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Conversion of an internal combustion engine to supply of hydrogen or other gaseous fuels

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The article contains practical knowledge on the process of converting a compression-ignition combustion engine to various types of gaseous fuels, including hydrogen. The content of the article is related to the completed project of this type of adaptation of an industrial engine. The process of preparing a gaseous fuel combustion system, the design of the ignition, power supply, safety, and power regulation systems are described. The basic functions of the adaptive engine control system are presented, which allow for the adjustment of its control parameters to the physicochemical properties of the gaseous fuel used. The preliminary results of tests of the engine powered by hydrogen or natural gas are also presented.

Key words: *hydrogen, spark ignition engine, conversion, adaptive control system, natural gas*

1. Introduction

In the era of searching for new sources of power for vehicles and machines, the use of hydrogen as a new energy carrier in transport is a very promising solution [14]. In the transition period, hydrogen can be used as a fuel in commonly known internal combustion engines (ICE), creating a bridge between traditional motorization and modern drive systems with hydrogen fuel cells. It can also help in building hydrogen distribution infrastructure and in shaping social awareness of the new energy carrier. A major advantage of hydrogen is the lack of geopolitical limitations, because hydrogen is not a fossil fuel dependent on local natural resources, but can be produced anywhere on the globe where we have access to water and electricity [5]. Hydrogen can be used in all transport sectors, both in wheeled [11, 12] and rail vehicles, in maritime transport [10], as a drive for industrial machines, and also as aviation fuel. When powered by hydrogen, the problem of vehicle range disappears, and its operation does not burden the environment. In practice, the conversion of IC engine to hydrogen fuel is a complex task, requiring interference in both the engine design and the control system, and this applies to all engines, both compression-ignition, spark-ignition, and engines powered by gaseous fuels. Due to the large scope of necessary changes, the conversion of an engine to hydrogen fuel is not possible using methods known from the practice of conversion to fuel with gaseous fuels such as natural gas, biogas, or propane-butane. In this case, the preparation of the engine to hydrogen fuel should be carried out in the process of its production [6, 7, 15].

In the Department of Automotive Vehicles of Cracow University of Technology, the first works on hydrogen fuel supply for ICE were carried out in the 1980s, a team of scientists led by Prof. Kordziński on the hydrogen drive of IC engines [8, 9]. Their continuation was the implementation in the years 2012–2018 of the project: "Use of waste hydrogen for energy purposes", in which a power plant with a rated power of 1 MW was developed and built, powered by waste hydrogen from the chemical industry [1]. The main difficulty in using this fuel to power engines was due to the contamination of hydrogen with various hydrocarbons and the frequent and rapid changes in the gas composition. For instance, the share of hydrogen varied from 60 to 90% in a time shorter than 1 minute [4]. The power plant consisted of three SI engines with a power of: 2 × 400 kW, 1 × 200 kW, equipped with an innovative hydrogen injection system, a system identifying the quality of the supplied hydrogen and a remote control and monitoring system [2, 3, 13]. The extension of this project is the work carried out since 2020, concerning the modernization of the hydrogen injection system of IC engines and the control system and operational safety systems, including the development of our own, electronically controlled systems of the mixing and injection system of the hydrogen engine supply system. The results of this work were used in the adaptation of a modern, 5-cylinder industrial engine from the Scania company to hydrogen supply.

2. Theoretical considerations

The basics of the operation of piston combustion engines powered by hydrocarbon fuels are based on the use of the exothermic oxidation reaction of hydrocarbon fuel, which supplies heat to the working medium. The main working medium of IC engine is always atmospheric nitrogen, regardless of the type of hydrocarbon fuel or alcohol used (Fig. 1). The share of the remaining components of the working medium, which are products of complete combustion, such as CO_2 and H_2O, varies depending on the share of carbon and hydrogen in the fuel molecule, and the share of oxygen is significant only in relation to compression-ignition engines. The gaseous toxic components included in the working medium do not play a major role in terms of its operating parameters.

In the case of fueling the engine with hydrogen, the composition of the working medium changes, with atmospheric nitrogen still being the main working medium, but the share of the remaining components changes, among which there is no CO_2, while the share of oxygen depends on the excess air coefficient used when fueling the engine with hydrogen (Fig. 2).

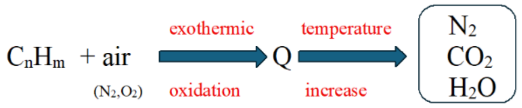

Fig. 1. Schematic diagram of the combustion process of hydrocarbon fuels in a combustion engine

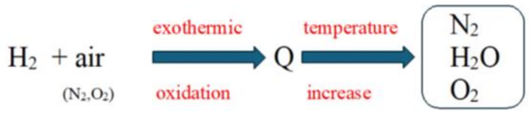

Fig. 2. Schematic diagram of the hydrogen combustion process in a combustion engine

An important factor influencing the heat flow rate released during combustion is the amount of oxygen in the cylinder. Therefore, the volume fraction of fuel in relation to the volume of air is very important (Fig. 3). In this case, hydrogen is not a good fuel compared to other fuels, especially gasoline. Therefore, a lower unit power of the engine should be expected.

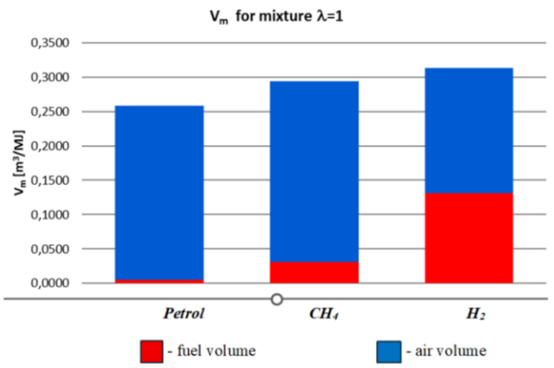

Fig. 3. Volumetric share of fuel in the stoichiometric mixture related to the energy unit

Another unfavorable feature of hydrogen is the course of the combustion process, which takes place at a very high speed and, in the internal combustion engine, leads to combustion anomalies and the impact effect of the gas force on the piston crown. Therefore, the only parameter that effectively influences the control of the flame movement in the combustion chamber of the piston internal combustion engine is the value of the excess air coefficient in the hydrogen-air mixture, and also, although to a lesser extent, the value of the ignition timing.

All of the above-mentioned features of hydrogen supply to the internal combustion engine create specific problems that must be addressed when undertaking the conversion of a specific type of engine.

3. Conversion of an internal combustion engine to hydrogen fueling

3.1. Research object

The object of the research and conversion to hydrogen power was an industrial engine type DI09 074M manufactured by Scania. It was a 4-stroke, turbocharged, diesel engine designed for marine applications. Basic technical data of the engine is as follows:

- Number of cylinders – 5
- Displacement – 9.3 L
- Cylinder bore × stroke – 130 mm × 140 mm
- Compression ratio – 18
- Rated power – 199 kW
- Pistons made of aluminum alloy
- Toroidal combustion chamber
- 4 valves per cylinder
- Fuel supply system – electronically controlled unit injector system
- Individual cylinder heads and wet cylinder liners
- Electrical installation voltage – 24 V
- Engine weight (with oil and coolant) – 1150 kg.

3.2. Combustion system

The basic task of converting the engine to hydrogen power is to develop a new combustion system. In the standard version, the engine is a compression ignition unit equipped with toroidal combustion chambers located in the piston. Changing the engine's operation from compression ignition to spark ignition requires significant design changes to the combustion system. In addition to the need to place a spark plug in the combustion chamber, it is necessary to reduce the compression ratio and use a combustion chamber with different geometric parameters. For this purpose, a design analysis of the existing combustion system in the engine was necessary, the result of which determined the possibility of converting the existing structure to power gas fuels, especially hydrogen.

This analysis required dismantling the engine, consisting of removing the heads and pistons. The measurements of the geometry of the channels in the cylinder head, intended for mounting the injectors, showed the possibility of mounting the spark plugs and placing integrated ignition system modules, consisting of spark plugs and high-voltage coils.

The piston structures of the converted engine were subjected to a detailed analysis. On the one hand, an analysis of the piston design was carried out, paying attention to the type of material, the location of the cooling channels, and the thickness of the walls subject to processing.

The standard engine piston (Fig. 4) was equipped with a typical, toroidal chamber combustion, commonly used in compression-ignition engines.

Due to the combustion process in the spark-ignition engine, it is necessary to design a new shape of the combustion chamber and reduce the compression ratio. Based on theoretical knowledge and design experience, a combustion chamber placed in a so-called cup-shaped piston was selected, which, thanks to the large surfaces of the squeezing zone in the final phase of the compression process, guarantees high charge swirl. At the same time, this type of conversion of the standard piston allows for selecting the appropriate compression ratio value. Figure 5 shows the design of the piston intended for the engine powered by gaseous fuels and an executive drawing showing the basic dimensions in relation to the standard version, necessary for the conversion process.

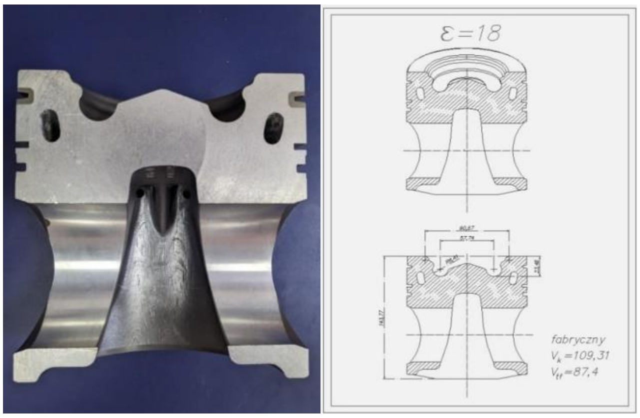

Fig. 4. Inventory of the standard engine version – the piston cross-section

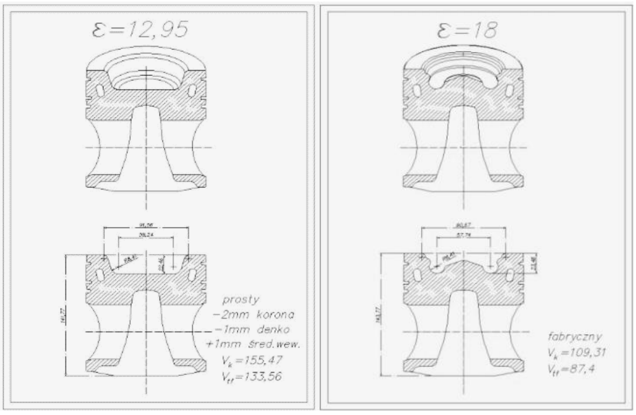

Fig. 5. Design of the engine piston for an engine powered by gas fuels, including hydrogen, and a production drawing for the conversion

Designing the shape of the combustion chamber required a series of theoretical analyses involving computer simulation of the thermal and mechanical loads of the combustion system, and in particular the piston (Fig. 6). An important element of the analysis was the selection of the appropriate geometric dimensions of the combustion chamber, which, on the one hand, met the requirements for the compression ratio, and on the other hand, the strength properties of the individual piston elements, especially the bottom, which transfers the highest value of gas force. This is important, especially when powering the engine with hydrogen, when the high speed of the combustion reaction causes large, momentary increases in pressure and temperature, loading the piston.

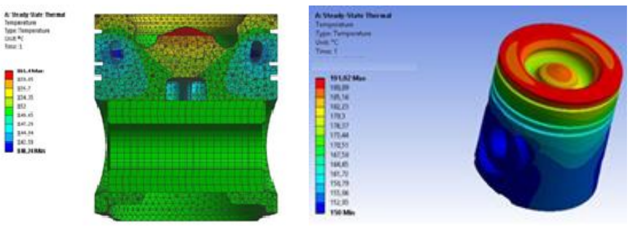

Fig. 6. Theoretical model analysis of thermal and mechanical loads of the standard version of the piston

Theoretical analyses showed the possibility of converting a standard compression-ignition engine piston after the above-mentioned design changes, using it in an engine powered by gaseous fuels. The designed piston met the requirements of an engine powered by gaseous fuels, including hydrogen.

3.3. Intake system

The compression-ignition engine, which is the object of conversion, is equipped with a classic power supply system implementing qualitative power regulation, which does not provide for throttling the air flow into the cylinders. In the case of spark-ignition engines, power is regulated by a quantitative method, and in engines powered by gaseous fuel with a large flammability range, also by a quantitative-qualitative method. Therefore, the intake system should be equipped with a valve to throttle the air flow.

In the designed engine designed to be powered by various gas fuels, including hydrogen, which is characterized by a very wide flammability limit, quantitative and qualitative power regulation is planned, which places special requirements on the accuracy of the selection of the excess air coefficient feeding the engine. In connection with this, the engine is planned to be equipped with a throttle module (Fig. 7), which is controlled by a stepper motor. Thanks to this solution, the degree of throttle opening can be included in the group of parameters constituting input signals to the electronic control module of the entire engine.

Fig. 7. Throttle module, during installation in the engine intake system (left), module with stepper motor controlling the throttle position

Placing the throttle module in the engine intake system changes its geometric dimensions, moving the original intake manifold away from the engine cylinder head body by a distance equal to the length of the module. In order to compensate for this dimension, elements fastening the gas fuel injectors with appropriately selected dimensions were designed (Fig. 8).

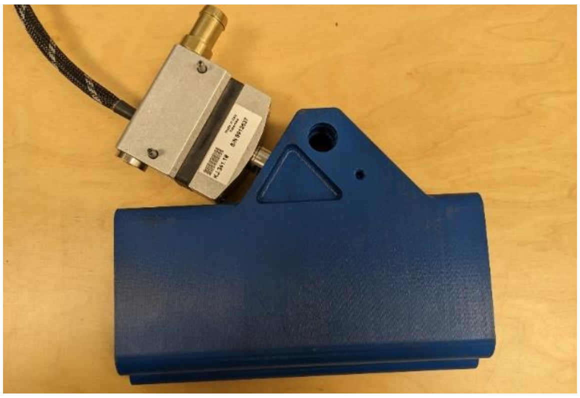

Fig. 8. Injector mounting body (in the photo – one of the prototypes printed using the 3D method from standard plastic)

These elements, called injector bodies, were designed using modern design tools and manufactured using the 3D printing method. An appropriately selected polymer material saturated with aluminum powder, which is resistant to high temperature and the chemical effects of hydrogen, was used to make the bodies. In addition, this material is characterized by plastic susceptibility and a controlled tearing process. This is a very positive feature from the point of view of operational safety, because in the event of the so-called flashback (backfire), depending on the intensity of this process, the body material may only undergo plastic deformation or crack without generating dangerous fragments.

3.4. Gas supply system

The engine, which was the subject of conversion to a gas fuel supply, was a compression ignition engine equipped with UIS (Unit Injector System) type pump injectors for diesel fuel injection. The entire standard power supply system was built into the engine. The developed concept of powering the engine with gas fuel assumed the use of an indirect gas fuel injection system to individual engine intake channels. The power supply system consists of a fuel rail in the form of a pipe made of acid-resistant steel, to which gas fuel is supplied at a pressure of not less than 4 bar (Fig. 9). The value of the gas fuel pressure in the fuel rail is controlled by a pressure sensor.

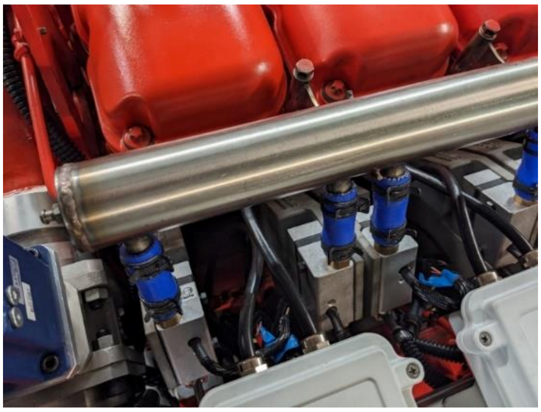

Fig. 9. A part of the fuel rail of the engine powered by gas fuels

From the fuel rail, gas fuel is transferred to the injectors through short pipes made of a plastic resistant to the chemical effects of the gas fuels used. Due to the design of the charge exchange system in the engine, which is equipped with two intake valves, and also due to the possibility of more precise selection of the dose of injected fuel, two injectors were used in the converted engine to supply each of the engine cylinders. These are serially produced, electronically controlled injectors designed for engines powered by natural gas (Fig. 10). For the needs of the implemented project, the injector dosing characteristics were made after previous calibration activities, thanks to which there was a guarantee of equal dosing of gas fuel in relation to the control signal.

The injectors were installed in developed injector mounting bodies (Fig. 11), which were made using the 3D printing method. In addition to the function of mounting the injectors, these bodies act as extensions of the intake channels, filling the space between the intake manifold and the heads, which changed after the introduction of the throttle body in the engine intake system.

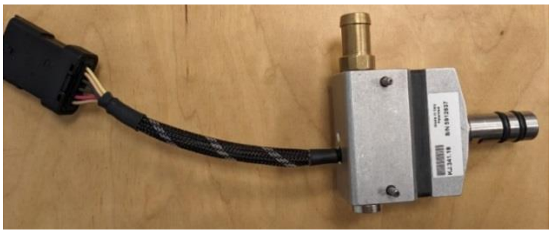

Fig. 10. Electronically controlled gas fuel injector

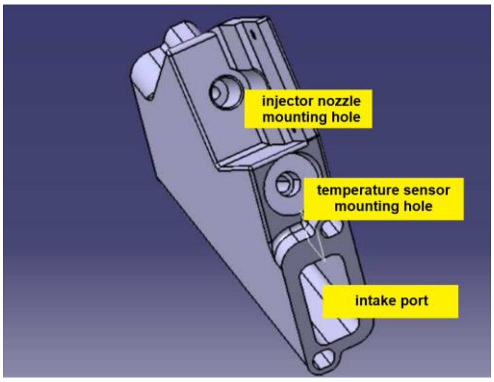

Fig. 11. Body of gas fuel injector

A characteristic feature of the bodies is the placement of special nozzles inside them, which are an extension of the injector nozzles, allowing gas fuel to be injected into the cylinder directly onto the intake valve. The developed power supply system provides for sequential gas fuel injection, synchronized with the position of the intake valves. Such a system largely prevents the risk of gas fuel accumulating in the engine intake channels, which may pose a risk of its explosion (Fig. 12).

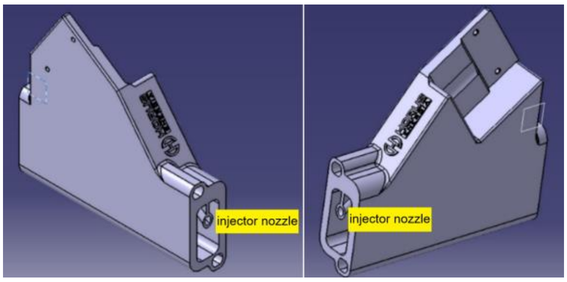

Fig. 12. Position of the gas fuel injector nozzles in the injector body

The arrangement of the injector bodies with injectors supplying gas fuel to the subsequent engine cylinders is shown in Fig. 13.

Fig. 13. Arrangement of gas fuel injectors in the engine (2 injectors per cylinder)

3.5. Ignition system

A conversion of the compression ignition engine to an engine powered by gas fuels involves developing an ignition system from scratch. Ignition modules from Denso, mass-produced for the automotive industry, were used. A single module consists of a spark plug integrated with an ignition coil. Modules of this type were placed in specially prepared sockets in the cylinder heads after the built-in injectors. Preparing the sockets required mechanical machining of the cylinder heads, together with the valve covers, and placing sleeves and seals protecting the ignition modules from external factors. The arrangement of the ignition modules in the engine is shown in Fig. 14.

Fig. 14. Arrangement of ignition modules in the engine

3.6. Control system

The control system designed and manufactured at the Cracow University of Technology is the most important system of the engine, designed to be powered by various gas fuels, including hydrogen. The engine uses an integrated electronic control system for individual processes that make up the full engine cycle in various operating conditions. This system uses the LabView software environment, which allows for multi-component regulation of all engine parameters in adaptive mode. It concerns both the control of basic systems necessary for the engine to operate, such as the power supply system and the ignition system, but also integrates signals from all sensors equipped with the engine. For this purpose, an electrical installation was developed, consisting of wiring harnesses creating a network of connections between the control parameters used.

The most important system of the engine powered by various gas fuels is the combustion process control system. In the developed solution, the basic role in controlling the operation of the combustion system is played by the value of the exhaust gas temperature exiting individual cylinders and signals from the knock sensors. These two parameters are linked in adaptive mode with the fuel supply system, which selects the appropriate value of the excess air coefficient, and with the ignition system, which selects the appropriate ignition timing. This type of system is also an element of the engine operation safety system, which can implement the engine shutdown procedure, e.g. in the event of a lack of combustion in one of the cylinders (exhaust gas temperature from a given cylinder is too low) or in the event of exceeding the set knock combustion threshold, which can no longer be corrected by appropriately setting the ignition advance angle. This system is also integrated with many other sensors transmitting signals related to operational safety. An example of this is the individual mixture temperature sensors, located in the engine intake channels, which decide to cut off the fuel supply in the event of the so-called backfire.

In the standard version, the engine was equipped with mechanically activated pump injectors by camshaft cams. During the adaptation of the engine to a gas fuel supply, it was necessary to make a new measurement system, requiring the installation of additional sensors necessary to synchronize many engine operating parameters. The developed system uses signals taken from the flywheel ring gear and the camshaft drive gear. The signal generated from them determines the instantaneous angular position of the crankshaft. Based on this parameter, the control system defines:

– fuel injection angle
– ignition timing
– knock detection zone
– engine speed
– and other engine parameters.

Figure 15 shows the location of both sensors. These are Honeywell LCZ260-30 sensors operating based on the Hall effect.

Fig. 15. Crankshaft and camshaft position sensors

Fig. 16. Cassettes with the main engine control system

The main control units are located in cassettes attached to the engine block (Fig. 16).

Injector operation is controlled by individual control units (Fig. 17), which support each of the two injectors per cylinder. The operation of these controllers is integrated and synchronized with the operation of the main control system.

Fig. 17. Cassettes with individual injector drivers for each cylinder

4. Preliminary tests

4.1. Start-up tests

The tested engine was equipped with a complete set enabling start-up tests and initial measurements of operating parameters. Start-up tests of the engine were carried out in the Laboratory of ICEs of the Cracow University of Technology on a test stand equipped with a 500 kW Zoellner eddy current brake (Fig. 18). It should be emphasized that the research did not provide for a change in the supercharging system, therefore the engine was equipped with a Holset turbocharger, used in the standard version of the engine.

Fig. 18. Engine on the test stand in the Laboratory of ICEs of the Cracow University of Technology

Start-up tests were carried out while fueled with two selected types of gas fuel (natural gas or hydrogen), which present different properties in terms of use as fuel for ICEs. The first tests were carried out while the engine was fueled with natural gas. During these tests, the functioning of individual engine components was checked, including mainly components and systems developed during the engine conversion. Tests of the functioning of the control system and safety systems were performed.

The next stage of the initial start-up tests was to feed the engine with hydrogen. In both cases, starting the engine powered by natural gas or hydrogen did not cause any problems, and the tests performed to check the operation of the control system, including the operation of the adaptive functions, were positive.

4.2. Initial bench measurements

The methodology of the measurements consisted of measuring selected operating parameters of the engine in operating conditions corresponding to its use in cooperation with a generator in a power generator. Therefore, measurements were carried out while the engine was running at a constant rotational speed of 1500 1/min and with variable load. The determination of engine control parameters, such as the excess air coefficient and the ignition advance angle in the initial tests, was selected individually to the engine operating conditions. During the measurements, all measured engine parameters were subject to control, while parameters important from the point of view of the conducted research, which were of an exploratory nature, were recorded. These parameters were:

- engine torque
- intake manifold absolute pressure
- excess air coefficient λ
- fuel consumption.

Based on these measured values, the following were calculated: engine effective power, specific fuel consumption and overall efficiency.

Initial tests of the engine control system operation and measurements of selected parameters, which were carried out while fueled with natural gas or hydrogen, were positive. In both cases, engine start-up did not cause any problems, and the tests performed to check the operation of the control system, including the operation of adaptive functions and the operation of safety systems, showed convergence with the design assumptions. Since the tested engine is designed to work with an electric generator, the engine speed was constant and amounted to n = 1500 1/min.

Initial tests have shown that when the engine is powered by natural gas and the ignition timing and excess air coefficient are adjusted, as determined by the developed controller, the effective power of the engine reaches the assumed value, while when the engine is powered by hydrogen, the effective power is approximately 30% lower. This significant difference in the obtained effective power value resulted from other physicochemical properties of the fuels used, and mainly from the calorific value of the mixture, which is significantly lower for the hydrogen-air mixture used, compared to the calorific value of the natural gas-air mixture. The second reason for the reduction in power when powered by hydrogen was the significantly lower energy of the exhaust gases flowing into the turbocharger, which significantly reduces the boost pressure and prevents the delivery of a larger mass of the hydrogen-air mixture. The turbocharger, which the engine is equipped with, was adapted to the exhaust gas flow generated in the process of diesel combustion, in which the thermodynamic parameters of the exhaust gas stream significantly differ from those parameters obtained when powered by natural gas or hydrogen.

5. Conclusions

The implementation of the project has shown that it is possible to convert a conventional combustion engine to be powered by various types of gas fuels with significantly different properties. This type of conversion is a complex issue that requires comprehensive technical analysis and development of an appropriate methodology for conducting work, taking into account the specific design features of the engine. In this case, it is not possible to develop a universal conversion system, similar to the methods used when adapting combustion engines to power, for example, natural gas or LPG. The necessary design changes should be introduced in the combustion system, ignition system, and power supply system. The most important thing here is the development of a control system that interactively combines the parameters of the ignition system and power supply system with the value of the engine's operating parameters. At the same time, the properties of the engine's construction materials should be taken into account, mainly in terms of exposure to thermal loads, mechanical loads resulting from the gas force, the course and dynamics of which depend on the properties of the fuel used. An important aspect of conversion is also the need to ensure the safety of engine operation. Therefore, an appropriate system should be introduced to monitor the change in pressure and temperature in the charge flow path, both on the inlet and outlet sides. The obtained engine operating parameters depend significantly on the physicochemical properties of the gas fuel used due to the existing limitations. Such limitations include, among others, the tendency to self-ignite, resistance to knocking combustion, backfire into the intake system, combustion process temperature, calorific value of the mixture, or the properties of the construction materials used. A significant improvement in the engine operating parameters can also be expected after conducting an analysis of the cooperation of the turbocharger with the engine, taking into account its flow characteristics, allowing it to be adapted to the type of fuel used.

Nomenclature

CI	compression ignition
ICE	internal combustion engine
LPG	liquified petroleum gas
n	engine speed
SI	spark ignition
UIS	unit injector system
V_m	volume of mixture per unit of energy
ε	compression ratio
λ	excess air coefficient

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