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Hydrogen as a fuel for spark ignition combustion engines – state of knowledge and concept

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Accelerating the process of the transport and energy sectors increases the interest in fuels derived from renewable sources. The predicted three-fold increase in hydrogen production by 2050, driven by its falling production costs, justifies the direction of research aimed at its popularisation as a fuel for internal combustion engines (H2ICE). The presented article provides an overview of the state of knowledge on hydrogen combustion systems, which are currently the most attractive development path, mainly due to the well-developed production technology and relatively low recycling cost compared with fuel cells. The paper contains a comprehensive analysis of currently available solutions covering issues related to the production, storage, and transmission of hydrogen, with particular emphasis on the Polish market, which is one of the largest in Europe in terms of its production. The authors also propose their own concept of a hydrogen combustion system for application in an internal combustion engine. The presented solution is based on the idea of prechamber introduction in order to improve combustion process parameters and hence overall engine efficiency.

Key words: *H2ICE, alternative fuels, hydrogen combustion, hydrogen knock, polish hydrogen market*

1. Introduction

1.1. General

As an alternative fuel source for vehicles, hydrogen has many advantages, the most important of which is the elimination of carbon, which is a key aspect in the decarbonization of the transport sector. Due to its high gravimetric energy density (143 MJ/kg) hydrogen is classified as a high-energy fuel and is therefore an alternative to battery technologies [28]. The biggest disadvantage in the use of hydrogen to drive motor vehicles is its low volumetric energy density, which requires the use of relatively large tanks. Currently, mainly because of the geopolitical situation, a very important factor is the possibility of producing hydrogen anywhere in the world, which of course requires the selection of the appropriate technology, but allows for a given region to become energy independent [31].

1.2. Historical background

The emergence of the concept of the hydrogen economy dates back to the 1970s and originally referred to the replacement of fossil fuels in transport with hydrogen fuel [8]. At that time, the main stimulus for development was the fuel crisis, which largely contributed to the development of research directions in the field of alternative fuels. The decline in the popularity of alternative sources of vehicle propulsion coincided with the stabilization of the oil market in the 1980s, but the topic returned in the next decade thanks to the popularization of activities for climate protection. During the so-called second wave of hydrogenation of the economy, solutions aimed at the popularization of hydrogen as a fuel have been superseded to a large extent by electric vehicles, which to this day constitute an increasing percentage of vehicles on the market. Currently, we are dealing with the third wave of hydrogenation of the economy, mainly because of the extension of this concept to sectors such as metallurgy, agriculture, and the chemical industry. A clear stimulus for the development of the hydrogen economy in Europe was the announcement by the EU of the Hydrogen Strategy in 2020 and the entry into force of the Directive of the European Parliament and of the Council of EU on the promotion of the use of energy from renewable sources (the so-called RED II directive) in 2018. Their main goal is to achieve climate neutrality by the EU by 2050 (European Green Deal). In order to achieve this, it is necessary to increase the share of renewable energy sources in the electricity production process and replace fossil fuels commonly used in transport with alternative fuels such as hydrogen.

2. Polish hydrogen market

2.1. Poland in comparison to other EU Member States

The development of hydrogen technologies in the world was also reflected in Poland, as a result of which, in 2021, the Polish Hydrogen Strategy was announced, defining specific goals for building a hydrogen economy in the next decades. Analyzers show that in the next dozen or so years, hydrogen, in particular green, may become the basis for the functioning of the industry in Poland [10]. Currently, Poland is one of the largest hydrogen producers in Europe. Four countries account for more than half of hydrogen consumption in Europe: Germany (22%), the Netherlands (14%), Poland (9%) and Belgium (7%). Hydrogen production in Poland is dominated by production for companies own needs, mainly for the chemical sector. Its largest producers are Grupa Azoty (approx. 400 thousand tonnes per year, of which includes 600 tonnes of merchant), PKN Orlen and LOTOS Group (approx. 145 thousand tonnes per year each) [13].

Table 1. Polish companies with experience in selected branches of the hydrogen market [25]

Economic activity	Name of company	Range of operation
Production	Jastrzębska Spółka Węglowa (JSW)	Hydrogen separation from coal gas
	Lotos, Polskie Sieci Elektroenergetyczne (PSE)	Hydrogen separation from coal gas
	Sescom	Sale of PV powered electrolysers
	Grupa Azoty	Production of merchant grey hydrogen
	Polenergia	Production and utilization of green hydrogen; cogeneration adoption to hydrogen combustion
	RB Consulting	Electrolysers distribution
	Zespół Elektrowni Pątnów Adamów Konin (ZE PAK)	Application of biomass powered electrolysers
	PKN Orlen	Application of RES powered electrolysers
	Tauron Wytwarzanie	Production of SNG; Hydrogen production from RES powered electrolysers; CO_2 capture systems
	Wałbrzyskie Zakłady Koksownicze „Victoria”	Hydrogen separation from coal gas
	Stalprodukt	Methane steam reforming
Storage	PGNiG	Hydrogen pumping into distribution networks; underground storage
	Stako (Worthington Industries Group)	Pressure vessels
Application	Lotos Group	Hydrogen refuelling stations
	PKP Cargo	Hydrogen application in rail vehicles
	H. Cegielski	Hydrogen powered locomotive prototype
	PKN Orlen	Hydrogen refuelling stations
	PGNiG	Hydrogen refuelling stations
	EC Grupa (Energocontrol Sp. Z o.o.)	Fuel cells development
	APS Energia (with Gdańsk Technical University)	Hydrogen emergency power supply system
	Remontowa Holding	Conceptual design of hydrogen powered marine units
	Solaris	Hydrogen powered buses production
	Polenergia (with Siemens)	Hydrogen combustion in gas turbines
Pipeline transfer	PGNiG	Hydrogen blending in pipelines
Instruments	Intergaz	Gas meters
	cGAS controls	Pressure tanks
	Emag Serwis	Sensors
	Frankoterm	Cryostatic devices

Poland, as one of the largest hydrogen producers in Europe, has highly developed technologies for its production and use mainly in the field of chemical and energy industries. With this state of matter in mind, it is justified to think that in the near future the development of hydrogen technologies will also be reflected in road transport.

2.2. Predictions in numbers

The annual demand for hydrogen in Poland in 2040 is expected to exceed 100 TWh, of which 20 GW will come from electrolysers. The total installed RES capacity at that time is to be 60 GW. It is planned to produce hydrogen as part of three main paths: the use of surplus RES (energy storage), the operation of a separate part of RES in an off-grid system integrated with electrolysers, and distributed production for local needs, e.g. vehicles refueling [10].

3. Hydrogen production methods

3.1. Colors of hydrogen

Currently, approximately 96% of the hydrogen produced in the world is estimated to come from the processing of fossil fuels, mainly as a result of the steam reforming of natural gas, which is currently considered the most economical hydrogen production technology [19]. In the near future, this share will be reduced in favour of electrolysers powered by renewable energy sources, which should significantly contribute to reducing the carbon footprint and lowering the prices of green hydrogen production. Depending on the primary energy sources used in the production of hydrogen, different colours are used in order to describe it [17, 30] as it is shown in the Fig. 1.

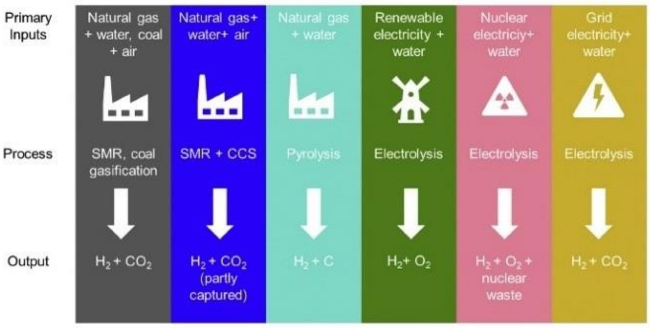


Fig. 1. Hydrogen production technologies in relation with colours [1]

3.2. Methane steam reforming

Natural gas steam reforming is the most widely used hydrogen production process today. The reforming process takes place at high temperatures, ranging from 1023–1223 K, in the presence of a nickel catalyst. The reactions take place in oven tubes filled with the catalyst. Water vapor is added to the methane. As a result of this process, a gas mixture containing mainly carbon monoxide and hydrogen, known as the synthesis gas, is obtained. The efficiency of the process is estimated at 75%, but its disadvantage is the generation of large amounts of CO_2, up to 12 kg per 1 kg of hydrogen (gray). The syngas created in the steam reforming process is used for the Fischer-Tropsch synthesis toward the production of the so-called synthetic hydrocarbons. The undoubted advantage of syngas is the absence of nitrogen. One of the ways to reduce CO_2 emissions is CCU and CCS technologies, which enable the reduction of CO_2 emissions by up to 95%. We are then talking about blue hydrogen [49].

3.3. Methane pyrolysis

Another method of hydrogen production, which is a subject of investigation, is natural gas pyrolysis. The process involves splitting of methane into solid carbon and gaseous hydrogen. To make the reaction possible and achieve relatively high conversion rates, process temperature should be maintained at a level of 1773 K [6]. Since the solid carbon obtained from the reaction is easy to handle and is considered as unharmful to the environment, the main problem is the high cost of reactors and their complexity. However, the gases obtained in the process require additional treatment to remove impurities (Fig. 2). Methane pyrolysis is a relatively low energy-consuming process, and if this energy comes from renewable resources, hydrogen could be produced on an industrial scale without almost any CO_2 emissions. Hydrogen obtained in this method is described as turquoise.

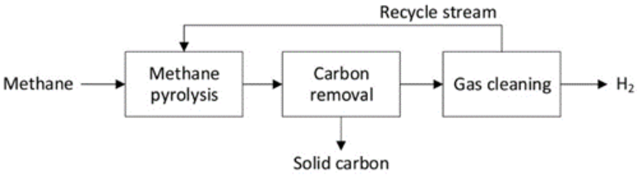


Fig. 2. Schematic diagram of methane pyrolysis process [17]

3.4. Coal gasification

Coal gasification is the oldest method of producing hydrogen. It was used when natural gas was not yet available. The coal is heated and mixed, in the presence of a catalyst, with steam, which gives us synthesis gas. Hydrogen and other chemicals are extracted from this gas or burned to generate electricity. There have been many scientific studies focused on reducing emissions of pollutants such as nitrogen and sulfur oxides, mercury and carbon oxides [16, 23].

3.5. Biomass

Hydrogen can also be produced from biomass derived from plant and animal wastes, using pyrolysis and gasification processes. When biomass is used to produce gas fuel, no carbon dioxide is emitted into the environment. Unfortunately, the unit price of hydrogen obtained using biomass is much higher than that of hydrogen derived from fossil fuels [5]. The biological processes of producing hydrogen from biomass are fermentation, anaerobic fermentation, and metabolic processes; however, they are considered as inefficient compared to traditional hydrogen production techniques [15, 33].

3.6. Electrolysis

In the future, the most supported method of producing hydrogen in the European Union will be the production of hydrogen by electrolysis of water using electricity from renewable energy sources. Unfortunately, currently the production of hydrogen with the use of electricity reaches approx. 4% of the total production. Moreover, most of this hydrogen is a by-product of chlorine production in the brine electrolysis technology called white hydrogen (formed as a by-product of further chemical reactions). If the hydrogen is produced by electrolysis of water, and the electricity used comes from renewable sources, this hydrogen is called green. Green hydrogen is emission-free and has the greatest potential to reduce greenhouse gas emissions. During the electrolysis of water, the chemical bond between the hydrogen and oxygen is broken in the solution to form hydrogen and oxygen gas. Currently, the overall efficiency is around 50–60% depending on the use of cell technology. About 9 liters of water and about 50 kWh of electricity are needed to produce 1 kg of hydrogen [4]. Recently, research in this area has focused mainly on reducing the cost of hydrogen production through the use of carbon-based materials electrodes [21].

Currently, the potential for red hydrogen production in newly developed fourth-generation nuclear reactors using high-temperature electrolysis of water vapor on cells with solid oxidants is being discussed [35].

4. Hydrogen storage

Hydrogen as a fuel has many storage options. It can be stored in the form of a compressed gas, a liquid, or in the form of metal hydrides, chemically bonded or on the surface of materials, e.g. carbon materials with a large surface, such as graphite or carbine nanotubes [12, 48]. Currently, gaseous compressed hydrogen is mentioned as the most promising and also the most effective technology for its storage, mainly because of the relatively simple method of carrying out this process [26]. Hydrogen compressed in this way tends to volatilize, but there are ways to counteract this phenomenon by using appropriate tanks to minimize storage losses.

Depending on the application, these tanks can be divided into small tanks for short-term storage (e.g. car tanks) with 99% efficiency and high discharge rate, and large-size industrial tanks ensuring long-term protection of hydrogen reserves [43].

In the view of materials used, the tanks for short-term hydrogen gas storage can be divided into:

- metal tanks – cylinders made of steel or aluminum, used to store hydrogen at a pressure of up to 20 MPa, used mainly for laboratory purposes
- reinforced tanks – made of aluminum, reinforced with glass or carbon fiber with a maximum working pressure up to approx. 30 MPa
- composite tanks – built based on glass or carbon fiber with a metal insert with a storage pressure of up to approx. 40 MPa, they are twice lighter than in the case of metal tanks
- carbon fiber tanks covered with a polymer layer – withstanding pressures up to approx. 70 MPa, commonly used in hydrogen powered vehicles (FCHV) [7].

Due to the high permeability of hydrogen in the tanks, polymer coatings are used to limit the volatilization of hydrogen [2].

The pressures required for hydrogen road transport tanks are in range of 35–50 MPa. On the other hand, in the case of applications in hydrogen powered vehicles, mainly because of ensuring the appropriate range, the hydrogen pressure in the tank is 70 MPa. Research is currently underway to reduce the size of the tanks, mainly by increasing the maximum storage pressure. Currently, at a pressure of 70 MPa, compressed hydrogen has approximately 15% of the volumetric energy density of gasoline (Fig. 3), which entails the need to use larger tanks.

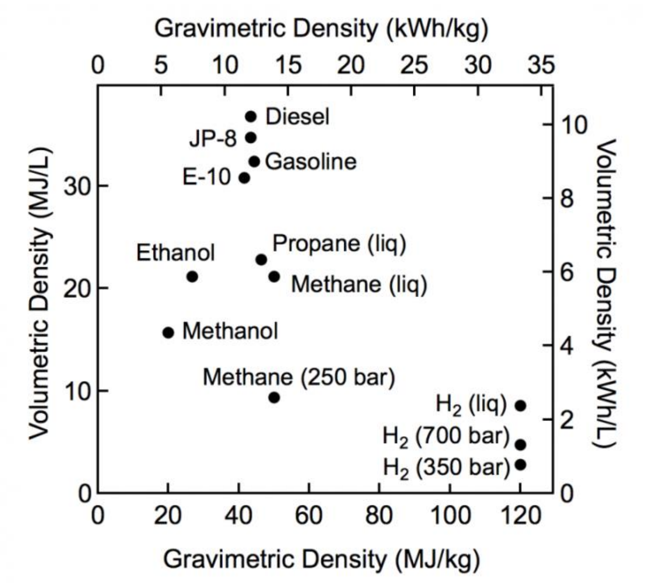


Fig. 3. Comparison of specific energy and energy density for selected fuels based on their LHV [44]

For long-term storage of hydrogen on an industrial scale, geological storage is indicated as the best solution [42]. There is a method of storing hydrogen in underground storage facilities created as a result of the exploitation of oil or gas deposits. Currently, work is underway in Poland to store hydrogen in salt caverns, which are already used as natural gas storage facilities [41]. Their use minimizes the risk of hydrogen contamination while allowing its safe storage. This solution is used in the USA and UK, and recently also in Germany. The pressure level in the underground tanks is between 2 and 18 MPa.

An alternative to hydrogen storage is condensation, which allows it to increase its volumetric energy density by more than three times, thus reducing the size of the tanks. However, this process is burdened with higher compression energy, which in the case of condensation amounts to 30–40% of the energy contained in the fuel, compared to 15–20% in the case of gas compression. In addition, this type of storage requires the temperature to be kept at 20 K, which increases the cost of hydrogen storage, therefore condensation is considered as a technology for short-term storage [47].

5. Hydrogen combustion engines – H2ICE

5.1. Hydrogen vehicles

Hydrogen fuelling of internal combustion engines is an idea known and implemented for many years, however, due to legal regulations limiting the possibility of using fossil fuels in transport, there is a noticeable increase in interest in the development of hydrogen propulsion technology. In recent years, there has been an increase in the market share of fuel cell vehicles (Fig. 4), characterized by higher efficiency than H2ICE, which are no less attractive alternatives due to well-developed production technologies and high production potential.

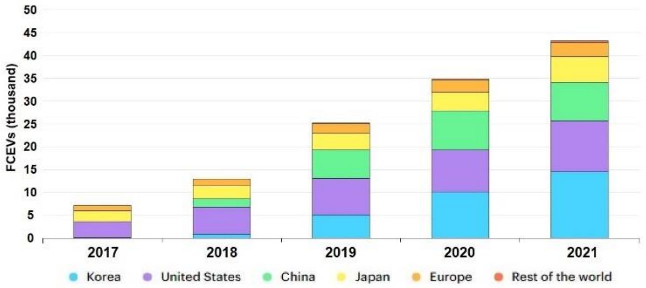
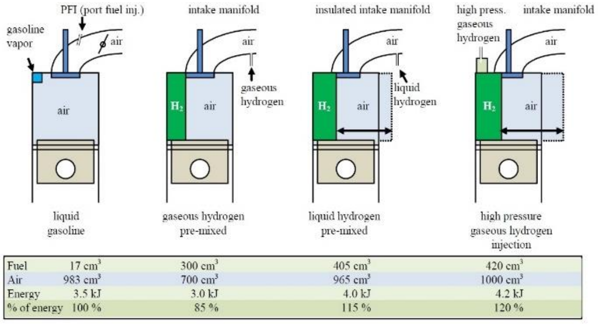


Fig. 4. Fuel cell vehicle stock by region, 2017–2020 [20]

The process of introducing hydrogen as fuel to internal combustion engines on a large scale is carried out gradually, starting from large generating units, engines for propulsion of floating units and traction units [14, 29]. In recent months, there has also been an increase in interest in this technology among manufacturers of heavy duty vehicles.

Due to the form of hydrogen supply to the combustion chamber, two main methods can be distinguished: gaseous and liquid hydrogen injection. While hydrogen in the liquid state is characterized by a higher energy density than in the gaseous state, it requires maintaining the temperature at the level of 20 K, which generates a high cost of such an installation. Depending on the location of the injector, these systems are divided into direct and indirect injection (Fig. 5).



Fuel	17 cm^3	300 cm^3	405 cm^3	420 cm^3
Air	983 cm^3	700 cm^3	965 cm^3	1000 cm^3
Energy	3.5 kJ	3.0 kJ	4.0 kJ	4.2 kJ
% of energy	100 %	85 %	115 %	120 %

Fig. 5. Hydrogen injection systems [32]

5.2. Hydrogen combustion

The process of hydrogen combustion in an internal combustion engine generates some problems and the main reason for that is the so-called dual nature of hydrogen knock. With respect to definition, knocking is assumed to be incorrect combustion of an air-fuel mixture resulting in the generation of uncontrolled pressure waves acting against the main combustion source leading to a decrease in overall engine efficiency [18]. Practice shows that despite the high autoignition temperature and compression resistance of hydrogen resulting from the high octane number (RON > 130) it is very likely to achieve knocking phenomena [37]. The reason for such state seems to be the low ignition energy of hydrogen and the fact that the octane number is not an appropriate parameter in order to describe the properties of gaseous fuel. As research shows a much better indicator of describing the probability of a heavy run of the engine while combusting hydrogen, the so-called methane number proposed by Ryan et al. [34]. It is a parameter that describes the percentage content of methane in the reference mixture of hydrogen and methane. Since methane is assumed to have the highest index, hydrogen is considered to be the most vulnerable to knock occurrence with MN = 0 (Table 2).

Table 2. Methane number of selected gaseous fuels [24]

Fuel	Hydrogen	Coal gas	Propane	Natural gas	Methane
MN	0	24–30	34	75–95	100

Dual nature of hydrogen knock is an outcome of two main mechanisms of its occurrence. The first one called heavy knock is described as air-fuel mixture autoignition at the end of compression stroke as a result of elevated temperature and pressure in combustion chamber. It occurrence being a highly undesirable phenomena leads to engine thermal load increase and excessive wear of crank system bearings. The other mechanism of incorrect hydrogen combustion described in literature as light knock results from unstable combustion of ignited air-fuel mixture initiated by the controlled source of combustion and it is assumed to be less harmful to engine durability and performance than heavy knock, however, still being undesirable [40]. Hydrogen knock occurrence is also affected by other engine parameters such as compression ratio, which has a direct impact on its operation is shown in the Figure 6. The intensity of knock is a parameter used to describe it is pressure pulsation intensity and in case of light knock is assumed to fit in the range of 20–100 kPa.

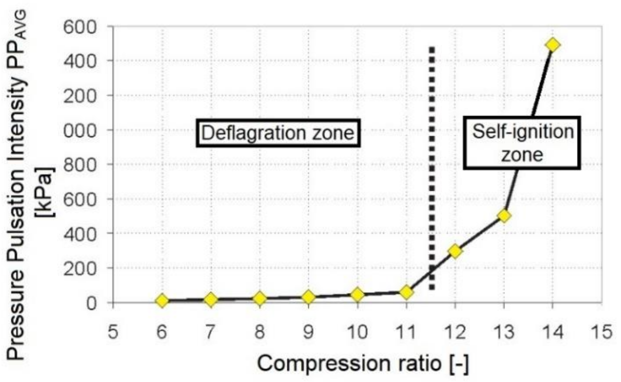


Fig. 6. Compression ratio influence on pressure pulsation intensity [38]

There are many ways to hamper knock occurrence in H2ICE among which the most effective ones are lean engine operation with SCC [22], modification of engine operation cycle (ex. Miller cycle with split injection) [45], water anti-detonant direct injection [9] into combustion chamber or dilution of hydrogen rich gases with exhaust gas recirculation [39]. Research shows that in case of hydrogen fueled engines modifications in combustion chamber geometry might result in better control of combustion process [46].

6. Hydrogen combustion system concept

Basing on conducted literature review authors of following paper are proposing their own idea of hydrogen combustion system for application in an internal combustion engines. The main idea of system is introduction of prechamber into engine cylinder head since its main task is to increase control of air-fuel mixture formation. The system main function is to impede risk of light knock occurrence by stabilization of pre-ignited flame propagation, thus allowing for higher compression ratio implementation. System design presented in the Fig. 7 consist of two injectors allowing for formation of mixtures with different equivalence ratios in main chamber and prechamber independently and resulting in stratified charge combustion.

Presence of active prechamber enables formation of ultra-lean mixture in region of ignition which should allow for decrease in flame propagation rate so charge in main chamber will ignite in more ordered matter. Author’s considerations are based on research conducted with use of gas-powered engines equipped with prechambers giving promising results [3, 36]. System being the subject of following chapter is under constant development and it is also considered to apply direct hydrogen injection in the future as it exhibits acceptable results [11].

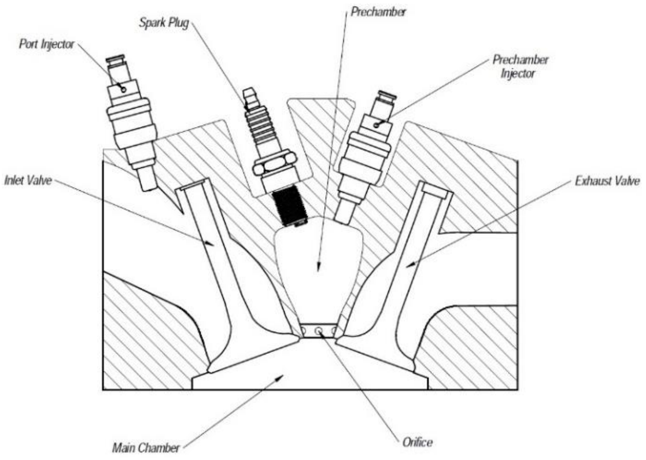


Fig. 7. Scheme of system proposed by the authors [27]

7. Conclusions

Conducted analyzes indicate that in the near future, the dominant method of obtaining hydrogen will be electrolysis, in which electricity will be obtained from renewable sources such as wind, sun or water; however, the current pace of development of renewable energy does not offer any opportunity to meet the demand for hydrogen in the future; therefore, it is necessary to introduce appropriate legislative changes regarding the production, transmission, and storage of hydrogen and to create financing opportunities.

According to the research, it is expected in the near future to observe increased interest in solutions that will allow for the use of hydrogen as a fuel for combustion engines, especially regarding to Polish market, thus it is justified to conduct research in this field.

The effectiveness and profitability of hydrogen storage are strictly related to the need to ensure the permeability of the tank at the lowest possible level while ensuring its high energy efficiency at the same time. Therefore, the dominant trend for hydrogen storage in vehicles is gaseous form with increased pressure.

In the near future, storage of large volumes of hydrogen for industrial purposes will be dominated by underground caverns obtained from rock salt deposits.

Direct hydrogen combustion in an internal combustion engine brings a lower energy expenditure than the combustion of hydrocarbon fuels; however, the authors perceive the possibility of improving the efficiency of this process by increasing the resistance to hydrogen knock precisely in the way of separating the combustion process into its initiation in the prechamber and main combustion in the main chamber.

Nomenclature

CCU	carbon capture and utilization	MN	methane number
CCS	carbon capture and storage	LHV	lower heating value
EU	European Union	RES	renewable energy sources
FCHV	fuel cell hydrogen vehicle	RON	research octane number
H2ICE	hydrogen fueled internal combustion engine	SCC	stratified charge combustion

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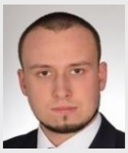

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