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The use of hydrogen as a fuel in road transport on the Polish path to climate neutrality - a literature review

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Abstract

Hydrogen is expected to be one of the most important fuels meeting stringent emission standards shortly. Using hydrogen as a fuel in an internal combustion engine (ICE) is an alternative application to replace hydrocarbon fuels that, when burned, produce harmful gases such as carbon monoxide and hydrocarbons, particulate matter, and greenhouse gases. This work provides an overview of the latest research results and future challenges and opportunities related to the use of hydrogen to power ICEs. The article presents the work of various research centres describing the technical use of hydrogen as a fuel in motor vehicles with combustion engines. Specific chemical and physical properties of hydrogen used in combustion engines were presented. The article presents modern research on a hydrogen-powered ICE. First, the basics of hydrogen engines are described, examining the engine-specific properties of hydrogen, followed by a review of the existing literature. Attention was paid to the fundamental importance of optimising the air composition from the point of view of combustion quality, NO_x emissions, engine efficiency, and performance. Another issue under consideration is cleaning exhaust gases to meet future emissions regulations for hydrogen-fuelled combustion engines.

1. INTRODUCTION

The Earth's population is growing every year, and the continuous improvement of industry causes an increased demand for energy, which leads to the depletion of natural fuel resources. In addition, the combustion of fossil fuels produces emissions of substances harmful to the environment and people, as well as greenhouse gases. A significant part of pollution can be observed in urban areas due to road transport.

Road transport, in particular, is responsible for around one-fifth of the EU's total greenhouse gas emissions, with emissions showing an increasing trend. The case for moving towards zero-emission mobility [EU regulations] becomes even more robust and transparent in the EU's drive to reduce energy dependence as soon as possible, given that road transport accounts for one-third of the EU's total energy consumption. The REPowerEU [EC REPowerEU] plan highlights the need to increase energy savings and efficiency in the transport sector and accelerate the transition to zero-emission vehicles, combining electrification and renewable hydrogen to replace fossil fuels.

One of the critical elements of the European Green Deal [EU regulations] is achieving climate neutrality by 2050 and increasing the ambitious interim target by reducing net greenhouse gas emissions by at least 55% by 2030

compared to 1990 levels. These targets align with the EU's commitment to global climate action under the Paris Agreement. The crisis caused by Russia's invasion of Ukraine is another argument for reducing the EU's dependence on fossil fuels, as highlighted in the REPowerEU plan [EC REPowerEU], which presents actions to save energy, diversify supplies, replace fossil fuels and make smart investments and reforms in all sectors of the economy.

Due to the above environmental protection problems, a fuel is sought for which its distribution and consumption on a global scale would allow for the reduction of both the use of non-renewable fuels and the concentrations of undesirable compounds. An alternative fuel that meets these requirements is hydrogen. It occurs naturally in the environment and can be obtained in a form suitable for use as fuel through appropriate chemical reactions. In addition, hydrogen can be described as an emission-free fuel. Only nitrogen oxides (NO_x) are noticeable in the exhaust gases. It is not only an excellent fuel but also an energy carrier.

For this reason, work is also being carried out to popularise the use of hydrogen in fuel cells. Thanks to the general availability and advanced development of piston engines, hydrogen solutions may cause the popularisation of hydrogen as an alternative fuel and a practical energy source. The gradual process of disseminating hydrogen fuel

in Poland is regulated by the Polish Hydrogen Strategy with a perspective until 2040 [Barańska, Petelski 2022, Graff 2020]. The hydrogen strategy assumes the launch of P2G (power-to-gas) installations with a minimum capacity of 1 MW by 2025. The purpose of commissioning this type of installation will be to support the stabilisation of the operation of distribution networks. In addition, until 2025, it is also assumed that hydrogen will be co-combusted in gas turbines, that there will be support for R&D in creating co- and polygeneration systems, and that there will be development of energy storage facilities based on hydrogen technologies and R&D in compact P2G and G2P systems. In the 2030 perspective, the strategy assumes, among other things, the launch of co- and poly-generation installations, such as CHP plants with a capacity of up to 50 MWt. According to the strategy's assumptions, hydrogen is the leading fuel in these installations. By 2030, it is also assumed that hydrogen will be used in processes related to energy storage [Polish Hydrogen Strategy 2021].

Hydrogen also plays a significant role in urban, road, rail, sea and aviation transport. The implementation of vehicles using fuel cells will be an essential step towards the decarbonisation of one of the most emission-intensive sectors of the economy [Polish Hydrogen Strategy 2021]. According to the estimates resulting from the strategy, over the next five years, the demand for hydrogen in transport in Poland may amount to almost 3,000 tonnes, more than half of which will be intended for urban transport. In the next ten years, the demand for hydrogen in vehicles may increase and oscillate around 22,500 tonnes per year [Polish Hydrogen Strategy 2021].

The strategy assumes that by 2025, Poland will have at least 100 hydrogen buses in its fleet, and by 2030, their number may increase tenfold. By 2025, 32 hydrogen refuelling stations are planned, mainly in agglomerations and densely populated areas [Polish Hydrogen Strategy 2021].

The hydrogen strategy also assumes that in 2025, the first hydrogen trains will appear on Polish tracks, and design work on watercraft using hydrogen in the form of ammonia or methanol will start [Polish Hydrogen Strategy 2021].

The above-described assumptions of the hydrogen strategy concern only issues related to the production of hydrogen and its use in transport and the power industry as an energy carrier. The entire strategy includes many other issues related to, among others, the use of hydrogen in the industry. Focusing on the above-selected matters, it should be noted that hydrogen has high potential as an energy carrier. Since hydrogen-related problems are just starting to begin across Europe, any plans should be cautiously approached. Energy storage may be one of the critical points of the hydrogen strategy, as the efficient development of storage facilities using hydrogen or its production at renewable energy sources may be an important factor supporting the regulation of the national power system.

The potential of using hydrogen as a fuel was also noticed in the articles of Horváth et al. [2023], Szałek et al. [2021] and Tatarewicz et al. [2023], in which simulations were

carried out regarding using hydrogen as a fuel in transport. The articles clearly show that hydrogen will be the primary fuel for transport.

2. HYDROGEN PRODUCTION METHODS

Hydrogen is ordinary on Earth, unfortunately, only in small part in its pure form. For this reason, it must be obtained from products, which can be fossil raw materials or renewable energy. Methods of securing hydrogen can be distinguished according to the primary raw material [Wiącek 2011]:

- water;
- liquid and gaseous hydrocarbons;
- ammonia;
- ethanol;
- and methanol.

Due to the type of chemical reaction to which this raw material is subjected:

- gassing;
- decomposition;
- electrolysis;
- steam reforming;
- and partial oxidation.

Nowadays, the least-emission methods of obtaining hydrogen using renewable energy sources are being sought to depart from conventional fossil fuels. To get hydrogen from hydrocarbon fuels at the lowest cost of environmental pollution, undesirable compounds (e.g. CO₂) must be separated or "captured" by sequestration from chemical reaction products. The primary fossil raw materials used to produce hydrogen are coal, oil and natural gas, which are the dominant sources of hydrogen at the moment. Methods using renewable energy sources predict the value of hydrogen in the industry. However, they currently account for a small percentage of hydrogen production. It is estimated that 48% of hydrogen is produced by methane reforming, 30% by oil refining, 18% by coal and 4% by water electrolysis. The most popular hydrogen production processes are [Bogucka, Pikoń 2020, Levchenko 2021]:

- steam reforming of natural gas;
- coal or coke gasification;
- water electrolysis;
- partial oxidation of hydrocarbons;
- biomass gasification;
- and biological methods.

Currently, several ways exist to make hydrogen [Stępień 2021]. The most popular method is steam-methane reforming, which is efficient (65%–75%) and inexpensive but has high CO₂ emissions [Stępień 2021, Boretti 2019]. Coal gasification is another option, but it's not as good (45% efficiency), and the CO₂ output is high. Water electrolysis is another option, but it requires a lot of electricity and is expensive. Plus, the amount of CO₂ released depends on

Table 1. Hydrogen properties compared with gasoline, diesel and methane [Ciniviz et al. 2012, Stępień et al. 2021, Stępień 2021]

Property	Hydrogen	Methane	Gasoline	Diesel
Formula	H ₂	CH ₄	C ₈ H ₁₈	C ₈ H ₂₀
Carbon content (mass%)	0	75	84	86
Lower (net) heating value (MJ/kg)	119.9	45.8	43.9	42.5
Density (at 1 bar & 273K; kg/m ³)	0.089	0.72	730-780	830
Volumetric energy content (at 1 bar & 273K; MJ/m ³)	10.7	33.0	33x10 ³	35x10 ³
Molecular weight [g/mol]	2.016	16.043	~110	~170
Boiling point (K)	20	111	298-488	453-633
Auto-ignition temperature (K)	853	813	~623	~523
Minimum ignition energy (MJ)	0.017	0.30	0.29	-
Stoichiometric Air/Fuel Ratio (kg)	34.3	17.2	14.6	14.5
Quenching distance (at 1 bar & 298 K at stoichiometry; mm)	0.64	2.1	~2	-
Laminar flame speed in air (at 1 bar & 298 K at stoichiometry; m/s)	1.85	0.38	0.37-0.43	0.37-0.43
Diffusion coefficient in air (at 1 bar & 273 K; m ² /s)	8.5x10 ⁻⁶	1.9x10 ⁻⁶	-	-
Combustible Range (%)	4-75	5-15	1.3-7.1	0.6-5.5
Adiabatic flame temperature (at 1 bar & 298 K at stoichiometry; K)	2480	2214	2580	~2300
Octane number (R+M)/2	130+	120+	86-94	-
Cetane number	-	-	13-17	40-55

the source of electricity. You can also use other methods, like biomass gasification, biomass-derived liquid reforming or microbial conversion of biomass [Stępień 2021, Boretti 2019]. If you want emission-free hydrogen, you must use a solar-hydrogen system, but that's expensive. In 2016, 96% of hydrogen was made from fossil fuels [Stępień 2021]. Of course, when you use fossil hydrocarbons, CO₂ is created while reforming. It needs to be captured and stored to keep it from entering the atmosphere [Stępień 2021, Dimitriou, Tsujimura 2017, Faizal et al. 2019].

3. HYDROGEN AS FUEL

3.1. Physical and chemical properties of hydrogen

On the globe, hydrogen practically does not occur in its free state, but it is present in many other compounds, such as water, organic compounds, bases and acids. In its free form, it is referred to as H₂. It is odourless, colourless and tasteless [Wiącek 2011]. Due to its low molecular weight and high calorific value, hydrogen has the highest energy-to-mass ratio. This results in an explosion force about 2.5 times greater than conventional fuels [Idzior et al. 2013]. The low atomic mass is also associated with the low density of hydrogen in gaseous and liquid forms [Daszkiewicz et al. 2013].

Adding hydrogen fuel as an admixture or using it as a stand-alone fuel can improve performance for both spark-ignition and compression-ignition engines. Thanks

to the speed of combustion, low combustion energy, wide flammability limits and many other aspects, a more efficient combustion process distinguishes hydrogen fuel by up to 60% [Wiącek 2011]. Table 1 lists the properties of hydrogen and the properties of conventional fuels. The main features corresponding to the processes in the combustion chamber are highlighted in red.

Compared to other fuels, the flammability range of hydrogen is much better, ranging from 4% to 76% by volume in air. This is a significant advantage compared to other fuels due to the possibility of operating on leaner mixtures using hydrogen. Due to the complete combustion of hydrogen, it saves the amount of fuel burned. Moreover, due to a wide flammability range, heat losses caused by the walls of the combustion chamber are reduced, which increases the engine's thermodynamic efficiency [Stępień et al. 2021].

The hydrogen-air mixture burns almost seven times faster than mixtures of conventional fuels with air. The higher combustion rate also makes the accurate indicator run similarly to the ideal one, which proves its high thermal efficiency. A hydrogen-fuelled engine comes closest to achieving a perfect cycle when running on a stoichiometric mixture. In addition, when working on a stoichiometric mixture, the hydrogen flame spread rate is greater than the gasoline flame. Slowing the spread of the flame can be caused by leaning the mixture, but then the overall engine efficiency is also reduced.

Moreover, the engine's overall efficiency also decreases due to the engine's problems with breaking the mechanical

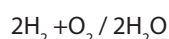
resistance of the engine on a lean mixture (low useful power). At the same time, the speed of flame propagation and its temperature affect the concentration of toxic compounds, combustion stability and thermodynamic efficiency. It is also worth noting that with full combustion of hydrogen, the mass ratio of air to fuel for the stoichiometric case is as much as 34.4, while in the case of gasoline, it is 14.7 (Tab. 2.1) [Stępień et al. 2021, Stępień 2021].

The minimum ignition energy is the smallest mixture that causes ignition with an ignition source. Observing the combination of this quantity (Tab. 1), one notes a minimal value corresponding to hydrogen. In the case of a hydrogen-air mixture, the low weight of the ignition energy may cause the flame to return to the intake system or premature ignition, resulting from trace amounts of unburned lubricating oil and hot exhaust gases and the combustion chamber [Stępień et al. 2021, Stępień 2021].

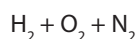
In addition, the hydrogen-air mixture is characterised by a short flame-extinguishing distance at the cylinder wall. This property results from the difficulty of extinguishing the hydrogen flame to the flames of other fuels, which results in the mixture burning in the gaps (e.g. between the piston and the cylinder) and returning the flame to the intake system through an open intake valve. It is also worth noting a feature of hydrogen, which is high diffusivity. Thanks to this property, hydrogen perfectly mixes with air, creating a mixture and becoming a safe gas (when hydrogen escapes due to a leak, it quickly disperses in the air [Stępień et al. 2021, Stępień 2021]).

What happens when hydrogen is burned?

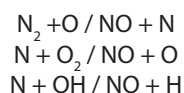
Hydrogen combustion is one of the simplest chemical reactions in a pure oxygen atmosphere. Combustion proceeds through:



Except for a small number of specialised high-energy applications, such as rocket engines, the vast majority of hydrogen combustion occurs in the presence of air. When hydrogen is burned, the mixture is more precisely a combination of



Hydrogen burns with a scorching flame, and the temperatures generated in this phase can be high enough to split normally stable molecules, referred to as "thermal NO" or the "Zel'dovich mechanism" [7,41,42]:



Hydrogen combustion can generate NO (nitric oxide) as a secondary waste by-product. NO is a critical air pollutant that reacts rapidly in the atmosphere to form nitrogen dioxide (NO₂). NO₂ is a globally regulated air pollutant that

is harmful to one's health and which, in turn, contributes to photochemical ozone pollution and particulate matter (PM_{2.5}). [Stępień et al. 2021, Stępień 2021, Brzeżański et al. 2013, 2019].

The potential formation of NO_x as a by-product of hydrogen combustion is rarely discussed when discussing the pros and cons of its use as a future climate-friendly fuel. However, there is a risk that the adoption of hydrogen as a combustion fuel, if not properly managed, may lead to some unintended consequences due to the co-emission of harmful NO_x. Ciniviz and Brzeżański in the articles [Ciniviz et al. 2012, Brzeżański et al. 2013, 2019] noted that the dual-fuel hydrogen engine has characteristics that enable operation at lower equivalence factors at a part load, resulting in reduced NO_x emissions and increased thermal efficiency, thereby reducing fuel consumption. The main problem of dual-fuel hydrogen-powered engines are NO_x [Folentarska et al. 2016]. One of the methods to effectively reduce NO_x emissions is exhaust gas recirculation (EGR). Thanks to the dilution effect, EGR effectively reduces NO_x emissions, where the oxygen concentration in the intake decreases.

Furthermore, a significant decrease in volumetric efficiency is observed as EGR rates increase (reductions of approximately 15% are noted compared to dual-fuel hydrogen without EGR). At the same time, adding EGR to the operation of two hydrogen fuels may increase particulate emissions compared to the process of two hydrogen fuels without EGR. As a result, when operating on two hydrogen fuels from EGR, smoke is produced at a level similar to the regular operation of a compression-ignition engine. In addition to NO_x reduction, when EGR is added, there is an increase in unburned HC, CO and CO₂ emissions. Another method is to introduce liquid water into the combustion chamber. Water injection can also prevent knocking and pre-ignition when burning hydrogen. In this case, water acts similarly to diluents such as EGR, cooling the charge and reducing the combustion rate. However, water injected into the intake manifold reduces the volumetric efficiency [Ciniviz et al. 2012, Korakianitis et al.]. Concerning the use of hydrogen in vehicles, hydrogen in motor vehicles can be used in several ways:

- pure hydrogen;
- percentage addition of hydrogen to the classic hydrocarbon fuel;
- H₂CNG (methane with the addition of hydrogen);
- and as a fuel cell.

The first three can be used as fuel for a conventional ICE to run on hydrogen.

The use of hydrogen as a fuel for ICEs and fuel cells (FCs) in vehicles has emerged as a potential trend in the future of transportation. A range of fuels can power ICEs, but this necessitates adjusting the engine controller and ensuring the compatibility of engine components with the fuel used [Al-baghdadi et al. 2020]. Hydrogen has the advantage over FC technology of greater tolerance to pollution, more mature ICE technology, lower consumption of

rare materials, and ease of adaptation of ICEs to run on hydrogen [Al-baghdadi et al. 2020]. Since the last century, H₂ICEs have been a research subject [Boretti et al. 2019, Dimitriou, Tsujimura 2017, Faizal et al. 2019]. A comparison of the torque and power output of the ICE with the electric motor as the power source in battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) is illustrated in Figure 1 [Stępień 2021]. The torque of an electric motor is extreme at slower engine speeds but decreases as engine speed increases hyperbolically. The power output of an electric motor is uniform as each motor has a fixed power rating to prevent overheating and damage to electrical wires. On the other hand, the torque of an ICE remains more or less constant as engine speed rises (especially with supercharged engines), meaning that the power output of the ICE is higher at higher engine speeds. As seen in Figure 1, there is an excess of power output from the ICE once a certain speed is reached, and this is an advantageous and typical feature of combustion engines, including those powered by hydrogen.

Ciniviz, in an article, noted that for compression ignition (CI) engines, hydrogen can be used as an additive to diesel fuel for several reasons:

- it increases the H/C ratio of the entire fuel;
- and the injection of small amounts of hydrogen into a CI

engine can reduce the heterogeneity of atomised diesel fuel due to the high diffusivity of hydrogen, which makes the combustible mixture better mixed with air and more homogeneous [Szwaja et al. 2009].

In this way, the formation of hydrocarbons, carbon monoxide and carbon dioxide during combustion can be avoided entirely; however, trace amounts of these compounds may be formed as a result of partial combustion of lubricating oil in the combustion chamber [Saravanan et al. 2009].

Brzeżański et al. [2019] proved that adding hydrogen directly to the engine intake duct increases the engine's operating range without the risk of knocking. Using an appropriate direct injection strategy allows for the combustion of a charge with a reduced excess air coefficient close to the stoichiometric composition. As a result, the maximum cylinder pressure increases, and engine performance significantly improves. At the same time, significant increases in pressure in the cylinders do not cause any knocking. Injecting hydrogen directly into the piston engine cylinder during both the compression and combustion processes allows using hydrogen as a fuel equivalent to conventional hydrocarbon fuels.

However, hydrogen cannot be used as the only fuel in a CI engine because the compression temperature is insufficient to initiate combustion due to its higher self-ignition temperature [Saravanan et al. 2008]. Therefore, hydrogen cannot operate in a diesel engine without the help of a spark plug or glow plug. This makes hydrogen unsuitable for diesel engines as the sole fuel. For this reason, as reported in the literature, activities related to

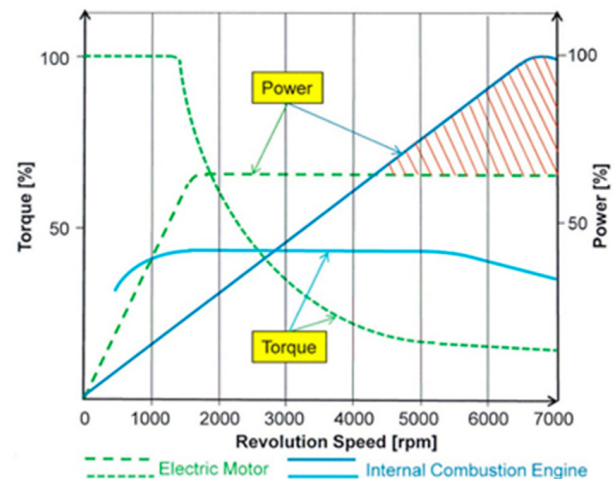


Figure 1. Comparison of ICE and electric motors (BEVs and FCEVs) [Stępień 2021]

fuelling a CI engine with hydrogen were based on the dual-fuel mode. In a dual-fuel engine, the primary fuel is introduced/carbureted or injected into the intake air, while combustion is initiated by diesel fuel, which acts as the ignition source. The amount of pilot fuel can range from 10% to 30%, with the remaining energy provided by the primary fuel. The hydrogen dual-fuel engine has characteristics that allow it to operate at lower equivalence ratios at part load, reducing NO_x emissions and increasing thermal efficiency, thereby reducing fuel consumption. The main problem of dual-fuel hydrogen-powered engines are NO_x [Saravanan et al. 2010]. One method to effectively reduce NO_x emissions is EGR. Due to its dilution effect, EGR effectively reduces NO_x emissions, which reduces the oxygen concentration in the inlet. Moreover, the reduction in volumetric efficiency with increasing EGR rates is significant (a reduction of approximately 15% is noted compared to operation on two hydrogen fuels without EGR). At the same time, adding EGR to the operation of two hydrogen fuels may increase particulate emissions compared to operating on two hydrogen fuels without EGR. As a result, when operating on two hydrogen fuels with an EGR system, the smoke level is similar to the normal operation of a diesel engine. In addition to the NO_x reduction, an increase in unburnt HC, CO and CO₂ emissions is also recorded when EGR is added. Another method is to introduce liquid water into the combustion chamber. Water injection can also prevent knocking and pre-ignition when burning hydrogen. In this case, water acts similarly to diluents such as EGR, cooling the charge and reducing the combustion rate. However, water injected into the intake manifold reduces the volumetric efficiency [Korakianitis et al. 2010].

Conventional diesel engines can be converted to operate on hydrogen–diesel dual mode with up to about 38% of full-load energy substitution without any sacrifice on performance parameters such as power and efficiency [Ciniviz et al. 2012, Das 2002].

Hydrogen can be used as a fuel directly in an ICE, almost similar to a spark ignition (SI) gasoline engine. Most previous research on H_2 as a fuel has focused on its use in SI engines. Hydrogen is an excellent candidate for SI engines as a fuel with unique and desirable properties, such as low ignition energy, very high flame spread speed, and a wide operating range. Hydrogen fuel, when mixed with air, forms a combustible mixture that can be burned in a conventional SI engine at an equivalent ratio below the lean flammability limit of the gasoline–air mixture. The resulting ultra-lean combustion produces low flame temperatures, leading to less wall heat transfer, higher engine efficiency and lower NO_x emissions [Abdelghaffar 2010, Gupta 2008, Wahab 2009]. Therefore, extensive research into pure H_2 as a fuel led to the development and successful commercialisation of the hydrogen engine. For example, Ford developed the P2000 hydrogen engine to power Ford's E-450 shuttle bus. BMW developed a 6.0-litre V-12 engine using liquid H_2 as fuel. This engine with an external mixture formation system has a power of about 170 kW and a torque of 340 Nm [Wahab 2009].

Natural gas is considered the preferred engine fuel, and the natural gas engine is implemented in both SI and CI engines. However, due to the slow-burning rate of natural gas and poor lean-burn ability, the natural gas SI engine has the disadvantage of having large cycle-to-cycle fluctuations and poor lean-burn ability, which reduces engine power output and increases fuel consumption [Huang et al. 2006].

Due to these limitations, natural gas with hydrogen for use in an ICE is an effective method to improve combustion speed, with a laminar combustion speed of 2.9 m/s for hydrogen compared to a laminar combustion speed of 0.38 m/s for methane. This may improve cycle-to-cycle fluctuations caused by a natural gas engine's relatively poor lean burn capability. This way, natural gas engines can reduce exhaust emissions, especially methane and carbon monoxide. In addition, adding hydrogen allows for increased fuel economy and thermal efficiency. The thermal efficiency of natural gas enriched with hydrogen was considered [Ciniviz et al. 2012].

Using a mixture of hydrogen and natural gas as a fuel comes with some challenges. One of the biggest challenges in using HCNG as an engine fuel is determining the most appropriate ratio of hydrogen to natural gas. When the hydrogen content increases above a certain level, abnormal combustion processes such as pre-ignition, knocking and back-ignition will occur unless the ignition timing and air-fuel ratio are correctly adjusted. This is due to the short quenching path and the higher hydrogen combustion rate, which causes the walls of the combustion chamber to heat up, resulting in more significant heat losses to the cooling water. As the hydrogen addition increases, the lean-burn limit increases and the maximum braking torque (MBT) decreases. This means there are interactions between the hydrogen content, ignition time and excess air ratio [Fanhu et al. 2003]. Hydrogen-powered ICEs (H₂ICE) have been the

subject of research since the last century [Heindl et al. 2009, Kawamura et al. 2010, Kawamura et al. 2009].

The electric motor's torque is very high at low engine speeds but decreases hyperbolically as engine speed increases. The power output of an electric motor is shown with a flat line because each electric motor has a fixed power rating to avoid overheating and damaging the insulation of electrical wires. In contrast, the torque of an ICE remains more or less constant as the engine speed increases (especially in the case of supercharged engines). As a result, the ICE has greater power output at higher engine speeds. This is a beneficial and typical feature of ICEs, including hydrogen-powered ones [Stępień 2021].

The hydrogen-powered ICE is the only known ICE that meets the strict regulations of the European Union. It also emits significantly lower levels of pollutants compared to diesel engines. Although NO_x are the only significant by-products of H_2 combustion, an advanced combustion process and a relatively simple exhaust gas treatment system can reduce these emissions to almost zero. Additionally, this technology can be implemented quickly and widely, with minimal delay, if diesel vehicles are phased out shortly. Different low-emission powertrains are being looked at for the future, including BEVs, fuel cell electric drives (FCEV), synthetic fuel combustion engines, hydrogen-powered combustion engines and hybrid powertrains. Each has advantages and disadvantages, making them suitable for specific applications [Stępień 2021].

Various alternative fuels, including ethanol, methanol, biodiesel, propane, natural gas and hydrogen, have been developed to reduce engine emissions compared to those caused by traditional liquid hydrocarbon fuels. Of these, hydrogen is the only fuel that has the potential to be completely free of hydrocarbon, carbon monoxide and carbon dioxide emissions. Furthermore, hydrogen has a much higher burning velocity in an engine combustion chamber (approximately six times that of gasoline) and a wide flammability range, allowing it to be burned in engines with different proportions of air (4%–75%). Research has demonstrated that a hydrogen-powered piston engine can be up to 5% more efficient than a diesel-powered one (44.5% for the prototype engine). This makes hydrogen one of the most essential fuel sources for the future, as its use will allow governments to meet increasingly stringent exhaust emissions standards. As a sustainable fuel, hydrogen can also reduce global dependency on fossil fuels and the level of exhaust emissions from motor vehicles. However, the emission level is still largely dependent on the method of hydrogen production [Stępień 2021].

Combustion is not the only way to use hydrogen as a fuel. It can be fed into electrochemical fuel cells to generate electricity directly, and this approach does not produce NO_x as a waste by-product. In principle, the energy efficiency of a fuel cell is higher than that of an ICE (the former is limited by Gibbs' free energy, and the latter by the Carnot efficiency). Without a doubt, fuel cells will be

an essential element of the future hydrogen economy, and their impact on air quality at the point of use is positive because they do not produce NO_x as a by-product. Fuel cell technologies, however, have a more limited application history than combustion and require a greater degree of technological transformation than modifying existing combustion approaches to include hydrogen [Stępień 2021].

Hydrogen used to power a fuel cell may prove revolutionary for the automotive industry. Electric cars are estimated to be only a transitional phase for vehicles powered by hydrogen cells. The operation of such a fuel cell is based on a chemical reaction that decomposes hydrogen, producing a proton and an electron at the anode, followed by the fusion of the base reaction elements at the cathode. These processes are also accompanied by the flow of electrons from the anode to the cathode, excluding the membrane. As a result of electrochemical reactions of oxygen and hydrogen, electricity, heat and water are produced. Hydrogen (pure or in a mixture) is continuously supplied to the anode, and oxygen as an oxidant (pure or in an air mixture) is supplied to the cathode [Levchenko 2021].

Hydrogen-powered fuel cells are characterised by high efficiency and work efficiency. Moreover, they generate energy with a high degree of resistance to interference. Furthermore, it is a scalable energy source because fuel cells can be combined into systems. The disadvantage of using fuel cells is the high cost of their production due to the specialised construction materials used in them, and obtaining hydrogen is also expensive [Levchenko 2021].

The use of hydrogen in combustion engines

Hydrogen has potential in applications that use SI engines and can deliver good performance. Its fast flame-spread, low ignition energy, and wide operating range allow the combustion process to be optimised. This can help reduce emissions of pollutants like NO_x. Hydrogen can be used with SI engines in three ways: manifold induction, direct introduction, or as an admixture to methane or gasoline. Hydrocarbon and carbon monoxide emissions are minimal when used in these ways, and performance is improved, especially under a part load. Additionally, the combustion of very lean mixtures with an equivalence factor of 0.1 is enabled.

However, SI engines are an inferior solution where high torque is required at low engine speeds. In such cases, engines operating at higher compression ratios, such as diesel, are usually used.

There are multiple benefits to hydrogen being used as an additive to diesel fuel in CI ICEs [Stępień 2021, Brzeżański 2019]. One of the primary advantages is that it improves the uniformity of the diesel fuel spray due to its high diffusivity. This allows for almost complete combustion of hydrocarbons, carbon monoxide and carbon dioxide. The engine's injector is an essential component in this process as it controls how compressed hydrogen is injected into the combustion chamber [Stępień 2021, Brzeżański 2019]. However, CI engines are unable to be powered by hydrogen as a main fuel, due to its higher auto-ignition

temperature. As a result, diesel fuel is used as the ignition source, and the main fuel is injected into the intake air or carburettor. Nitrogen oxide emissions can be reduced using EGR, but this can decrease volumetric efficiency. Although water injection into the intake manifold can also reduce NO_x emissions, it has the same effect as EGR in reducing volumetric efficiency.

3.2. Advantages and disadvantages of hydrogen fuel

The use of hydrogen fuel in a vehicle has many advantages and disadvantages. The advantages of hydrogen power include [Kruczyński et al.]:

- physical and chemical properties of hydrogen that favour the combustion process;
- possibility of using various forms of fuel, i.e., pure hydrogen, mixtures with a percentage of hydrogen, hythane;
- significant reduction in the concentration of unburned hydrocarbons, carbon monoxide and carbon dioxide as a result of the addition of hydrogen to gasoline;
- possibility of use in fuel cells;
- and achieving greater or similar overall engine efficiency in certain operating conditions compared to a conventional power supply.

The disadvantages of hydrogen fuel include [Kruczyński et al.]:

- special conditions for transport and storage of hydrogen;
- increased concentration of NO_x when hydrogen is added to fuels;
- and the need to adapt an engine powered by conventional fuel to hydrogen injection.

The main disadvantages of hydrogen fuel are its storage and transport. According to estimates, up to 40% of hydrogen energy may be released to the environment due to storage. Hydrogen's biggest problem in this aspect is its low density. Compressing and storing hydrogen in pressure tanks is the simplest and cheapest solution. Such tanks must be made of highly resistant materials for pressure and hydrogen diffusion. Materials other than metals are used for this purpose, meeting such requirements to reduce the weight of the tanks. Pressure tanks should be tested for impact resistance and overpressure. The tank must have a multi-layer structure to store hydrogen in the gaseous state. The outer layer must be made of a material with high tear strength. The inner layer is usually made of a polymer that is tasked with retaining hydrogen thanks to its molecular structure. Among these layers, there is a separating layer of carbon composite. In addition, the pressure tank equipment also includes a temperature and pressure sensor and a pressure regulator. Another method of storing hydrogen is its liquefaction. This solution's main advantage is energy loss up to twenty times lower than a pressure solution. Moreover, liquid hydrogen is much easier

to transport and has a higher density. The disadvantages of liquid hydrogen tanks include the required hydrogen storage temperature of -253°C (cryogenic temperature) and their high production costs [Marszałek 2019].

Hydrogen can also be stored as metal hydrides or other chemical compounds based on activated carbon. Hydrogen storage in metal hydrides is characterised by low process pressure, temperature, and safety. Metal hydrides can be reversible and irreversible. The first are solid alloys and organometallic combinations, which, at an appropriate pressure and temperature, are capable of repeated adsorption and desorption of hydrogen. Irreversible hydrides react mainly with water, getting rid of hydrogen, and as a result of this phenomenon, they cannot be reabsorbed at the point of desorption. Hydrogen storage in carbon compounds is based on an electrochemical reaction and adsorption on the surface of carbon solids. Hydrogen desorption from carbon compounds can be accomplished by providing the required energy to the carbon material. Tanks can also be made from carbon materials, the most common carbon forms being carbyne, graphite, graphene, carbon nanotubes and fullerenes [Marszałek 2019].

4. SUMMARY AND CONCLUSIONS

Hydrogen is undoubtedly an exciting alternative to conventional engine power in various respects. Popularising hydrogen in piston engines on a global scale may prove to be a solution to the problem of environmental protection due to the negligible concentration of toxic substances in the exhaust gases of hydrogen engines. The exception

is NO_x, which can be reduced thanks to purification systems, e.g., SCR. Moreover, the advantage of hydrogen fuel is its physical and chemical properties that favour the combustion process. Hydrogen is also the future fuel due to its possible use in fuel cells. However, the disadvantages of hydrogen fuelling are undoubtedly its storage and volatilisation due to its low density. One of the factors limiting the globalisation of hydrogen power is the need to obtain it due to complex chemical processes. Several issues must be faced to adapt a conventional engine, such as abnormal hydrogen combustion, synchronisation of injection, ignition and mixture, the impact of hydrogen on materials, injection setting, and design changes to the engine and components. This field has broad research potential due to various forms of hydrogen fuel (pure hydrogen, percentage addition to conventional fuel or hythane). As a result of experimental changes in the hydrogen concentration in the fuel mixture, it is possible to obtain a mixture with the best parameters under selected engine operating conditions. On the first pages of this strategy, we see that hydrogen can play a crucial role in energy storage. This is quite a correct assumption, as hydrogen energy storage will have many applications. It can be used, among other things, to make the network more flexible, as it can store energy seasonally and daily. Hydrogen can also be used, among other aspects, in road transport, aviation and shipping. The production of green hydrogen and its simultaneous use in energy-intensive industries and transport is a crucial tool for decarbonisation and achieving goals related to reducing greenhouse gas emissions. Thus, hydrogen will also find its application in areas where electrification is impossible or uneconomic.

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