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Conversion of a diesel internal combustion engine to hydrogen power

Piotr **Pietras** [a, *], Monika **Andrych-Zalewska** [b]

[a] *Faculty of Mechanical Engineering and Computer Science, University of Bielsko-Biala, Bielsko-Biala, Poland*
[b] *Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, Wroclaw, Poland*

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The aim of this study was to devise and design the conversion of a compression-ignition engine, to a spark-ignition engine powered by hydrogen. The second objective of the present study is to expand research into the use of hydrogen in heavy-duty engines used in rail vehicles, ships and trucks. The engine would be used to measure exhaust emissions with hydrogen fuel, noise levels, and engine performance in a controlled setting. The initial section of the article comprises an examination of the extant literature pertaining to the historical and contemporary limitations imposed on the emission of greenhouse gases in railway and truck transport operations. The subsequent section delineates the challenges associated with the application of hydrogen in combustion engines. The third chapter details the complex process of converting, a diesel compression-ignition engine into a spark-ignition engine fuelled by a hydrogen–air mixture, and the necessary modifications to engine subsystems, including fueling, ignition and control. The final chapter presents the possibilities of using the converted engine in research and development of future transport.

1. Introduction

1.1. Combustion process and harmful emissions

Modern internal combustion engines are powered by fuels composed of hydrocarbon chains and their combustion produces harmful greenhouse gases. Complete fuel combustion results in the emission of carbon dioxide (CO_2) and water vapor (H_2O). The combustion process of hydrocarbon fuels proceeds according to equation (2.1). During combustion, the longer hydrocarbon chains found in diesel fuel generate high mass values of harmful substances. An example of a gasoline combustion process was presented in equation (2.2), while the combustion of diesel fuel based on the longer hydrocarbon chain dodecane was presented in equation (2.3) [4, 18].

$$4C_nH_m + (4n + m)\,O_2 \rightarrow 4n\,CO_2 + 2m\,H_2O \qquad (2.1)$$

$$2\,C_8H_{18} + 25\,O_2 \rightarrow 16\,CO_2 + 18\,H_2O \qquad (2.2)$$

$$2\,C_{12}H_{26} + 37\,O_2 \rightarrow 24\,CO_2 + 26\,H_2O \qquad (2.3)$$

Research on exhaust emissions during engine operation has identified the chemical compounds and toxic substances emitted into the atmosphere, in addition to CO_2, that are harmful to humans and the environment, such as carbon monoxide (CO), nitrogen oxide (NO_x), hydrocarbons (HC), sulfur dioxide (SO_2), aldehydes, and particulate matter (PM) [10] (Fig. 1). Emissions of carbon monoxide and hydrocarbons are caused by an imperfect combustion process, which results from the complexity of the process and the lack of appropriate conditions for the process to fully complete. The uneven and ununiform composition of the fuel-air mixture results in a decrease in engine power, increased fuel consumption, and, above all, increased fuel toxicity, while simultaneously reducing CO_2 emissions. The formation of nitrogen oxides is caused by a reaction between nitrogen and oxygen, which, due to the occurrence of locally favorable pressure and temperature values, create carcinogenic NO_x. Simultaneously, fuel contamination and the combustion of other operating fluids, including

* Corresponding author: ppietras675@gmail.com (P. Pietras)

engine oil, result in the production of additional harmful compounds and substances [10, 12, 15].

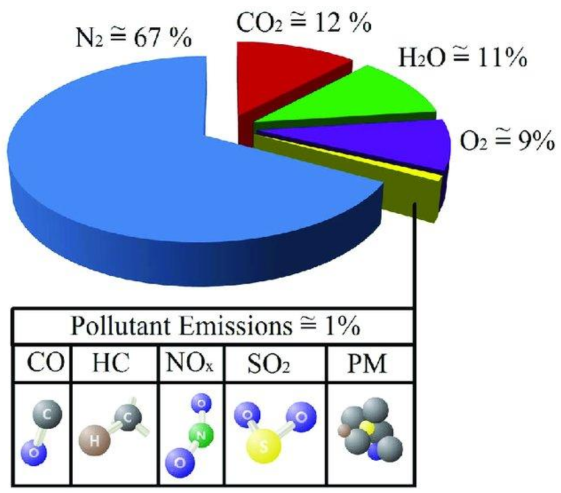

Fig. 1. Volumetric fractions of exhaust gas components for a compressed-ignition engine [12]

Exhaust gases emitted by vehicles powered by hydrocarbon fuels have a negative impact on the natural environment as well as human health. Nitrogen and sulfur oxides are formed through oxidation, which occurs during the engine combustion process. This reaction produces sulfuric and nitric acids with a low pH, which fall onto the ground, buildings, and plants in the form of rainfall. Vehicle exhaust emissions are harmful, especially in cities with high traffic density. This leads to an increased concentration of carbon monoxide, particulate matter, nitrogen oxides, and sulfur dioxide in the area. The mixture of harmful compounds and water vapor, when it reaches a high enough concentration, can lead to smog. According to research conducted at Harvard University in Boston, poor air quality contributes to an increased risk of cancers, including lung, prostate, colon, and breast cancers [8, 20].

1.2 Exhaust emissions from rail transport

Rail transport constitutes one of the key sectors of modern logistics, serving both passenger and freight operations. Since its inception in the 19th century, the railway industry has evolved from steam traction to the widespread use of diesel and electric locomotives. Today, railway networks remain extensive and diversified across different regions of the world. The highest concentration of railway lines is found in Europe and Asia; however, the availability of electrified routes varies substantially between and within these regions. Consequently, diesel-powered locomotives are still commonly employed, particularly in freight transport and for shunting operations in sidings and marshalling yards. Although hydrogen fuel cell technologies and other alternative propulsion systems are under active development, internal combustion engines emitting harmful pollutants are expected to remain in operation for many years. While individual railway sections generally exert a limited impact on ambient air quality, exhaust emissions – especially nitrogen oxides (NO_x) and particulate matter (PM10) – within marshalling yards and logistics centres remain a significant environmental concern.

For railway vehicles manufactured before 1990, only a limited number of technical measures can be implemented to reduce pollutant emissions. Solutions such as diesel particulate filters (DPF) or complete remotorization – provided that suitable engines are available – represent the most feasible retrofit options. A broader range of emission control technologies, including selective catalytic reduction (SCR) systems and DPFs, can be applied to railway vehicles produced after 1990. However, practical constraints related to available space and vehicle weight considerably limit their implementation.

In line with the European Union's continued efforts to achieve climate neutrality and reduce transport-related exhaust emissions, emission standards have also been established for rail vehicles. Although these regulations are less comprehensive than the Euro standards applied to road vehicles, they still represent a significant challenge for manufacturers. Currently, the railway sector accounts for approximately 3–4% of total nitrogen oxides (NO_x) and particulate matter (PM2.5) emissions within the transport sector. Across all industrial sources, railways contribute only about 0.8% of total pollutant emissions. Despite these relatively low overall figures, the share of diesel locomotives in local emissions – particularly within shunting and marshalling yards – is substantially higher. Moreover, exposure to exhaust gases poses a notable health risk to railway personnel, including train drivers, mechanics, dispatchers, and train managers [4].

1.3 Emission standards for rail vehicles

For non-road mobile machinery (NRMM), the European Union has introduced a separate set of exhaust emission regulations known as the Stage standards, first implemented in 1997. In the subsequent years, the permissible limits for harmful exhaust components—including nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO_2), and sulfur oxides (SO_x) – have been gradually tightened. Stage III standards were introduced in versions A and B between 2004 and 2010, followed by the introduction of the highly restrictive Stage IV standards, which enabled the operation of significantly lower-emission locomotives (Fig. 2) [7].

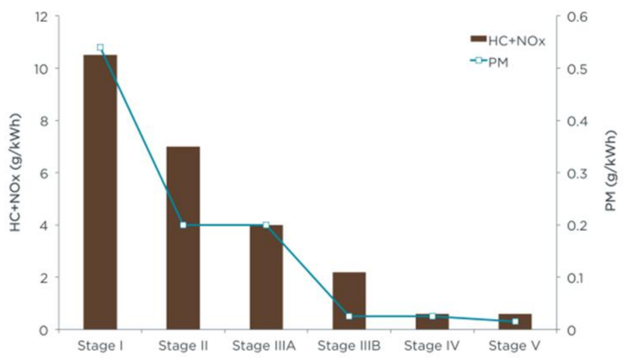

Fig. 2. Changes of limits for PM and HC+NO_x in exhaust emissions during years [7]

Currently, the Stage V standards apply to all non-road equipment and machinery emitting harmful gases that are not intended for use on public roads. This category includes power generators, construction and agricultural machinery, scooters, snowmobiles, boats, personal watercraft, and, most importantly, rail vehicles powered by internal combustion engines (Table 1) [7].

Table 1. Exhaust emission limits for Stage V [7]

Engine Category	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PM [g/kWh]	PN [g/kWh]
RLL-c/v-1	3.50	HC + NO_x < 4.00		0.025	–
RLR-c/v-1	3.50	0.19	2.00	0.015	1×10^{12}

Modern rail vehicles typically employ a series-hybrid configuration, in which a diesel engine converts the chemical energy of the fuel into mechanical work to drive an electric generator. The generated current is subsequently transmitted to electric traction motors that power the locomotive's axles. A less common configuration involves the use of a hydraulic transmission system, where a motor pump replaces electric traction motors to drive the axles.

The compression-ignition engines used in locomotives predominantly operate on diesel fuel which, despite partial substitution with bio-components, continues to emit harmful substances. In recent years, modernization efforts within the railway sector have focused on upgrading engines by integrating catalytic systems designed to reduce the emission of toxic exhaust gases. Concurrently, research has been undertaken on the use of synthetic and biofuels, as well as on the adaptation of internal combustion engines to operate on gaseous hydrogen.

The principal objective of the present research was to develop a conceptual design for the conversion process of a diesel engine to hydrogen fueling. The key aspects of the modification include changes to the mixture ignition system and the redesign of the intake and fuel supply systems. Owing to the structural similarity of heavy-duty diesel engines to traction units, their comparable technical parameters, and the availability of detailed technical documentation, a heavy-duty diesel engine was selected as the basis for conversion. The study aims to identify the required modifications, system adaptations, and the technical challenges associated with converting conventional diesel engines – regardless of their intended application – to hydrogen power

1.3. Alternative fuels for combustion engines

Due to the increased awareness of the harmful effects of hydrocarbon fuel combustion products on the environment, as well as on human life and health, scientific research was conducted into the use of alternative fuels starting from the 1970s. Research centers around the world, including in Poland, were examining the impact of fuels on toxic exhaust emissions, engine performance, and engine parameters. The stringent exhaust emission standards introduced by the European Union and increased awareness of the hazards of petroleum-derived fuels have led to increase in research spending on alternative fueling methods for combustion engines. As a result, the most promising and future-oriented fuels currently include: biofuels based on plant fractions, synthetic fuels, alcohol-based fuels: methanol and ethanol, hydrogen, methyl esters, and fuels based on natural gas in various forms, such as Liquefid Natural Gas (LNG), Liquefied Petroleum Gas (LPG), and Compressed Natural Gas (CNG). Only a few of them, including hydrogen, can qualify as fully ecological fuels, because during the combustion process it does not emit any harmful carbon-based substances, and thanks to diversified production processes it can be obtained without any cost to the natural environment [22].

2. Problems with hydrogen combustion

2.1. Supplying hydrogen to the engine

Hydrogen indirect injection

Hydrogen can be delivered to the engine in two different ways, each influencing the design, combustion process, and the resulting energy and usable power. The first method of hydrogen delivery is gas injection into the intake port, which creates a hydrogen-air mixture. This mixture then enters the combustion chamber through an open intake valve. Indirect injection allows for significantly greater ignition repeatability, especially when fueled with a leaner mixture. Hydrogen is delivered to the intake manifold using individually controlled injectors. These allow for significantly improved injection timing precision, along with the selection of the appropriate gas mass injected. This allows for better control of the stoichiometric mixture concentration, which impacts engine control and performance [1, 2].

However, this method is not without its drawbacks. Especially important are factors related to engine safety and operational refinement. The formation of a hydrogen-air mixture in the intake manifold can result in hazardous phenomena such as premature ignition, and the possibility of flashback. Indirect fueling also delivers mixture of a low energy density to the cylinder. This is due to the high volumetric fraction of hydrogen in the fuel mixture compared to a mixture created with hydrocarbon fuels such as gasoline andel. The increased amount of hydrogen significantly reduces the number of oxygen atoms, which translates into a reduction in the energy released during combustion. Indirect injection technology is currently more accessible and developed than the alternative method of delivering hydrogen to the combustion chamber. Solutions utilizing this technology are cheaper and simpler to design [13].

Hydrogen direct injection

The second method, currently in development, utilizes the technology of direct hydrogen injection into the combustion chamber during the compression stroke. This method requires continuous and precise monitoring of engine operating parameters, particularly those related to the combustion process, piston operation, and pressure changes at individual piston positions. Hydrogen is most often delivered using controlled injectors, which, in addition to thermal and mechanical durability due to the operating conditions, must also provide a higher flow rate than injectors used for indirect injection. This is due to the shorter window for hydrogen and air delivery to the combustion chamber while maintaining the appropriate mass, ensuring high performance and smooth engine operation.

The use of direct hydrogen injection eliminates the problem of flashback and premature ignition of the hydrogen-air mixture in the intake manifold. At the same time, by supplying hydrogen to the cylinder, the amount of oxygen supplied to the combustion chamber can be increased. This allows for higher thermal efficiency values for hydrogen-powered combustion engines, which in such cases is approximately 40-48%, and allows for approximately 10-15% greater power output than engines powered by hydrocarbon fuels. Direct hydrogen injection technology is currently under continuous development and forms the basis of many research processes in state-of-the-art combustion engines [13].

2.2. Impact of hydrogen on engine components

Due to its small atomic diameter, hydrogen diffuses very easily within the crystalline structures of, for example, iron. As a fuel, it is a compound that negatively affects the mechanical, thermal, and chemical resistance of metals and their alloys (Fig. 3). This is due to the solubility of hydrogen in metals, which, according to Sieverts' law, occurs even at room temperature. The degree of dissolution is directly related to the temperature and pressure of the metal, as well as the precise elemental composition of the alloy.

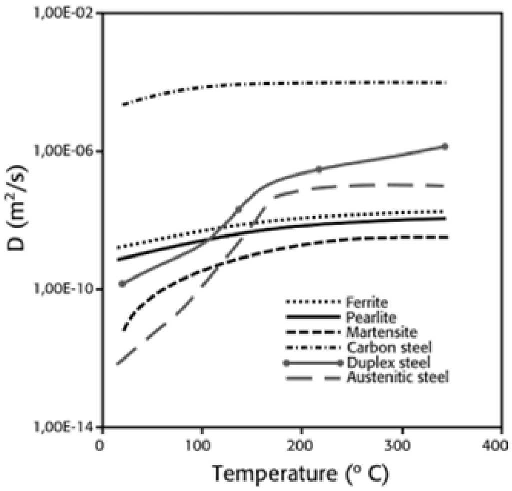

Fig. 3. A graph showing the change in hydrogen penetration into metals used to build combustion engines, depending on hydrogen temperature [5]

The most common effect of reduced mechanical strength due to hydrogen diffusion in metals and their alloys is known as hydrogen embrittlement. This phenomenon involves a loss of material plasticity, i.e., its extensibility and deformability, which over time causes cracking of components under loads lower than the material's yield strength or values achieved in calculations without taking into account the influence of hydrogen [16].

3. Compression-ignition engine conversion

3.1. Existing solutions for converting a diesel engine to hydrogen fuel

A successful example of converting a diesel engine to hydrogen fuel was demonstrated in the research conducted at the Cracow University of Technology. The team was led by Prof. Brzeżański, developed a modern test stand (Fig. 4) as part of the project "Adaptation of a modern compression-ignition engine to hydrogen power" carried out between 2020 and 2024. The adaptation concerned a R5 (5 row) compression-ignition engine [2].

The test stand consists of: an internal combustion engine, a modern adaptive control system, a hydrogen supply system, a ventilation system to ensure safety, and an eddy current brake responsible for generating braking torque. Using measuring equipment and a special control system developed by scientists with the LabView software, it is possible to ensure safe operation and conduct a wide range of scientific research [1, 2].

Fig. 4. The test stand with an internal combustion engine adapted to run on hydrogen at the Krakow University of Technology [2]

3.2. Preliminary project of adapting the CI engine to hydrogen power

Using technological solutions developed by scientists from the Krakow University of Technology, as well as other available research and scientific studies, a preliminary design for the conversion of the SI engine for heavy-duty, which was produced in the second half of the 20th century, was developed. The engine's design necessitated modifications to the engine itself, which would have to be made during the project's implementation. These modifications stem from the different chemical and physical properties of gaseous hydrogen compared to the diesel fuel normally used to fuel the compressed ignition (CI) engine.

Due to the impossibility of hydrogen combustion in the engine compartment via compression ignition, it was necessary to change the combustion method and create a spark ignition system. At the same time, due to the change in fuel and the need for highly accurate dosing, the existing mechanical fuel supply system was removed, the combustion chambers were reshaped, and a modern, fully electronic ignition and injection system was designed.

3.3. Piston-crank system conversion

The change in the shape and volume of the combustion chamber was related to the change in the fuel mixture ignition method and the change in fuel type. The chemical parameters of hydrogen and the combustion rate of the hydrogen-air mixture should especially be noted as different. Without piston modifications and maintaining the compression ratio, which for the original engine was 15.8, there was a significant likelihood of undesirable phenomena occurring during the hydrogen mixture combustion process. Studies have shown that the occurrence of hydrogen knock increases exponentially, especially when the compression ratio exceeds 11.5–12.0. The significant increase in pressure pulsation is the result of uncontrolled auto-ignition of the mixture, taking place at a distance from the flame triggered by the spark plug (Fig. 5) [17].

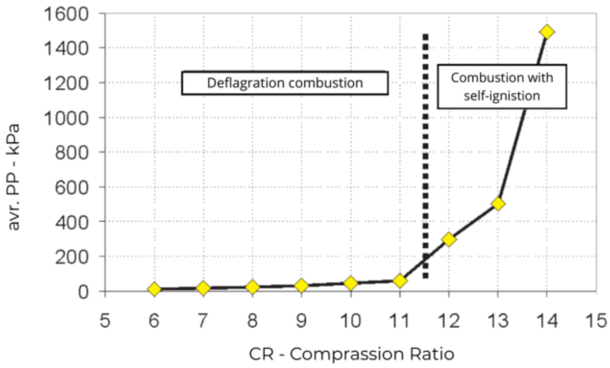

Fig. 5. The intensity of pressure pulsation PP_{av} depending on the compression ratio during hydrogen combustion at an ignition angle of $\alpha_z = 0°$ [17]

Engine knock leads to a significant reduction in indicated pressure, which translates into a drop of engine torque, instantaneous power, and final efficiency [17]. The piston modification was preceded by an analysis of available solutions based on the experience of other research centers that have also undertaken modifications to hydrogen combustion engines. The most common method for achieving a reduced compression ratio of 9.00–11.00 is to simply increase the volume of the combustion chamber.

The conducted piston modification was done to increase the total cylinder volume when the piston is at bottom dead center (BDC) and the volume of the combustion chamber plus the remaining cylinder volume when the piston is at top dead center (TDC).

Calculations were performed using an Excel spreadsheet and basic formulas. The original piston was compared based on dimensional data regarding cylinder displacement and the empirically measured combustion chamber volume. The calculation results were shown in Table 2. To achieve the assumed compression ratio of $\varepsilon < 11.00$, the combustion chamber volume had to be increased from 95 cm^3 to a value no less than 165 cm^3. As the combustion chamber volume increased, the compression ratio decreased. The compression ratio change for the volume range from 95 cm^3 to 230 cm^3 was exponential (Fig. 6).

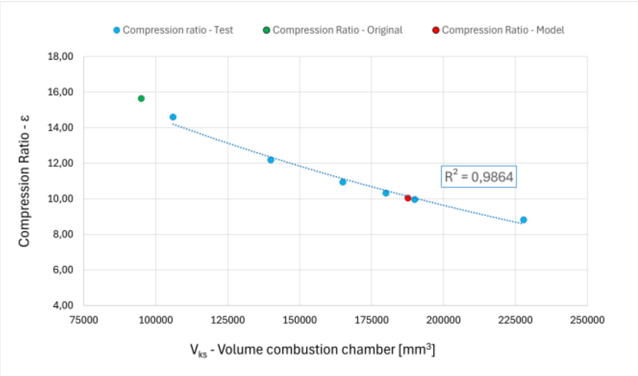

Fig. 6. The relationship between the change in compression ratio in the engine and the change in combustion chamber volume (equation coefficient R^2 = 0.9864)

Then, a 3D model of the piston with a modified combustion chamber was prepared using the Inventor program (Fig. 7).

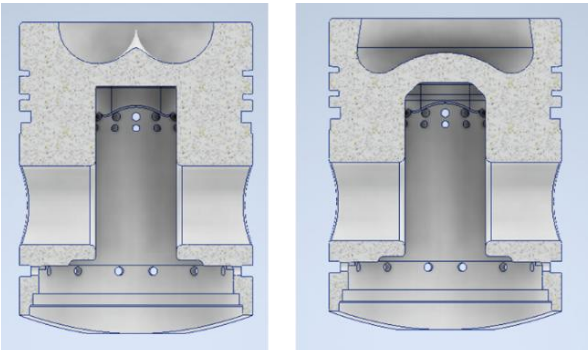

Fig. 7. Comparison of the cross-section of the SW680 engine piston before (left) and after (right) modification of the combustion chamber to reduce the engine compression ratio

Analytical calculations were performed to determine the temperatures and pressures in the combustion chamber that can be expected to occur at specific points in the process for spark-ignition engines. [21] Formulas for the spark ignition (SI) engine were adopted due to the change in the method of combustion of the fuel-air mixture. The calculated values were recorded in Table 2.

Table 2. Temperature and pressure values at individual points of the combustion process for a hydrogen-powered SI engine [21]

No.	Name	Symbol	Value
1	Ambient temp.	T_1	293 K
2	Compression end temp.	T_2	560.32 K
3	Combustion end temp.	T_3	3175.72 K
4	Ambient pressure	p_1	0.101 MPa
5	Compression end pressure	p_2	1.962 MPa
6	Max theoretical combustion pressure	p_{3T}	13.080 MPa
7	Max real combustion pressure	p_{3R}	11.120 MPa

The calculated values were then used as boundary conditions for simulations using ANSYS software. The completed model was subjected to a stress simulation, which showed deformations and stresses in the piston, along with a thermal simulation, which determined the temperature distribution. The results of each simulation were presented below (Fig. 8–13).

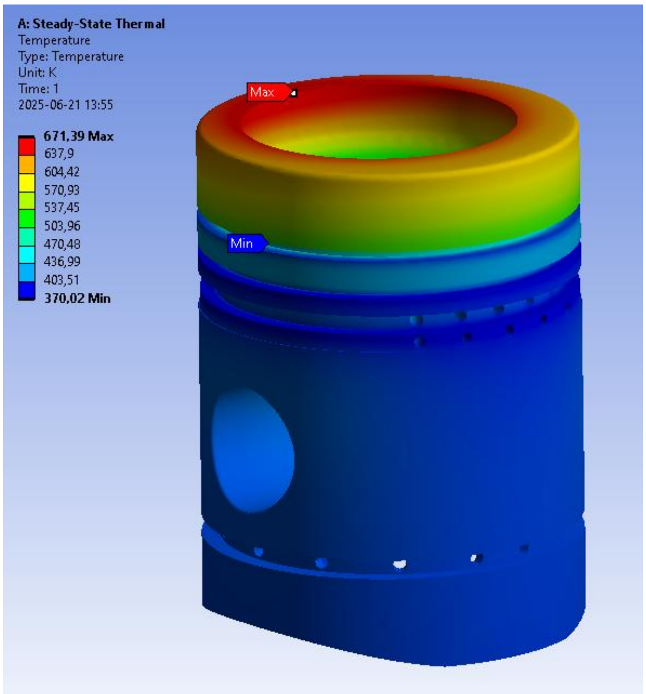

Fig. 8. Section view of the piston steady-state thermal simulation result obtained in the ANSYS program. Figure shows temperature distribution

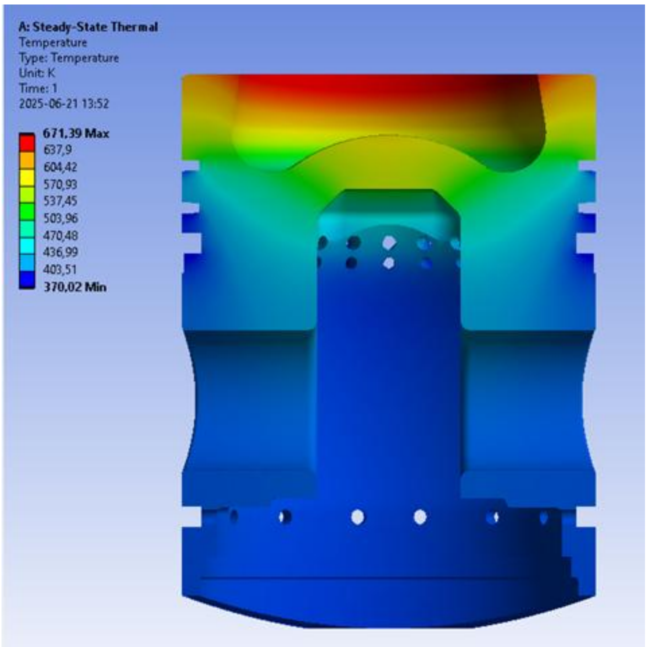

Fig. 9. Full view of the piston steady-state thermal simulation result obtained in the ANSYS program. Figure shows temperature distribution

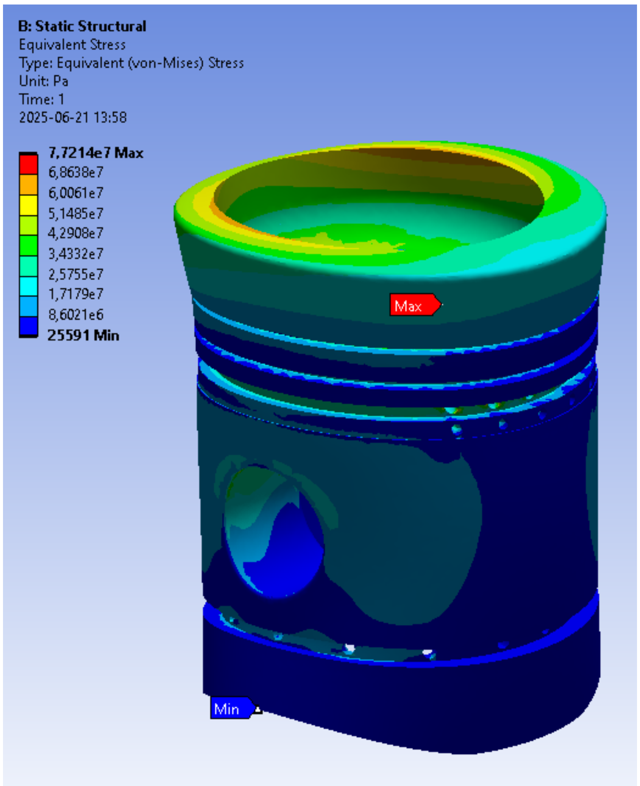

Fig. 10. Full view of the piston static structural simulation result obtained in the ANSYS program. Figure shows tension in model

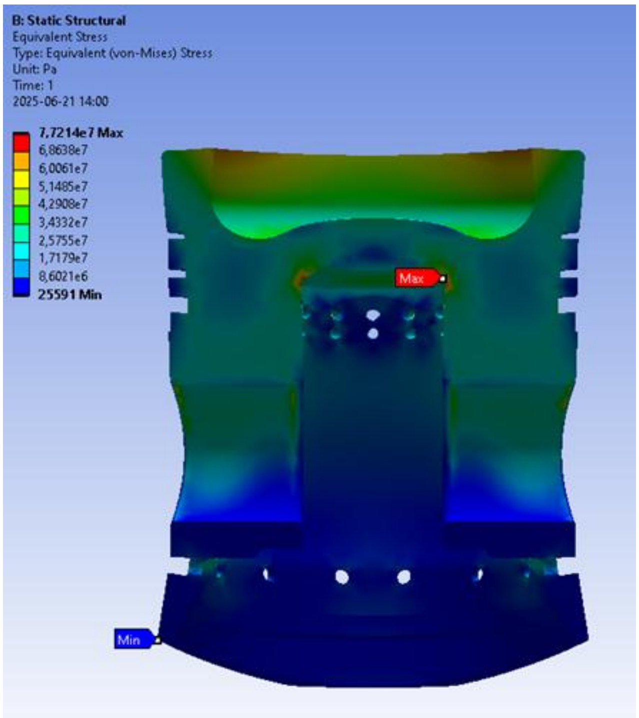

Fig. 11. Section view of the engine piston static structural simulation result obtained in the ANSYS program. Figure shows tension in model

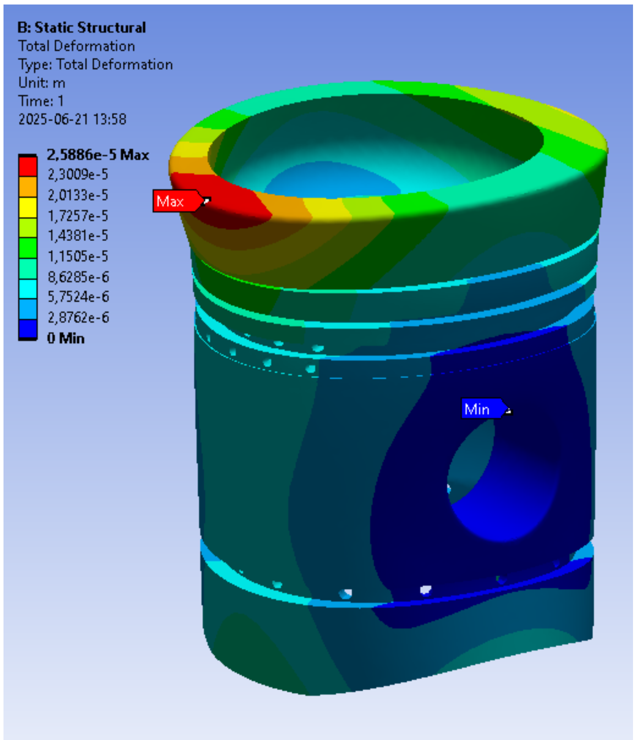

Fig. 12. Full view of the engine piston static structural simulation result obtained in the ANSYS program. Figure shows total deformation

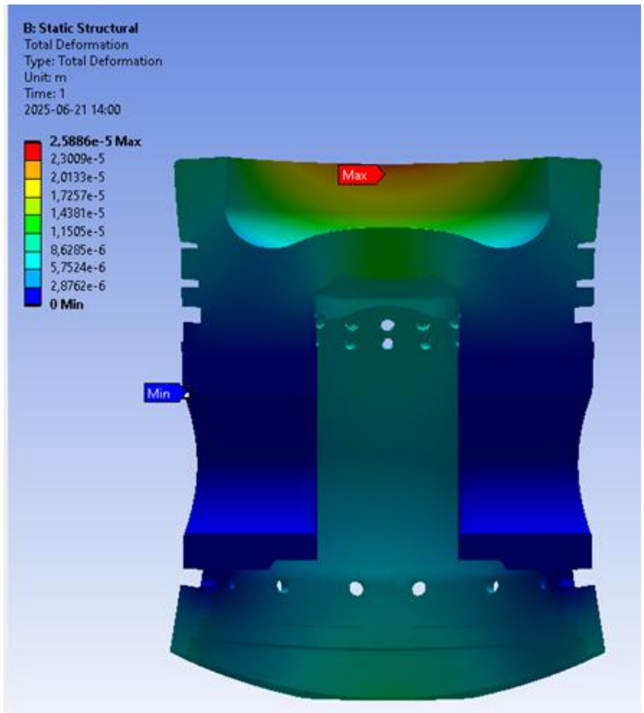

Fig. 13. Section view of the engine piston static structural simulation result obtained in the ANSYS program. Figure shows total deformation

3.4. Conversion of the engine fuel system to a hydrogen-air mixture

The original engine utilized a mechanical fuel supply system, which prevented the use of hydrogen as fuel due to its lack of precision and ability to adequately respond to changes in the combustion chamber. Therefore, the proposed engine adaptation required the removal of the existing injection system and its replacement with an electronically controlled system. Modern technology allowed for the use of both direct and indirect hydrogen injection methods. However, despite the benefits of direct injection, due to the high risk associated with uncontrolled combustion chamber ignition, the need for precise pressure measurements, and the use of high-flow injectors, the design opted for an injection system based on indirect hydrogen delivery into the combustion chamber [2].

The use of indirect injection technology in the new designed fuel system necessitated changes and adaptations to numerous other engine components, including those in other systems, such as the intake and exhaust systems, as well as to individual engine components such as the cylinder head and engine block. The proposed changes resulted in an increase in the overall size of the engine and the addition of new extra components within the fuel system (Fig. 14).

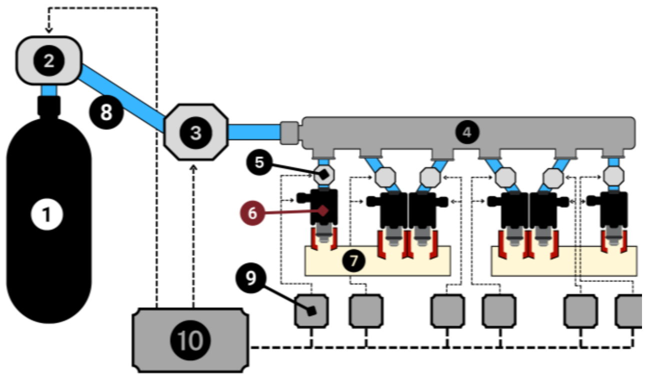

Fig. 14. Schematic diagram of the SW680 engine's hydrogen fuel system. 1 – hydrogen tank, 2 – control and safety valve system, 3 – measuring module equipped with the described test and measurement equipment, 4 – fuel rail, 5 – sensors measuring the combustion process in individual cylinders, 6 – injectors, 7 – cylinder heads with injection modules, 8 – fuel lines, 9 – engine control unit support modules, 10 – ECU engine control unit

The list of all modified or created fuel system components included:

- Phinia fuel injectors
- Bosch common fuel rail
- Injector mounting
- Modified cylinder head
- Power cables
- Modules supporting the engine control unit, including injection timing and angle
- Knock sensors
- Air ratio sensors
- Temperature sensors.

3.5. Injectors

Correct hydrogen combustion for stable engine operation using indirect injection requires an excess air ratio greater than $\lambda \geq 1.9$. Scientific research conducted in recent years has shown that feeding the combustion chamber with a richer mixture when indirect injection is used results in an increased number of combustion anomalies. Simultaneously, the risk of uncontrolled ignition in the intake manifold or flashback also increases. A lean hydrogen-air mixture is also one of the factors reducing the maximum specific power of the engine and the thermal efficiency of the system [13].

To select the appropriate injector, a series of calculations were performed, focusing primarily on calculating the hydrogen mass required to ensure a coefficient of $\lambda = 1.9$, while taking into account boundary conditions, including the maximum pressure resulting from the risk of spontaneous combustion of the hydrogen-air mixture. The performed calculations and the values obtained allowed the selection of an appropriate injector ensuring the necessary flow rate, which was made by Phinia. It uses of elastomer valve seal to prevent leak and enable quiet operation. PFI injector generates high opening force for system pressure up to 10 bars and static flow is up to 1.44 g/s. [3, 14, 15, 19].

Table 3. Technical data Phinia 3.5 PFI H2 [3]

No.	Feature	Multec 3.5 PFI H2
1	Static flow options	1.44 g/s (10 bar)
2	Operating pressure	up to 10
3	Maximum OD [mm]	17.0
4	Tip diameter [mm]	8.00
5	Solenoid resistance [ohms]	7.6
6	Electrical connector	Sumitomo PN 6189-0785

3.6. Injector mounting

In order to ensure the proper fuel-air mixture when using indirect injection it was necessary to design special injection modules, which were placed between the intake and exhaust manifolds and the engine cylinder heads. Four types of modules were created, differing in the mounting configuration of the sensors and injectors depending on their mounting location (Fig. 10a, b). All modules were designed for 3D printing using selective laser melting (SLM). To ensure adequate thermal and mechanical strength and maintain high precision, the modules must be manufactured to IT5 accuracy class from a thermally and mechanically resistant metal that will not significantly interact with hydrogen. One such material is the aluminum alloy AlCrTiVNi5, developed at the University of Alberta and characterized by resistance to temperatures exceeding 900°C, or the use of Inocel 625 alloy, whose strength parameters meet the criteria established during the design phase, both mechanically and thermally [1, 2].

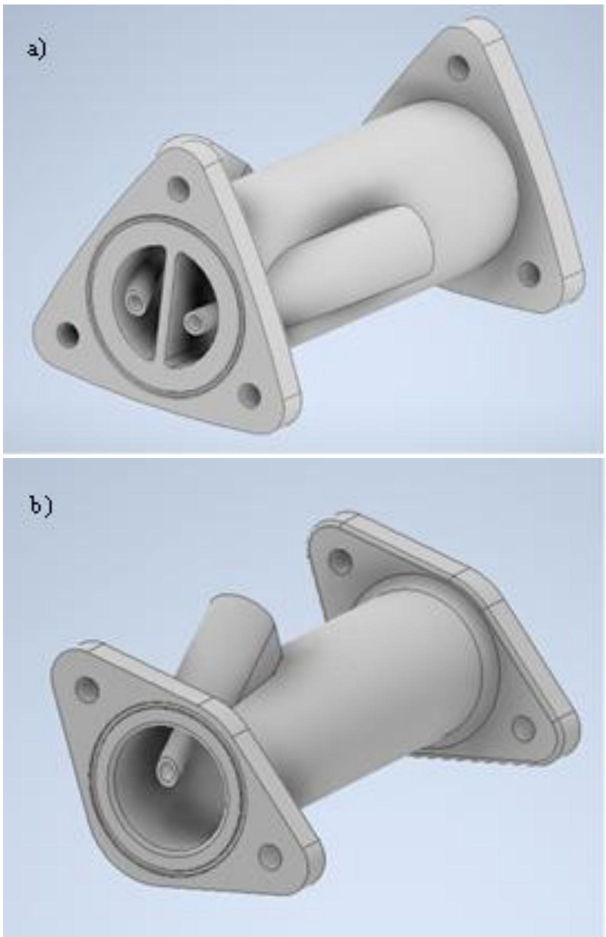

Fig. 15. Conceptual models of injector mounts designed in Inventor. a) module for two injectors – two cylinders, b) module for a single injector – one cylinder

3.7. Fuel rail

The original fuel system was not equipped with a common fuel rail; diesel fuel was delivered to individual injectors via fuel lines. As a result of the fuel system change, a common fuel rail was used instead for all injectors, utilizing a single fuel line. This design was connected with the pump and hydrogen tank. This significantly reduced the possibility of uneven hydrogen delivery to individual injectors and reduced the number of potential system failures and uncontrolled hydrogen emissions. The design involves the use of a prefabricated rail, manufactured from Bosch austenitic stainless steel, to ensure adequate fatigue strength, thermal resistance, and, above all, resistance to hydrogen permeation, as well as potential uncontrolled spontaneous combustion and flashback [9, 16].

3.8. Modification of the intake and exhaust channels in the engine head

Because the design uses individual injectors, combustion process sensors, and indirect hydrogen delivery for individual cylinders it also necessitated modifications be made to the intake and exhaust ports. The most significant change was the creation of separate ports responsible for delivering the hydrogen-air mixture to individual cylinders. Cast iron inserts were prepared and designed to separate the intake ports of the inner cylinders. MMA welding, i.e., welding with a suitably selected high-alloy austenitic coated electrode, was planned for the cylinder head modification.

3.9. Fuel supply system

Changes to the fuel system required the removal of the existing fuel lines from the project, which would not have allowed for the safe transport of hydrogen. Because they were made of materials that would react chemically and were susceptible to fatigue and hydrogen corrosion. Therefore, modern lines were chosen and installed. The multi-layer hose is composed of an inner layer manufactured from polyamide and a durable PA12 polyamide. The cable reinforcement consists of a single aramid fibre braid, which is additionally covered with a steel wire braid. The external layer is composed of polyurethane, a material that exhibits resistance to damage incurred by friction and bending. Their multi-layer construction ensures safety during the test stand's operation by limiting uncontrolled hydrogen emissions or fuel leakage.

3.10. Throttle

A key aspect of safe hydrogen combustion in an internal combustion engine is the continuous monitoring of the air mass entering the intake system. To this end, a throttle valve was designed, located at the starting point of the intake system, before the air filters, to control the amount of air mass reaching the test stand engine [2]. The designed throttle valve should provide the appropriate air mass for the engine and have an overflow that will provide a safety margin during the most demanding load tests. The prepared throttle mechanism should be equipped with a stepper motor, controlled by the main engine controller, allowing the test stand operator to adjust the throttle from the control panel.

3.11. Sensors responsible for the system operation

The designed engine is to be controlled using an electronic computer unit (ECU) specifically adapted for hydrogen-powered engines, as well as additional modules that support the controller in analyzing the received data. The engine control process is to be adaptive and based on qualitative and quantitative control [1]. This requires the use of sensors that allow for the acquisition of the necessary empirical data and, consequently, the proper operation of the diesel engine.

Due to technological advancements new sensors had to be introduced and new mounting locations found to properly fit them. This was necessary because the original 1980s engine, which was not factory-equipped with sensors, was not designed with any prepared space of installing them. Adding those sensors ensured accurate measurement of engine operating parameters, including exhaust gas temperature, exhaust gas pressure, air intake, and lambda. Proper fuel injection and throttle control required the installation of the following sensors on the injector modules and exhaust modules:

- Intake air temperature sensor
- Exhaust temperature sensor
- Exhaust gas oxygen content sensor (broadband lambda sensor)
- Knock combustion sensor.

3.12. Ignition system conversion

The switch from liquid diesel fuel to gaseous hydrogen fuel for the original engine necessitated a change in the combustion method and resulted in the creation of a new ignition system. Previously, the combustion reaction in the engine was achieved through the spontaneous ignition of a compressed fuel-air mixture. In the case of hydrogen, current technologies do not allow for controlled combustion through hydrogen self-ignition. As a result, a completely new ignition system had to be designed, allowing for safe and controlled combustion of hydrogen in the engine's cylinders using spark plugs. As a result the CI engine was converted to a SI engine.

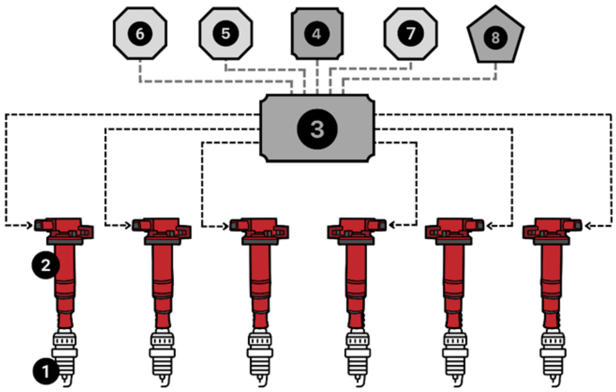

Fig. 11. SW680 engine ignition system diagram. 1 – spark plug, 2 – ignition coil with integrated ignition module, 3 – engine ECU, 4 – booster module, 5 – camshaft position sensor, 6 – crankshaft position and speed sensor, 7 – oil pressure sensor, 8 – battery voltage

The correct and complete combustion of hydrogen during engine operation is a key aspect of the proposed solution. Any combustion anomalies can be dangerous to the persons near to the engine, the test stand, or vehicle, as they significantly affect the thermal and mechanical strength of the engine and its components.

As discussed previously, the project opted for indirect injection, which has some disadvantages but significantly reduced the risk of rapid and uncontrol detonation combustion processes, which taking place in cylinder. At the same time, it was decided to create a fully electronic ignition system (Fig. 11) that would work in conjunction with the electronic injection system, using the same measurement data obtained by sensors and transmitted to the main engine control unit. This solution would allow for more precise adjustment of valve opening angle and ignition timing and duration, leading to improved engine performance, increased power, and increased efficiency while maintaining a deflagration-free combustion process.

The designed ignition system for the engine utilizes technologies commonly available in modern automotive applications. The system consists of an electronic engine controller, which is connected to sensors and injection controllers, while also connecting sensors related to ignition timing control. At the same time, the ignition system utilized individual ignition coils and spark plugs for each cylinder. This allowed for independent and easier generation of the necessary voltage. However, the use of this technology complicated the engine control process itself. This led to the introduction of additional modules supporting the ECU operation. The designed new ignition system for the original engine, powered by hydrogen, consists of the following components:

- 6× spark plugs
- 6× ignition coils with integrated ignition modules
- 1× ECU (Main Controller)
- Crankshaft and camshaft position sensors
- Oil pressure sensor
- Support modules and sensors that are components of the injection system.

4. Conclusion

The introduction of exhaust emission standards over the past decade and the growing importance placed on reducing emissions of harmful combustion products are driving the continuous development of alternative fuel technologies for vehicles. Hydrogen could be completely zero-emission fuel that can be used to power trains, ships and other vehicles utilizing fuel cell technology as well as modern combustion engines. However it could also emitted harmful gases, if they used non low or zero emission methods as coal gasification. This can reduce the emissions of exhaust gases that are harmful to both humans and the environment.

Adapting the diesel combustion engine to hydrogen fueling presents a set of challenges that needed to be overcome. In the course of the study, a design was formulated for the adaptation of a compression ignition engine to run on hydrogen. The necessary modifications to the crankshaft and piston system, fuel supply, and ignition system were taken into account. Strength analyses of the piston and models for mounting the injectors for the analysed engine were prepared. This is crucial to ensuring safe and controlled hydrogen combustion in the engine. The project requires augmentation to encompass more precise specific fuel consumption (SFC), fuel systems, hydrogen supply infrastructure, and adaptation of the test bench. The test bench, equipped with a modified engine, will facilitate the exploration of hydrogen as a fuel source for internal combustion engines. These engines are intended for utilisation in the domain of freight transport, specifically in rail and road freight vehicles.

Nomenclature

BDC	bottom dead centre
CI	compression ignition
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
DI	direct injection
DPF	diesel particulate filter
ECU	engine control unit
HC	hydrocarbons
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MMA	manual metal arc
NO_X	nitrogen oxides
SCR	selective catalytic reduction
SI	spark ignition
SLM	selective laser melting
SO_2	sulfur dioxide
TDC	top dead centre

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