel, for which critical stresses are within the range of 220÷ 260 MPa, according to the dependency given above. The maximum result of simulation reached a value of 372.8 MPa, and condition (4) was not met.

The results of the example simulation also show that the level of strains in materials is lower for ceramics than for the metal they were compared to. This is due to the absence of plastic strains in ceramics under the action of loads, and destruction occurs as a result of brittle cracking. The level of strains in Al₂O₃ and SSiC ceramics was lower by one order of magnitude in this analysis. Therefore, the simulation proves the advantages of ceramic materials over the steels conventionally used as pumping sections. It is a particularly (due to minimization of lateral forces in the piston-cylinder assembly) interesting alternative that is planned for application in the pump with hypocycloid drive.

2.3. Possibility of applying the gas desorption effect

The piston's relatively long stroke is a very important advantage of the pump – its value is equal to the reference diameter of the large gear. For the accepted module of the transmission, equal to 1, the stroke was 40 mm (for comparison, it is 8 mm in traditional CR pumps). In practice, this means achievement of a high discharge per cycle, which makes it possible to visibly reduce the forces present in the pump's mechanism. This task can be realized by using e.g. a simple hydraulic amplifier. The reduction of forces also make it possible to apply less demanding constructional materials. Increasing the piston's stroke simultaneously extended the pumping section. This, in turn, provides the possibility of using a double labyrinth seal additionally equipped with a channel leading off leaking fuel (e.g. to the injectors' overflow hose) – this will make it possible to minimize leakage of diesel oil to the lubricating medium found below it.

The most promising feature of the pump, due to the large stroke of its executive element, being a piston, is the possibility of applying the effect of gas desorption from the solution with nucleation of gas bubbles. This concept involves dissolving gas in fuel by means of an injection pump and then reversing this phenomenon at a later stage and releasing this gas from the solution during its injection. Here, the gas could be exhaust, air or CNG. Such a solution is characterized in that excess dissolved gas is spontaneously released when pressure is reduced, and this process is volumetric in nature. When released from the entire volume, the gas molecules then form scattered microbubbles with a tendency for merging. If a pressure drop occurs dynamically, then the microbubbles will not have time to merge, and their expansion serves as the stimulus for the appearance of additional internal forces, leading to rupturing of microbubbles' surroundings. The desorption effect is based on the release of gas molecules from the solution as well as on expansion and rupturing of the liquid phase's bonds.

The factors determining the occurrence and evolution of the dissolution process are temperature and proper pressure. Under normal, atmospheric conditions, the influence of temperature is significant, since gases' solubility in liquid is greater at lower temperatures. This effect was used in the production of carbonated beverages, during which lower temperature is provided for optimal dissolution of CO₂. The second of the factors mentioned is particularly important: since gases are weakly soluble in liquids, it is necessary to subject both fluids to high pressure. Assuming a constant temperature and that the liquid is an incompressible fluid, the amount of gas that will be dissolved in a given liquid is, in general, proportional to the pressure of this gas. This results from Henry's law, which applies to commonly used pressure values, which accepts Bunsen's absorption coefficient for the set pressure.

$$V_g = \alpha_v \cdot V_{ol} \cdot p \quad (5)$$

where:

V_g – volume of gas distributed in oil

α_v – the Bunsen absorption coefficient

V_{ol} – volume of oil

p – pressure value

It is precisely the pressure of the process that determines the absorption coefficient – the greater the pressure the greater the absorption – defined as the penetration of one substance (atoms) into a substance of continuous phase (gas, liquid) – of gas molecules. An equilibrium state is then achieved under a specific, instant pressure. As gas pressure increases, the number of atoms penetrating into the liquid also rises. Meanwhile, the state of complete saturation occurs when air molecules dissolved in the liquid are in equilibrium with the air molecules above the liquid. The equilibrium state is the state of equalized thermodynamic potential of the resultant solution and gaseous phase. This state, in which all parameters remain constant, is reached under unchanging pressure. It is possible to utilize the potential of this phenomenon when a negative pressure gradient occurs, and thus, in the case of injection of the fuel and gas solution into the combustion chamber – the gas contained in the liquid is then released.

The mechanism of gas desorption from the solution during unbalancing of the equilibrium state may occur in two ways. The cause is the rate of the decompression process, the value of the pressure difference between the state in which equilibrium is maintained and the lower accepted pressure. Hence, the greater the pressure difference, the more dynamic the process becomes [3]. A low rate of the process causes the forming microbubbles, uniformly dispersed in the solution, to expand and merge within the liquid's volume. At a later stage, they are released into the volume occupied by the gas that had previously expanded. Meanwhile, in a dynamic process, the gas also expands within the liquid's volume, but the microbubbles do not merge, instead forming small areas within the entire volume of the solution. The accompanying drop in the solution's pressure causes the gas in bubbles to be decompressed. This increases the volume of bubbles and generates additional internal forces which act in a manner that tears apart the inter-molecular bonds of the liquid. As a consequence, the atomic bonds of neighboring molecules are torn apart, as are the surroundings of the expanding gas [4]. Noticeable turbulence throughout the entire volume is the effect of this dynamic process.

The desorption effect was studied in detail by Kozak [5] – the subject matter undertaken by this author concerned fuel injection in diesel engines. One of the goals of the proposed concept was to achieve fuel spraying of comparable quality to the spraying achieved by high-pressure systems – under the condition that injection pressure was maintained at the relative low level of approx. 50 MPa. In his works, he demonstrated a positive influence on stream spraying and emission of harmful compounds when the effect was used (fig. 8). A special pump making it possible to feed air into the diesel oil and create the solution was used to feed the engine. Its design was similar to the design of a conventional piston pump – the difference was based on different proportions of the piston's stroke to diameter ratio and on the introduction of a check valve through which air was supplied.

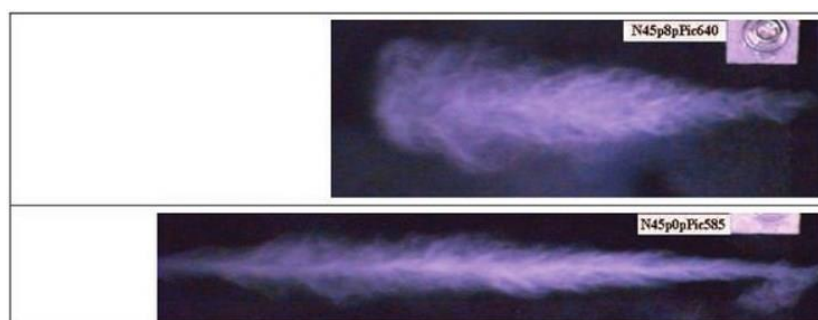


Figure 8. Changes in the shape of fuel streams with the application of the desorption effect (diesel and air – top photo) [5].

3. Summary

The fuel pump concept presented in the article is undoubtedly innovative. This design is characterized by a series of solutions that have not been encountered until now in the field of radial piston pumps. The pump's drive seems to be an interesting solution. On one hand, its greater reliability compared to classical solutions is expected due to the application of toothed wheels. On the other hand, the distribution of forces in the pumping section's system appears to be much more favorable. A characteristic feature of the discussed solution is also the separation of the pumping function from the lubrication function – this solution is intended to allow for the use of other-than-conventional fuels. Moreover, the pump is well suited for the application of engineering ceramics in its pumping section. The most promising aspect, however, is the effect of gas desorption with nucleation of gas bubbles, described in the final part of the article, which can be employed in the pump. All of the above aspects will be analyzed by the Authors – the pump has been made as a prototype at the time of writing of this article (fig. 9).

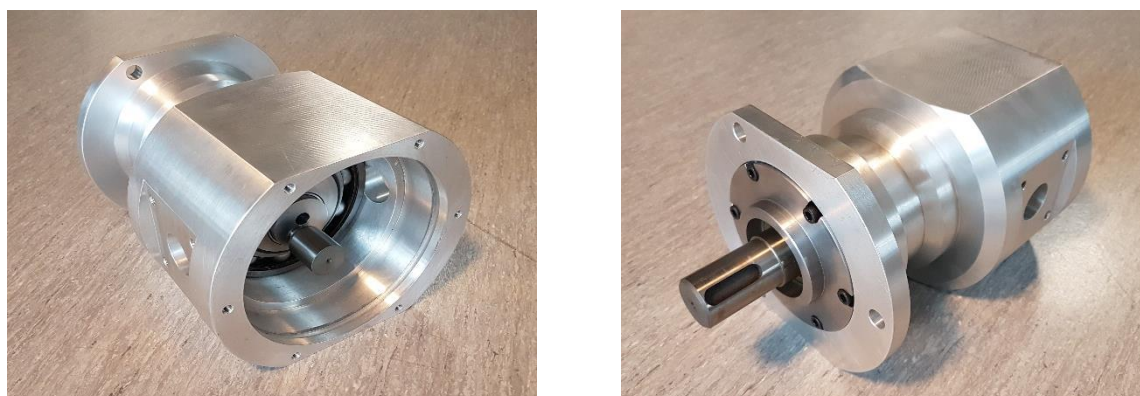


Figure 9. Hypocycloid pump prototype.

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