

Combustion Engine Injection Pump for Non-Standard Fuels (Coal-Water Slurry) – Concept and Design

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ABSTRACT

Diesel engines play a key role in heavy transport, but attempts to power them with non-standard fuels (e.g., coal-water slurry, CWS) encounter serious technical barriers in fuel systems. The article presents a new concept of a hypocycloidal injection pump adapted to power diesel engines with non-standard fuels such as CWS. This solution addresses the operational problems associated with the use of alternative fuels with a high content of water and solid particles, which cause, among other things, accelerated wear of fuel system components, deterioration of lubricating properties, and the need to supply larger doses of fuel due to lower calorific value. The aim of the research was to develop an injection pump capable of reliably feeding a coal-water slurry to the engine while maintaining operating parameters comparable to those of a traditional diesel fuel supply. The hypocycloidal mechanism used, replacing the classic cam, ensures linear piston movement without lateral forces. This made it possible to extend the piston stroke to approx. 40 mm (more than four times longer than in typical pumps) while maintaining the compact dimensions of the design. Thanks to the increased stroke, the pump can inject a significantly larger volume of fuel in a single cycle, which compensates for the low calorific value of CWS and allows the engine power to be maintained. The design also eliminates wear problems caused by fuel abrasiveness and low lubricity. The absence of lateral forces has enabled the use of hard ceramic coatings on the interacting components (piston and cylinder), and a separate lubrication system isolates the pump mechanism from fuel containing water and contaminants. As a result, the developed pump can provide safe and efficient engine fuel supply with non-standard fuels, reducing NOx emissions due to the presence of water in the fuel and extending the service life of the fuel system.

Key words: hypocycloidal pump, diesel engine, alternatives, injection system, coal water slurry

1. INTRODUCTION

Compression ignition (CI) engines, i.e. diesel engines, have been the basis of freight and heavy transport for decades.

Diesel engines dominate in heavy goods vehicles due to their unique characteristics: significant torque available at low revs, high thermodynamic efficiency, durability and economical operation. As a result, vehicles with these engines can efficiently transport multi-tonne loads over long distances, consuming relatively less fuel per unit of work compared to petrol engines. In road transport, this role is irreplaceable – in practice, until recently, diesel engines were the only realistic source of power for lorries and buses in the heavy-duty segment. As recently as 2019, approximately 81% of the energy consumed by the global fleet of buses and heavy-duty vehicles came from diesel fuel [7]. Despite the emergence of alternatives (such as LNG, hybrids and electric vehicles), diesel still accounts for a significant proportion of commercial vehicle propulsion.

The importance of diesel engines also lies in their widespread use in many sectors: from road transport, through construction and agricultural machinery, to shipping and railways. Over 90% of all global transport (including aviation and shipping) relies on petroleum-based fuels [20]. In the case of land transport, the share of diesel is particularly high in the freight segment – for example, in Europe, just a few years ago, more than half of new passenger cars were equipped with diesel engines, and in some countries this percentage reached ~70%. In heavy goods vehicles, on the other hand, almost 100% of the fleet uses compression ignition engines [8]. The reason for this is the mentioned higher efficiency (diesel engines achieve thermal efficiencies of 40-45% in the latest designs, higher than spark ignition engines) and better torque characteristics for heavy-duty tasks.

The significant role of diesel in transport also poses challenges, including those related to the fuels used in engines. Efforts should be made to diversify the use of fuels in combustion engines. Fuel transformation is important from the perspective of global climate policy. Transport accounts for approximately 10% of global greenhouse gas emissions [18] – Figure 1.

In addition, over 90% of the energy consumed in transport still comes from oil [3]. What is more, road transport alone generates nearly 45% of global oil demand [3]. With the

increase in transport (it is estimated that by 2050, demand for freight transport will double compared to 2023 [22]), there is an urgent need to find new fuels. Alternative fuels are therefore seen as the key to sustainable transport development, both in terms of climate protection and energy diversification. However, it is worth highlighting that although some alternatives have already gained a certain market share (e.g. bioethanol in South America, biodiesel in Europe, CNG/LNG in urban transport), a fully equivalent replacement for conventional diesel and petrol has not yet been found. Many promising concepts remain at the niche or experimental stage, and their widespread adoption requires further work on raw material resources and infrastructure [14]. In the search for alternatives to crude oil, not only fuels already in widespread use (such as biodiesel or CNG) are being considered, but also unconventional fuels – less obvious energy carriers, often with difficult physicochemical properties. This category includes, among others, emulsion fuels and suspensions, waste fuels (e.g. used cooking oil, pyrolytic oil) and fuel mixtures containing water. The idea behind them is simple: to use cheaper, readily available raw materials (e.g. coal, biomass, waste) to power engines, while reducing certain harmful emissions. However, practical implementation faces many difficulties related to the storage and feeding of such fuels into the engine.

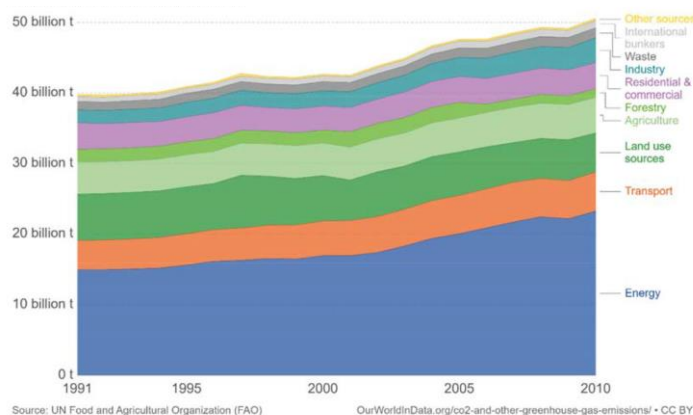


Figure 1: Global warming potential (GWP) in CO₂ equivalent tons by sector [18]

One of the technical difficulties is the issue of fuel storage and transport. Many non-standard fuels have unfavourable characteristics that make them difficult to store in a vehicle. For example, fuels containing significant amounts of water or solid particles may undergo stratification or sedimentation during prolonged storage. In such cases, it is necessary to continuously mix the fuel in the tank or add stabilisers to prevent the heavier fraction from settling. Another problem is the storage temperature range – water emulsions can freeze at sub-zero temperatures, while fuels with very high viscosity (e.g. vegetable oils, fuel oil) require heating before start-up. From a logistical point of view, non-standard fuels often do

not fit into the existing infrastructure – e.g. gaseous fuels require pressurised or cryogenic tanks, and carbon suspensions require special pump/mixer systems. All this means that the introduction of a new fuel involves additional costs and technical complications that do not occur with traditional diesel fuel.

However, the most important and demanding challenges are those related to the fuel supply and injection systems. The greatest difficulties usually arise at the stage of preparing the fuel-air mixture in the engine. Fuels with a viscosity different from that of diesel fuel can disrupt the atomisation process – fuel that is too viscous forms larger droplets, impairing heat exchange and combustion speed; fuel that is insufficiently viscous, on the other hand, may not provide sufficient lubrication for the precision components of the pump and injectors [5]. Lower lubricity is a common problem with alternative fuels: for example, pure FAME biofuel or alcohol fuels have a lower ability to form an oil film than diesel fuel, which accelerates wear on the injection pump's pumping sections. An even more serious challenge is the presence of solid particles or contaminants in non-standard fuel (such as coal in coal-water suspension, ash, sediments). They have an abrasive effect on fuel system components – pumps and injectors designed for clean fuel are subject to accelerated wear with such fuel if appropriate countermeasures are not taken [24]. Another issue is the lower calorific value of many alternative fuels. If the fuel contains a lot of ballast components (e.g. water, solvents), there is less energy per unit volume. In order for the engine to achieve the same power, the fuel system must supply a larger volumetric dose – which often requires enlarging the holes in the nozzles, increasing the pump output, changing the injection strategy (longer injection times), etc. [10]. Such modifications are necessary to maintain engine performance, but they can negatively affect combustion (longer injection = different pressure curve in the cylinder) and emissions.

Undoubtedly, unconventional fuels represent an interesting direction of development as a supplement to classic alternative fuels. They combine potentially low costs and the use of local resources with the prospect of reducing certain emissions, but at the same time place high engineering demands on fuel system designers. It is precisely these requirements that motivate the search for new solutions – such as special injection pump designs – to enable the safe and efficient supply of non-traditional fuels to diesel engines. This article aims to present an original concept for an injection pump adapted for the use of non-traditional fuels. Coal water slurry is presented in the article as such a fuel. Thus, the article shows how such fuel could be used in the proposed concept.

2. HYPOCYCLOIDAL DRIVE PUMP

The internal gearing hypocycloidal gear was patented as early as the 19th century. Depending on the selected ratio of wheel diameters, it allowed for obtaining various curves resulting

from the resultant motion. Its popularity was quite limited due to design and economic aspects. The drives and motors of the time did not transmit high power and torque, and the components were not durable. Therefore, the issue of improving the design of a system that converts reciprocating motion into rotary motion was not as important as it is today. Furthermore, compared to the traditional rack and pinion mechanism, the construction of a hypocycloidal gear was more expensive and difficult due to the high requirements for the gear teeth.

In recent years, there has been a resurgence of interest in hypocycloidal gears [1, 4, 21]. Designers are looking for ways to use them in internal combustion engines, among other things. An example of this is one of Porsche's latest patents, which covers a 6-stroke engine using a hypocycloid [12, 15]. In the work referred to in the article, it was decided to develop a hypocycloidal drive injection pump, which was intended to be a substitute for common rail injection pumps.

2.1 Pump design

Geometrically, a hypocycloidal gear consists of two wheels, the larger one (R) having internal teeth and the smaller one (r) having external teeth. Torque is applied to the smaller wheel, causing it to rotate, while the larger wheel does not rotate relative to the axis. The smaller wheel moves along the circumference of the larger wheel, and a selected point on the radius of the smaller wheel traces a curve called a hypocycloid. In order to create the pump's drive mechanism, a hypocycloidal gear with a gear radius ratio of $R/r = 2$ was used. This selection of gears allows for the resultant rectilinear motion, which follows from Copernicus' theorem: 'If a circle with a radius twice as small rolls without slipping inside a large circle, then any fixed point on the small circle moves in a straight line along the diameter of the large circle.' Figure 2 shows the theoretical assumptions of the mechanism, while Figure 3 presents the concept of movement, i.e. the diagram of the gear operation, and also marks the straight line along which the guide element of the mechanism moves.

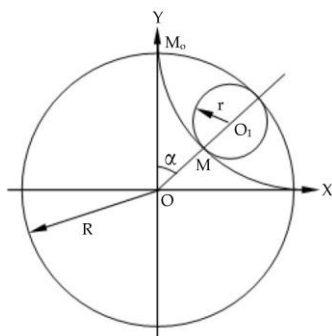


Figure 2: Theoretical assumptions of the hypocycloidal mechanism

The basic principle of operation of the hypocycloid gear in the case under consideration, which eliminates lateral forces in the piston-cylinder assembly, seems to have great application potential. For the above reasons, an attempt was made to apply the solution in the design of an injection pump, which could be a substitute for, among others, pumps used in common rail systems [2].

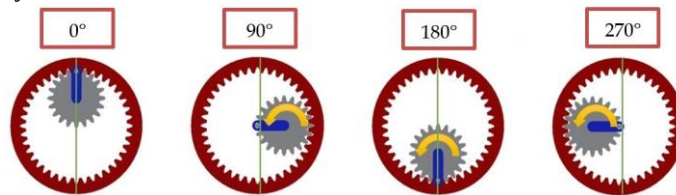


Figure 3: The principle of operation of a hypocycloid gear

Taking into account the hypocycloidal drive, a model of the proprietary pump was created using Autodesk Inventor software (Fig. 4). In the simplest variant with one pumping section, the pump is equipped with a main shaft (1) to which the drive is connected. An countershaft (2) is mounted eccentrically in this shaft in such a way that both elements can rotate relative to each other. The intermediate shaft has an external gear wheel that meshes with a toothed wheel (3) fixed to the pump housing. The support (4) is an element that meshes with the intermediate shaft on the discharge section side. An mandrel (5) is also mounted in the intermediate shaft, which interacts with the mount (6) using a bearing. A piston or, alternatively, a plunger (7) with a guide element is attached to the frame and is slidably mounted in the cylinder of the pressure section (8). The main shaft, support and mandrel are equipped with bearings.

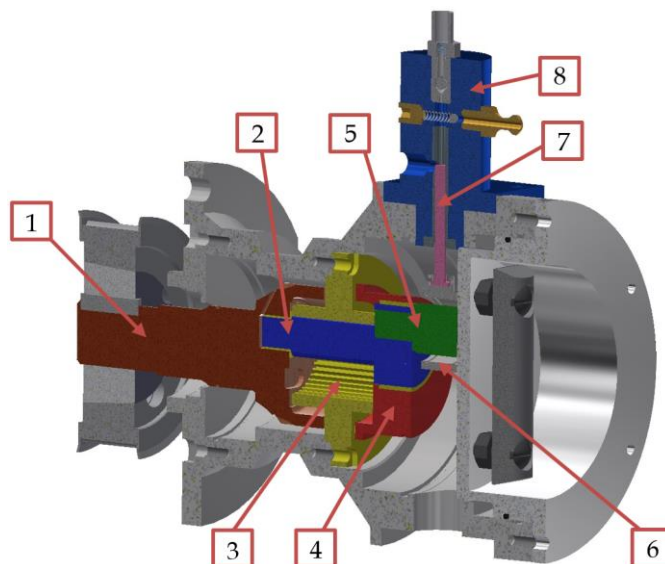


Figure 4: A simplified model of a hypocycloidal pump showing the most crucial components of the design: 1 – main shaft, 2 – countershaft, 3 – toothed wheel, 4 – support, 5 – mandrel, 6 – mount, 7 – plunger, 8 – pressure section

One of the most important advantages of the pump design is the large stroke of the working element, equal to the pitch diameter of the large gear wheel. In traditional common rail pumps, the stroke of the working element is no greater than 7–8 mm. For the assumed gear module and 40 teeth, the stroke of the actuator is 40 mm. Multiplying the piston stroke while maintaining its diameter allows for a significantly higher output per cycle. In practice, this solution can lead to two benefits:

- a) very small pump dimensions in relation to the output compared to conventional cam pumps,
- b) a significant reduction in the forces acting on the pump mechanism thanks to the use of high output to generate high pressures by means of a mechanical hydraulic amplifier.

2.2 Sealing of the pump pressure section

One of the basic characteristics of a hypocycloidal drive pump, resulting from the analysis of modern injection pump designs, is the use of an independent lubrication system. This solution involves the use of gear oil (in an additional circuit) to lubricate the pump components. This makes the lubrication process independent of the pumping process. This minimises the risk of damage to the pump components when using non-standard fuels.

The solution of oil-lubricated pumps was implemented in serial production (e.g. Bosch CP2 pumps), but practical use showed that these pumps had a common, very unfavourable feature. Due to the high pressures in the accumulator chamber, they were characterised by very high fuel leakage into oil-lubricated mechanisms. The lubricating medium, when combined with fuel, largely lost its properties and did not provide adequate protection for the interacting components. This phenomenon was particularly disadvantageous in pumps that used the oil circuit of an internal combustion engine. Leaks in the pump section led to the dilution of the engine oil, consequently increasing its volume and making it necessary to replace it. In the event of neglecting daily vehicle maintenance, which includes checking the oil level, this could even lead to damage to the car engine.

Due to the significant practical problems involved, this issue had to be examined in detail in order to propose a solution that would provide a high degree of certainty. To this end, studies were undertaken on the subject [16, 23, 26] and unusual designs of injection pumps used in combustion engine fuel systems were analysed. The pump manufactured by Hammelmann proved to be very interesting. This company manufactures high-pressure piston and rotary pumps capable of pumping various types of media (from rare liquids, e.g. methanol, to dense liquids, e.g. asphalt suspensions). The maximum delivery pressure of the pumps reaches up to 350 MPa, with a flow rate ranging from 100 l/min to 3000 l/min. The design and principle of operation, together with a

description of the individual components, are discussed using the example of the HDP series 2 pumps, and a cross-section of the pump with a description is shown in Figure 5.

Firstly, it should be noted that this is a plunger-type pump driven by a crank mechanism. The suction valve (3) and high-pressure outlet valve (1) are located in the head (2). The medium to be pumped enters the suction chamber (4), which has a relatively large capacity. This chamber is completely isolated from the crankcase (14) in terms of flow, and the thick walls of both bodies also provide thermal insulation. This solution makes it possible to pump media with high temperatures or high chemical aggressiveness. Filling the suction chamber with the pumped medium necessitated the use of a sleeve (5). Inside it, a labyrinth seal system (6) is installed, which cooperates with the cylindrical surface of the plunger (7) made of engineering ceramics. An additional low-pressure seal package (8) is installed between the crankcase (14) and the sleeve (5). It should be noted that in order to ensure good access to the interior of the pump during maintenance, the interior of the crankcase has been divided in such a way that the lubricating oil for the crank system does not occupy its entire volume. This solution required the use of an additional bellows seal (9), which isolated the interior of the crankcase from external conditions. The part of the crankcase responsible for power transmission contains a guide (10) that works with the connecting rod (11), which in turn works with the crankshaft (13). The shaft is connected to an external power source by means of a gearbox (12).

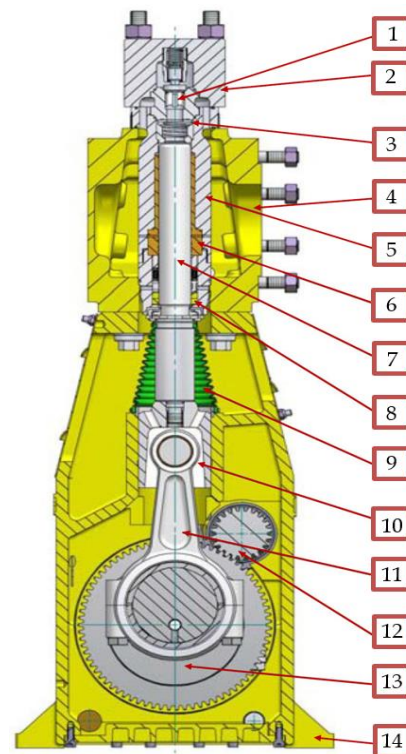


Figure 5: Hammelmann HDP Series 2 pump model [17]
(description in text)

When analysing the manufacturer's materials [9], it is worth paying attention to several elements and components of the pump in question due to their significant similarity to pumps used in common rail systems. In the design of the discharge section, it is notable that tightness is ensured at very high pressures (380 MPa). Examples of labyrinth seals used in Hammelmann HDP pumps depending on the maximum pressure are shown in Figure 6.

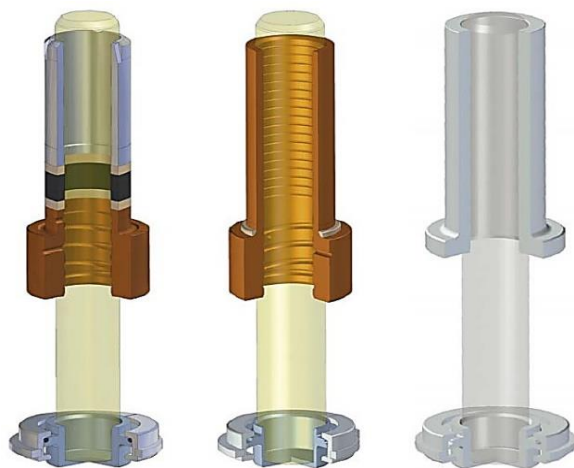


Figure 6: Labyrinth seal packages used in Hammelmann HDP pumps depending on maximum pressure values [9]

A similar solution was adopted in the hypocycloidal drive pump (Fig. 7). The use of labyrinth seals in the discharge section is a good way to ensure tightness at high pressures. However, it does not fully solve the problem of fuel leaks mentioned in the introduction to this chapter. This drawback can be significantly relieved by using a proper sealing system for the discharge section, together with the removal of any leaks from the sealing space. Due to the very high pressures, only a linear seal can be used, while maintaining a very high tolerance for the cylinder and piston. However, the linear sealing system does not completely prevent leaks, as the fuel accumulated in the channel may adhere to the side surface of the piston due to cohesive forces and be transported downwards, outside the sealing area, and thus enter the piston drive shaft space. Therefore, this system should be supported by draining the accumulated leaks using a drain, on which a pipe connected to a system with a pressure lower than atmospheric pressure is mounted, which generates negative pressure in the sealing channel area.

It should be noted that the volume of fuel leakage is closely related to the instantaneous pump output, back pressure and shaft speed. During the compression stroke, fuel is squeezed to a volume resulting from the difference in diameter between the piston and the cylinder. When the piston rises, the movement of fuel into the lower area of the space is counteracted by its movement, lifting fuel particles upwards by means of cohesive forces. After passing through the upper dead centre of the piston, the fuel is transported down the cylindrical surface

using the same phenomenon. To prevent it from leaking into the pump section drive mechanism, a linear seal is used, which is a groove formed on the surface of the cylinder section.

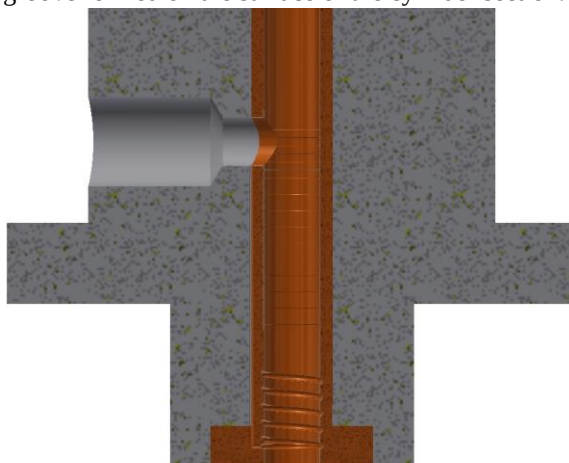


Figure 7: Fragment of a model of the pressure section of a pump with a hypocycloidal drive

In a classic linear seal arrangement, fuel leakage is collected in the sealing gap during the downward movement of the piston, while the upward movement causes the fuel to be taken from the edge and pressed back into the piston-cylinder area. The volume of fuel forced into the seal is the result of many factors and varies for each compression cycle, which is a disadvantage of this solution. If the volume of fuel exceeds the capacity of the sealing ring, the excess is transported to the lower area of the piston, from where it enters its drive mechanism. For this reason, it is advantageous to use a suction mechanism, which in practice prevents the maximum volume of the sealing groove from being exceeded by removing the accumulated fuel from it. It is important that there is a vacuum in the sealing groove to overcome the cohesive forces and the forces that take away the fuel during piston movement.

In this regard, a proprietary patented solution was used [11]. In addition to the use of a vacuum pump, negative pressure in the fuel system can be achieved by using a Venturi nozzle in the injector overflow line. Appropriate modelling of the nozzle geometry allows the desired negative pressure range to be achieved. By changing the ratio of the cross-sectional area of the supply line to the minimum diameter of the venturi, the correct vacuum value is obtained in accordance with Bernoulli's principle. An advantageous feature of the Venturi nozzle is that the aforementioned vacuum range for its fixed geometry will change with the change in fuel mass flow rate. The higher the vacuum obtained in the vacuum line, the greater the fuel flow that can be collected from the sealing area. The fuel flow in the overflow pipe will increase with increasing load, i.e. with increasing fuel dose and pressure. As mentioned earlier, the same factors contribute to an increase in leakage from the delivery sections, so it can be concluded that the natural operating characteristics of the Venturi tube correspond to the nature of the leakage changes.

The disadvantage of the fuel leak suction mechanism is that it significantly reduces the volume of fuel forming a lubricating film in the piston-cylinder area. This worsens the operating conditions of the precision pair, which is why it is important to introduce changes that will reduce the wear of the interacting components. The working conditions of the piston-cylinder pair can be improved by applying engineering ceramics to the surface of the cooperating elements. A significant increase in the surface hardness of the material has a positive effect on reducing wear. The use of this material seems particularly justified in a hypocycloidal drive pump, in which the drive section does not generate a force normal to the direction of fuel delivery, thus increasing the durability of the sputtered ceramic layer.

The author's solution for a vacuum sealing system for the pressure section of a high-pressure fuel pump uses peripheral linear seals formed on the surface of the pressure section cylinder. Between them there is a collection channel, which acts as a drain connected to the vacuum generating system pipe. This arrangement allows fuel leaks from the linear seals to be drained away. Figure 8 shows a schematic diagram of the solution. It is assumed that this system consists of a suction pipe (1) which is the overflow pipe for the injectors. A Venturi nozzle (2) is located in this pipe, to which a vacuum pipe (3) is connected, which is directly connected to the drain (4) of the collection channel (5) that drains leaks from the linear seal (6). This system is built into the cylinder (7) of the pressure section, in which the piston (8) moves.

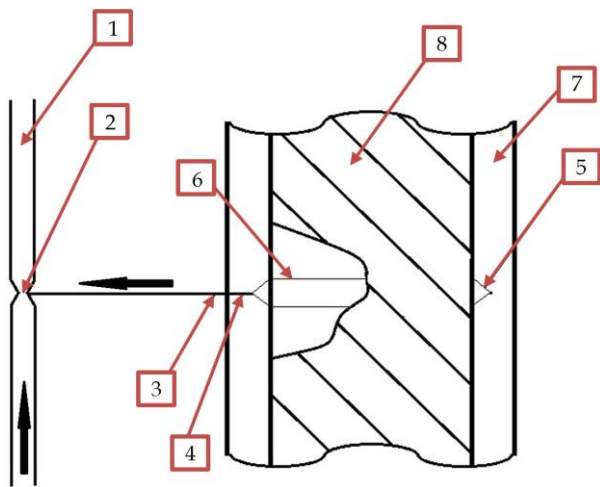


Figure 8: Conceptual diagram of the sealing method for the high-pressure discharge section; 1 – suction pipe, 2 – Venturi nozzle, 3 – vacuum pipe, 4 – drain, 5 – collection channel, 6 – linear seal, 7 – pressure section cylinder, 8 – piston [11]

3. USE OF A HYPOCYCLOID PUMP FOR UNUSUAL FUELS

Coal-water slurry (CWS) is a mixture of crushed coal in the form of particles of various sizes (1–200 μm) and water. The

proportion of coal in the suspension and the fineness of the particles vary within the mixture. These parameters have a significant impact on the nature of the combustion process and are largely dependent on the device in which the suspension is burned. The process of obtaining the suspension is two-pronged. For research purposes, CWS is most often obtained by physically mixing water with carbon particles. The grain size is determined by grinding the carbon particles using appropriate technology (mechanical mills, hydraulic methods). At the same time, the water is activated in order to obtain the correct stability of the solution. The prepared components are mixed together and stored for up to 7 days. In order to extend stability, a mixing process is used, which effectively extends the storage time. An important difference between crude oil and the suspension is the calorific value, which is approximately 20–21 MJ/kg, depending on the ratio of water to carbon. This means that in order to obtain similar engine parameters, it will be necessary to increase the amount (volume) of fuel injected in a single cycle. It can be concluded that the physical characteristics of the carbon-water suspension (Table 1) make it an attractive fuel for powering engines [6].

Table 1: Selected CWS and diesel fuel parameters [19]

FUEL		CWS	DIESEL
parameter	unit	value	
coal share	%	35–55 (mass)	80–88% (element)
calorific value	kJ/kg	12600– 18900	42300
kinematic viscosity (40°C)	mm ² /s	1,5 – 2,5	2 – 4,5
density	kg/m ³	1180–1220	820–845
storage temperature	°C	5 – 60	> -15
grain size	μm	0,5 – 120	
durability	days	3–24	150

3.1 Selected pump features in terms of CWS pumping

The hypocycloidal mechanism is a completely different idea for controlling the movement of the pump piston compared to the traditionally used cam. Changing the forcing element makes it possible to use materials and solutions that are impossible or difficult to adapt in classic common rail pumps. It turns out that increasing the piston stroke, separating the lubrication system from the fuel supply system, or significantly minimizing the lateral forces acting on the plunger significantly increases the application potential of the hypocycloidal pump in terms of pumping difficult fuels. One of the most important advantages of the pump design is the large stroke of the working element (piston or plunger) while maintaining the small dimensions of the pump, which is equal to the pitch diameter of the large gear wheel. In traditional CR pumps, the stroke of the working element is no more than 7–8

[mm]. For the assumed hypocycloid gear module of 1 and the number of teeth of 40, the stroke of the actuator is 40 [mm]. Multiplying the stroke of the piston while maintaining its diameter allows for a significantly higher output per cycle. This feature is particularly important when using carbon-water suspensions. Depending on the carbon content, these fuels have a calorific value not exceeding 20 MJ/kg for a 45% content. In practice, this means that in order to obtain a similar amount of energy in the combustion process, more than twice as much fuel must be supplied to the engine during the working stroke than in the case of diesel combustion. In addition, by using a pump output that is more than four times higher than conventional solutions, it is possible to relatively easily adapt the engine to the variable quality (calorific value) of coal-water fuel, resulting from the use of different types of coal and changes in the mixture ratio. On the one hand, the high water content in the fuel is a factor that prevents high cylinder pressures from being achieved, but on the other hand, it enables a significant reduction in nitrogen oxide emissions (Fig. 9).

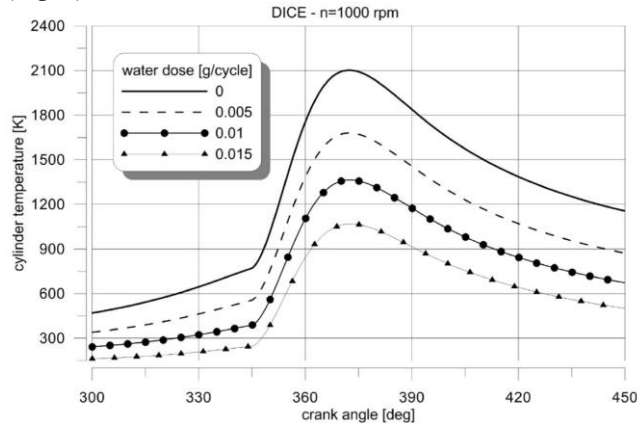


Figure 9: Variation of cylinder temperature for different water doses at 1000 rpm with constant coal dose [13]

Another effect of achieving a large piston stroke is the ability to easily utilize and control the implosion effect. This effect involves introducing liquid and gas into a single space, where the gas is dissolved in the liquid as the pressure increases due to a reduction in volume. During the injection process, when the pressure drops, the gas is released from the liquid, which has a positive effect on the atomization of the fuel stream, improving fuel spray. Thanks to the increased stroke and thus the increased volume of the section, it is easy to influence the parameters of the fuel and gas mixture. For CWS, fuel viscosity is an important parameter determining the injection process. The second important parameter for determining the characteristic values that define fuel atomization is its density. This parameter is approximately 1200 kg/m³ for the above-mentioned mass compositions. It is therefore significantly higher than for commonly used diesel fuels (approximately 835 kg/m³). In view of the above, the use of the implosion effect seems to be particularly beneficial in the case of CWS. This fuel is a mixture of liquid and solid phases, which worsens combustion conditions. The implosion effect

makes an important contribution to improving the quality of fuel injection and, consequently, the quality of its combustion [25].

The proposed pump solution eliminates the problem of lateral forces in the drive system. For the cam drive of the pump, the lateral force on the piston reaches values of up to 300 N. In addition to increased wear in the cam-piston (push rod) area, there is unfavorable piston skewing, leading to increased wear on the side surface of the cylinder and thus reduced section tightness. Many pumps use an additional guide element that is loaded with lateral force, but this solution is disadvantageous due to the increased number of friction pairs and the inertia of the moving parts. Due to the absence of lateral forces, it is possible to use ceramic engineering materials for the mating surfaces of the piston and cylinder. When pumping low-quality fuels, such as CWS, the hard surfaces of the ceramic layers help to reduce the wear of the precision piston and cylinder pair caused by carbon microparticles and organic contaminants. It is also important for the engine supply using a hypocycloidal pump to cover the surface of the pump valves with a layer of ceramic materials. The rapid and turbulent flow of the suspension during the suction and compression strokes of the pump, determined by the large piston stroke, causes very unfavorable abrasive phenomena, the impact of which can be significantly reduced by covering the above-mentioned elements with a sprayed ceramic layer.

As mentioned earlier, in the hypocycloidal pump solution, the piston drive has a separate lubrication system. As part of the external lubrication system concept, the idea of using oil from the internal combustion engine circuit was rejected. Despite the simplicity of the solution, it is disadvantageous from the point of view of contaminants present in the lubrication circuit and insufficient oil pressure in the bus, resulting from the location of the pump in the upper part of the engine. The proposed system includes an electrically driven oil pump. Thanks to this, in combination with the temperature control system, it is possible to adjust its output to the current load on the mechanisms and regulate the operation of the fan within the heat exchanger (Fig. 10). Synthetic gear oil, adapted to carry large, variable loads, has been proposed as the lubricant. All pumps currently used in motor vehicles are lubricated with pressurized fuel. In practice, this means that it is not possible to pump fuels such as carbon-water suspension or even other difficult fuels, for which the lubricity parameters and the presence of particles will prevent the correct operating conditions from being achieved. The use of a separate lubrication system avoids the problem of powdered carbon deposits in the pump bearings, oil channels, tooth foot edges, and other points of the mechanism ensuring piston motility. High unit pressures resulting from back pressure in the case of a classic cam-eccentric shaft pair in the presence of CWS will contribute to a very rapid process of destruction and scuffing of sliding surfaces.

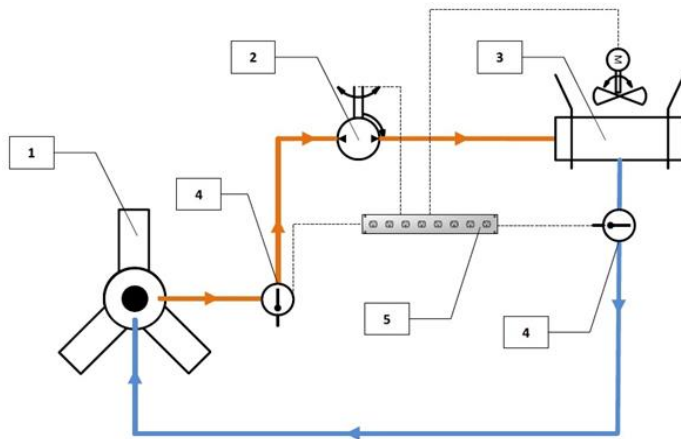


Figure 10: Lubrication system design: 1 – fuel pump, 2 – oil pump, 3 – heat exchanger with fan, 4 – temperature sensors, 5 – lubrication system control unit

4. CONCLUSIONS

The proposed hypocycloidal drive injection pump has a number of significant advantages in the context of supplying diesel engines with non-standard fuels. The most important of these is the multiple increase in fuel delivery efficiency per cycle thanks to the extended piston stroke – the pump can deliver more than four times the volume of fuel in a single stroke than standard systems. This enables the engine to be efficiently powered by fuels with reduced calorific value (e.g., CWS) without any noticeable loss of performance. Another advantage is the elimination of lateral forces acting on the piston, which reduces wear on friction elements and allows the use of high-hardness materials (e.g., ceramic coatings) on working surfaces. In combination with a separate lubrication system, which makes the pump independent of the lubricating properties of the fuel, this translates into a significant increase in the durability and reliability of the fuel system when operating with fuels with low lubricity and contaminated with particles. In addition, the large volume of the delivery section makes it possible to use the so-called implosion effect (dissolving gas in fuel under high pressure and rapid release during injection), which promotes better atomization of the fuel mixture and more efficient combustion of fuel suspensions.

Naturally, the use of fuels with different physical and chemical properties determines the need to modernize the engine and its accessories. The corrosive effect of water or intensive abrasive processes resulting from the presence of grains necessitate a change in the materials used and the operating concept of individual devices. From the point of view of the combustion process, it is very important to ensure the correct fuel supply parameters. The proposed solution of a hypocycloidal pump fits perfectly into the topic of broadly understood difficult fuels. High pump output, no impact of fuel on the piston drive mechanism, and the use of super-hard, abrasion-resistant

materials are just some of the many features that make the innovative hypocycloidal pump solution ideal for use in engines powered by difficult fuels.

Thanks to the above features, the hypocycloidal pump opens up new possibilities for the practical use of non-standard fuels. It can be used in vehicles and work machines, as well as in stationary industrial engines and generators, enabling the use of cheaper, locally available fuels (e.g., coal-water emulsions, waste fuels) without negatively affecting engine performance. This solution allows for the diversification of energy sources through the use of alternative fuels while maintaining high energy efficiency and engine performance. At the same time, it reduces the emission of harmful exhaust components (including a significant reduction in NO_x thanks to the high water content in CWS) and extends the life of the fuel system. As a result, the proposed pump eliminates key technical barriers associated with the operation of diesel engines powered by difficult fuels, which may accelerate the widespread use of these fuels in transport and energy.

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