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Use of hydrogen fuel in drive systems of rail vehicles

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The search for substitutes for modern fossil fuels incentivises the use of new propulsion systems (hybrid or electric) and the use of new fuels (gaseous, mainly hydrogen). The article discusses the basic issues related to hydrogen fuel: from its extraction, through the discussion of its properties to its use and applications. Analyzes of the energy consumption involved in its extraction or production were presented, classifying hydrogen in those terms. Great emphasis was placed on design solutions for the use of hydrogen in internal combustion engines, together with discussing the concept of its combustion. The methods of storing hydrogen in a condensed and compressed form were also presented, indicating at the same time the most modern solutions available, such as mixed systems – storage in cryo-compressed form. It has been shown that the combustion of hydrogen in internal combustion engines increases their efficiency, and at the same time significantly reduces the exhaust emissions of toxic gases – including the emission of nitrogen oxides.

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1. Introduction

The increasing need to reduce the consumption of fossil fuels drives the search for alternative energy sources for transport means. Currently alternative fuels can be divided into different types, one of which being gaseous fuels, which due to their properties can be used in new combustion systems (such as Turbulent Jet Ignition (TJI) [6, 25], homogeneous charge compression ignition (HCCI) [34] and reactivity controlled compression ignition (RCCI) [36]). Among these fuels, methane, which is a component of natural gas, is currently the most widely used. Its use in conventional combustion engines is quite common (in heavy-duty vehicles), especially due to its storage options. Storing natural gas in compressed form is a technology that is already widely developed and established. Despite the high compression pressure (up to 20 MPa) [11], such fuel is injected into the intake manifold at a pressure of up to 0.9 MPa. The storage of natural gas in liquefied form (LNG, temperature –162°C, pressure approx. 100 kPa) is much less popular [37]. Despite the fact that its energy potential is greater, the technology being too expensive has resulted in it not gaining the necessary interest in the market so far to reach widespread use.

Currently, a much more environmentally advantageous solution is to supply internal combustion engines with hydrogen, with the combustion products being mainly water vapor and nitrogen oxides as a result [31]. Trace amounts of other exhaust components, which are the products of combustion of engine oil, can also be observed in these solutions [27, 38]. Nevertheless, such engines can meet stringent exhaust emission norms.

Another future-proof solution for powering means of transport (including rail transport) is the use of electric drives. The rapid development of lithium-ion batteries (including for rail vehicles) [23, 32] and the announcements of the promises of solid-state batteries production [24, 26] resulted in continued interest in such energy sources.

A comparative analysis of the energy storage costs was shown in Fig. 1. The energy potential of hydro-

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gen, as well as conventional fuels, is still significantly greater than that offered by batteries. In 2020, these costs in the case of hydrogen were over 20 times lower (in €/kWh) than in the case of Li-Ion batteries. A further reduction in these costs is expected in the coming years (much faster in the case of hydrogen than batteries). This may result in these costs reaching about 30 times the share of the existing costs by 2025, with a much greater advantage for hydrogen than before. Along with the reduction of hydrogen storage costs, one can expect an increase in the energy density of hydrogen (in kWh/kg) at a pressure of 35 MPa (currently hydrogen is stored at a pressure of 70 MPa). This energy density is about 20 times lower for Li-Ion batteries. Hence it is possible that hydrogen may become more advantageous alternative as a fuel to electric drives in vehicles.

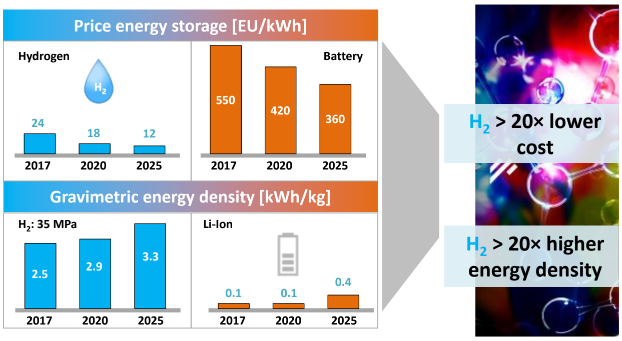


Fig. 1. Energy density of hydrogen and Li-Ion batteries [35]

The analysis of modern vehicle drives efficiency has shown, however, that the efficiency of the electric drive (over 90%) is more than twice as high as that of the combustion engine (over 40%). If the over 20 times greater value of the mass energy density is also taken into account, the result is an approximately 10-fold increase in the effective range for a hydrogen-powered vehicle (Fig. 2). Such considerations lead to the conclusion that hydrogen, being a clean and ecological fuel, can be a direct alternative as a viable choice in fuel supply for combustion engines as well as fuel cells in modern vehicles.

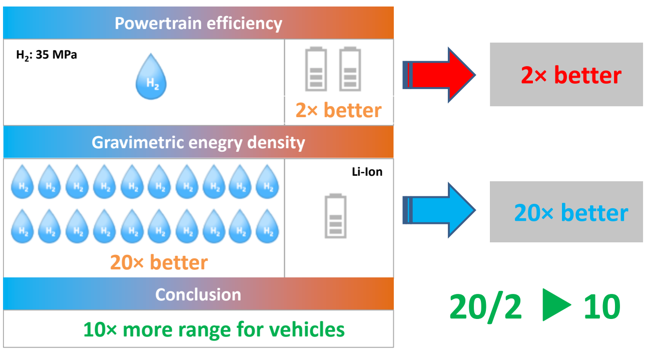


Fig. 2. Energy density of hydrogen at the pressure 35 MPa compared to Li-Ion batteries [35]

The production of hydrogen is still largely related to fossil fuels, and the cheapest method is still steam reforming of natural gas (the so-called grey hydrogen) – Fig. 3. Currently, 75% of the world's production of hydrogen comes from natural gas. Steam reforming with CO_2 capture is an interim production method. It is possible to use CCS (Carbon Capture Storage) or CCU (Carbon Capture Utilization) technology. Thanks to them, the produced hydrogen can be almost emission-free (referred to as blue hydrogen). The use of black coal for the process results in what is called black hydrogen to be produced while brown coal is used to make brown hydrogen (production of both these types of hydrogen results in CO_2 emissions). The production of hydrogen from methane in the pyrolysis process (often called turquoise hydrogen) results in the production of hydrogen and carbon in solid form.

Another, more modern method of hydrogen production is obtaining it through a nuclear reaction process. Such hydrogen is referred to as red hydrogen (or sometimes as pink or purple hydrogen).

The most desirable color of hydrogen is green – produced in the electrolysis process, the electricity of which comes exclusively from renewable sources.

If the energy comes from solar energy, the hydrogen produced is called yellow, and if the hydrogen production is powered from natural geological sources, it is referred to as white hydrogen.

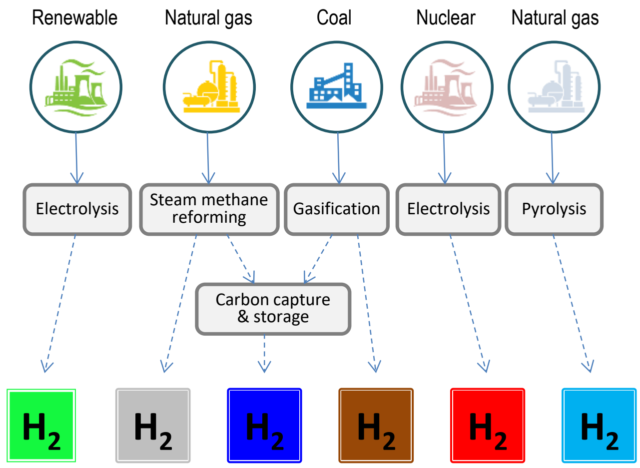


Fig. 3. Methods of hydrogen production and the associated "colors" of hydrogen made [15]

The characteristics of the types of hydrogen were presented in Table 1. Currently, 96% of hydrogen is produced from fossil fuels [13]. It is estimated that about 25% of net global warming in recent decades was caused by the release of methane. The production of 1 kg of hydrogen (grey) produces 13.3 kg of carbon dioxide. The efficiency of this process does not exceed 60%. The production of blue hydrogen produces

Table 1. Properties of different "colors" of hydrogen [3]

Characteristic	Green	Blue	Grey	Red	Turquoise	Brown
Energy source	Renewables	Natural gas or coal	Natural gas or coal	Nuclear	Natural gas	Brown coil
Feedstock	Water	Natural gas, coal, oil, biomass	Natural gas	Water	Natural gas	Brown coil, biomass
Technology	Electrolysis	Reforming + CCS, Gasification + CCS	Reforming, Gasification	Electrolysis	Pyrolysis	Gasification
By-products	Oxygen	CO_2	CO_2	Oxygen, nuclear waste	Carbon (as a solid)	CO_2
Motional environmental footprint	Minimal;	Low	Medium or high	Minimal GHG, nuclear waste products	Medium	High

only 1.7 kg of CO_2, with a process efficiency of 50%. Hydrogen from electrolysis accounts for only 4% of world production. The production of green hydrogen only causes 0.5 kg of CO_2.

The efficiency of the process is about 60–80%, however, its production (1 kg) requires about 9 dm^3 of water and an energy input of 50 kWh. The production of blue hydrogen causes CO_2 emissions of 1 kg (when produced from natural gas), and 2.4 kg (when produced from coal). Much higher values of carbon dioxide emissions are obtained in the production of grey (8.5 kg) or black (20 kg) hydrogen [39].

The consumption of hydrogen in the European Union in 2018 was 8.3 million tons [21]. The largest share of this was used by refineries (44%), ammonia production took about 34%, chemicals – 12% and other industries – about 10%. The largest producers of hydrogen in Europe are Germany (2.5 million tons per year) and the Netherlands (1.5 million tons). Annual hydrogen production in Europe in 2018 reached 11.5 million tons.

The Polish Hydrogen Strategy up to 2030 with a perspective of 2040 is a strategic document that defines the main goals of the development of the hydrogen economy in Poland and the directions and actions necessary to achieve those goals. Hydrogen has been classed by type into conventional, low-emission and renewable. Its detailed characteristics have been shown in Fig. 4.

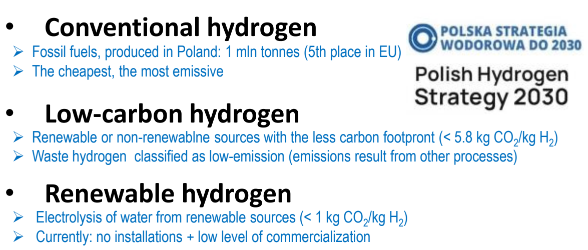


Fig. 4. Polish classification of hydrogen fuel [29]

2. Properties of hydrogen

Hydrogen is the lowest density gas (of all gases) being about 14 times lighter than air. In terms of energy density, it is the most efficient of all currently used fuels. Unlike other fuels, its combustion does not produce any other harmful by-products (however, it combines with atmospheric nitrogen to form nitrogen oxides). It can be stored in a liquefied or compressed form (Fig. 5). Hydrogen can be stored in compressed or liquefied form (at a temperature of –253°C). The curves relating to the change in volumetric energy density show much higher values for hydrogen stored in a liquefied form. The maximum storage values for compressed hydrogen are 70 MPa (composite tanks). Such tanks contain 71 kg/m^3 of liquefied hydrogen (at a temperature of 20 K, and pressure of 0.4 MPa), a value that is greater than when storing compressed hydrogen (39.1 kg/m^3 – at 70 MPa and room temperature).

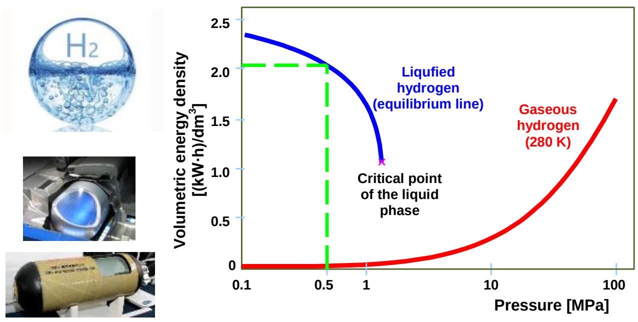


Fig. 5. Physical parameters of liquefied and compressed hydrogen [20]

Modern hydrogen storage solutions also use hybrid approaches in mixed systems, which use the features of cryogenic systems (LH_2 – liquefied hydrogen) and compressed hydrogen systems (CH_2 – compressed hydrogen) described in Fig. 6. In such conditions, hydrogen is kept at a temperature of about –233°C. Additionally, it is possible to use modern hydrogen-absorbing materials. Their applications increases the variety of hydrogen storage. At ambient pressure, the density of hydrogen is 0.3 g/dm^3, at 15 MPa it is 10 g/dm^3, at 35 MPa – 28 g/dm^3, and at 70 MPa – 40 g/dm^3. Liquefied hydrogen has a density of about 71 g/dm^3, however, hydrogen-absorbing materials may offer similar values or even exceed them: such as adsorbents (MOF-5 < 70 g/dm^3), metal hydrides – complex hydride (70–150 g/dm^3), chemically bound – chemical storage (70–150 g/dm^3) and water (111 g/dm^3) [30].

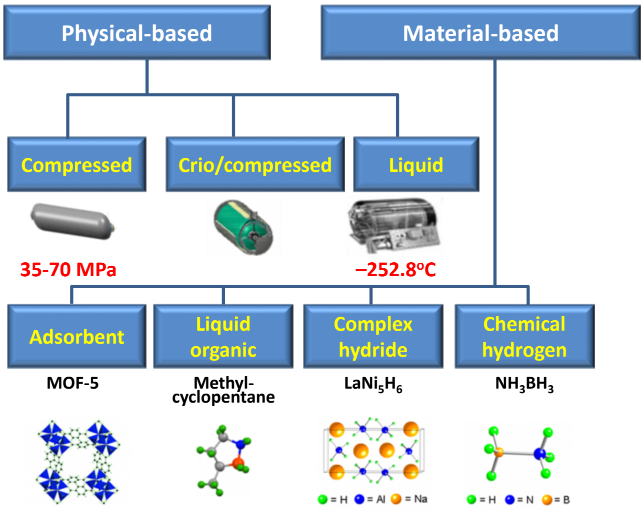


Fig. 6. Characteristics of hydrogen storage [14]

A comparative analysis of specific energies of various motor fuels shows high values of the volume density of liquid fuels (diesel oil, gasoline) – Fig. 7.

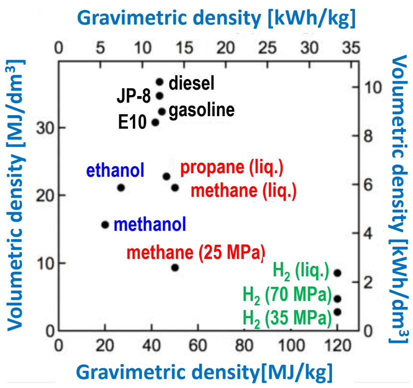


Fig. 7. Energy specifications for liquid and gaseous fuels (including hydrogen) [14]

Methanol and ethanol containing oxygen in their molecule have significantly lower values. Liquefied fuels (propane, methane) have similar values of volumetric density. Gaseous compressed fuels, such as hydrogen, exhibit the lowest volumetric density values. However, their mass indicators are completely different: the maximum values can be obtained using liquefied and compressed hydrogen. This is partly due to the nearly three times higher calorific value of hydrogen than other fuels. Gaseous fuels (even when compressed or liquefied) require a storage tank with a greater volume than needed for an equal mass of liquid fuels.

3. Hydrogen storage in vehicles

The outlined storage of hydrogen in liquefied or compressed form can be supplemented by intermediate conditions. These make it possible to limit the pressure of hydrogen (when compressed) with a simultaneous increase in its temperature (when liquefied). This is known as cryo-compressed hydrogen. Hydrogen in the liquefied form can reach a density of 63 g/dm^3 (Fig. 8). During its compression to 70 MPa and at t = 15°C, its density reaches the level of 40 g/dm^3. By limiting the pressure to 30 MPa while maintaining a temperature of 38 K (–235°C), it is possible to obtain a hydrogen density of 80 g/dm^3. This value is twice as high as during its compression (70 MPa). It is also a value greater than the previously indicated values for storage density in metal hydrides.

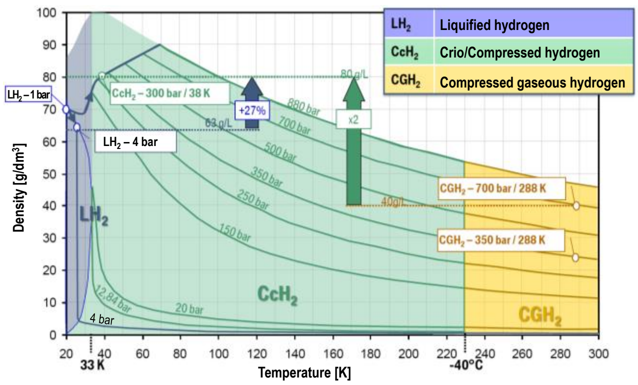


Fig. 8. Hydrogen storage conditions [5]

Steel tanks can be used for storing hydrogen compressed up to 35 MPa while also making it possible to use the cryo-compressed form of hydrogen storage (Fig. 9). The time it takes to refill hydrogen tanks is about 5 minutes, at the supply pressure: compressed gas (CH_2: 320 bar), or cryo-compressed gas (32 MPa). For example, in the considered vehicle tanks (Fig. 9), 260 kWh of energy (7.8 kg of hydrogen) can be stored in the cryo-compressed form, while in the compressed form this is only 83 kWh (2.5 kg H_2). Tank leakage losses are below 3 g/day (which is less than 1%/year).

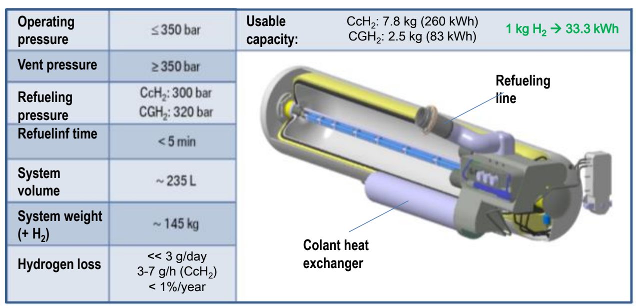


Fig. 9. Hydrogen fuel tanks [22]

Hydrogen is the fuel with the highest calorific value among all fuels for the transport sector, amounting to 120 MJ/kg (Fig. 10) and that value is independent of how it is stored. The volumetric energy of liquefied and cryo-compressed hydrogen are similar (the latter is 4% lower). Cryo-liquefied hydrogen densities are the highest (80 kg/m^3), about 15% greater than that of liquefied hydrogen, and about 50% greater than that of compressed hydrogen. The calorific value of methane is more than 2 times lower than that of hydrogen, and its storage may take a compressed or liquefied form. The energy differences of typical transport fuels were shown in Fig. 10.

Fuel	Composition	E [MJ/kg]	E [MJ/dm^3]	ρ [kg/m^3]	P [bar]	T [°C]
Diesel	C_9-C_{22}	41	34	820-845	ambient	ambient
Gasoline	C_4-C_{12}	43	32	710-770	ambient	ambient
GTL	C_9-C_{22}	43	34	775	ambient	ambient
LPG	Propane, buthane	46	25	540	2-8	ambient
CNG	Methane	50	9	160-190	200-250	ambient
LNG	Methane	50	21	400-500	8	–170/–130
CGH_2	Hydrogen	120	4,2	28-40	250-700	ambient
CcH_2	Hydrogen	120	9,6	80	280	–220
LH_2	Hydrogen	120	10	68	4	–240

Fig. 10. Fuels as energy sources for transport means [2, 7]

The transport performance indicators of the analyzed fuels were visualized in Fig. 11. The specific energy of hydrogen in liquefied and compressed form is similar, however, it is 7 times greater than the specific energy of Li-Ion batteries.

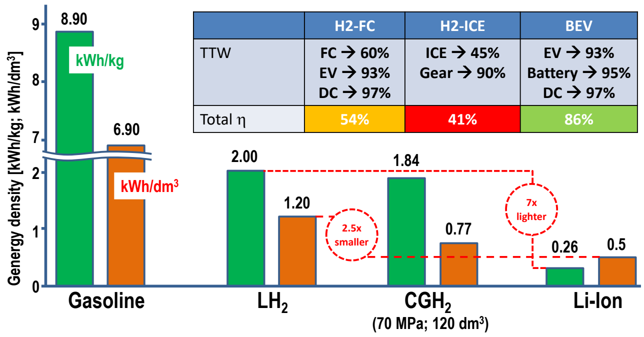


Fig. 11. Hydrogen vs. batteries in vehicle propulsion systems [18]

However, the scale of the technological progress to date has been determined by the energy density of gasoline, amounting to 8.9 kWh/kg. It should be noted that liquid fuels have an over four times greater energy density value. The comparison of the volumetric energy density leads to similar results. The benefit of using hydrogen comes from the analysis of its use in fuel cells and internal combustion engines. As a fuel it allows for zero-emission propulsion for means of transport along with high efficiency of drive system components.

4. Uses of hydrogen in combustion engines

Hydrogen supply for combustion engines has been a well-known topic since the 1950s. Currently, with the level of combustion systems development, hydrogen can be supplied in the form of direct or indirect injection (Fig. 12). Modern designs of hydrogen-powered engines exceed conventional units in terms of power, while achieving a similar level of torque. This is because direct hydrogen injection makes it possible to increase the density of the dose supplied to the cylinder. Indirect hydrogen injection displaced a part of the supplied air with fuel (even in a liquefied form) – Fig. 13. Direct injection enables full air intake with additional injection of the liquefied fuel. As a result over 20% more energy can be supplied, compared to conventional petrol injection in the standard PFI (Port Fuel Injection) system.

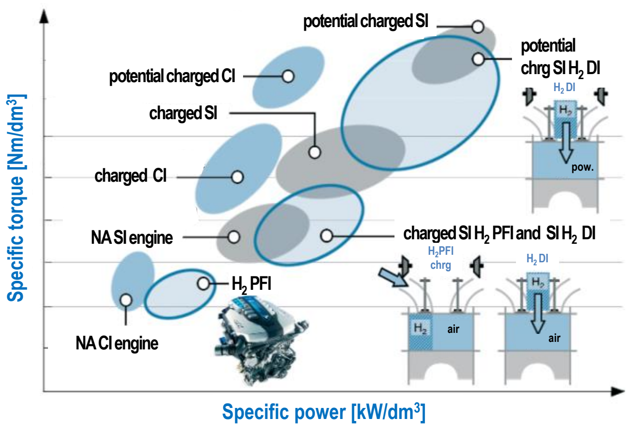
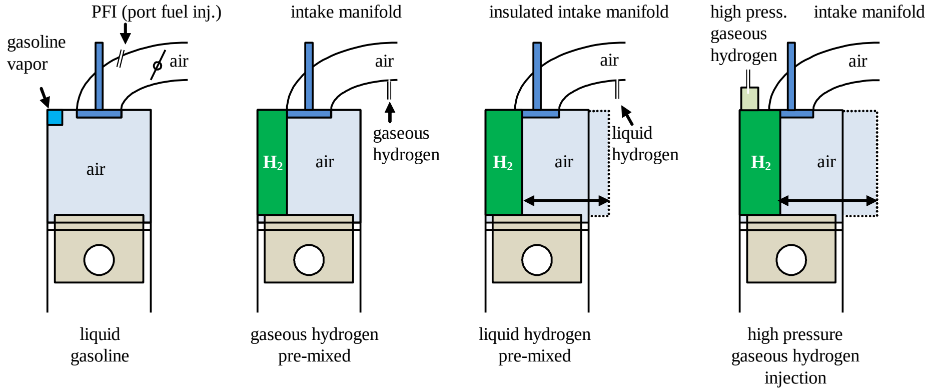


Fig. 12. Combustion engines concepts [17, 19]

Concepts of high-pressure and cryogenic injection of hydrogen into the cylinder are currently in development (Fig. 14). High-pressure hydrogen injection is to be performed at a pressure of 15–30 MPa and a temperature of –40–120°C. Such conditions make it possible to increase the energy density of the fuel. Cryogenic injection is considered as an indirect injection into the intake manifold.

In such conditions, injection is performed at a pressure of 3–6 bar (similar to typical PFI systems) and a temperature of –220–60°C. This eliminates the fuel dose losses due to hydrogen expansion (previously described for indirect gas injection).

Modern fuel injection in spark ignition engines is performed with the injector on the side or in the central location of the chamber (Fig. 15). Side injection (air-guided) allows lean loads to be burned to a limited extent. Spray-guided injection allows the complete combustion of lean liquid mixtures and is considered a future-proof solution in internal combustion engines.



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. 13. Hydrogen injection systems for combustion engines [2, 4, 17]

Figure 15 shows a view of the combustion system that can be supplied using gas and cryogenic (indirect) injection. The presented mean indicated pressure characteristics point to a much greater potential of cryogenic fuel doses. 30% higher maximum p_e values (mean effective pressure, IMEP) were obtained with cryogenic fuel supply.

Modern hydrogen-powered combustion engines operate using lean mixture combustion (Fig. 16). This means that the characteristic peak in nitrogen oxide formation is skipped over. The air excess ratio ($\lambda = 2$) is achieved when burning hydrogen with a large excess of air (34 kg of air and 1 kg of fuel are needed for stoichiometric combustion). The hydrogen combustion conditions at $\lambda = 1.8$–2.0 require the use of an exhaust gas recirculation system to reduce the production of nitrogen oxides. For higher values of the air excess ratio, no additional exhaust aftertreatment system is required. Characteristic areas of engine load (intermediate and maximum) were also shown in Fig. 16. Hydrogen supply to the engine results in high overall efficiency values of the internal combustion engine – about 44% in terms of the engine torque and power curve. By comparing the nitrogen oxide concentration in a compression ignition engine and an engine fueled by hydrogen, significantly lower NO values have been observed when supplying the engine with hydrogen. With increasing engine rotational va-

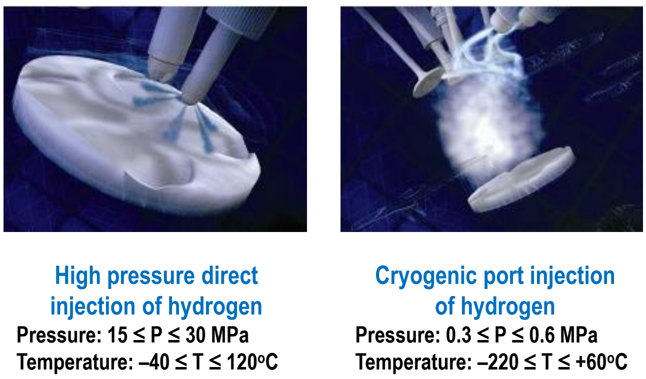


Fig. 14. Hydrogen supply systems in combustion engines [10]

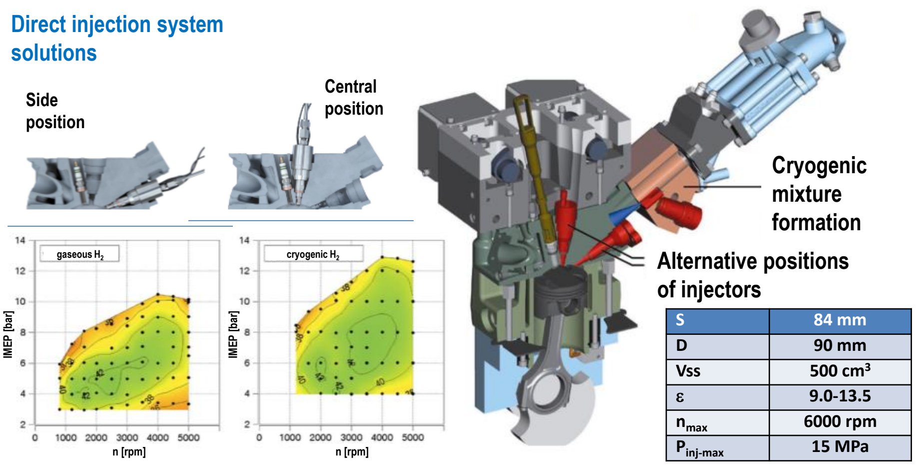


Fig. 15. Solutions for direct and indirect injection of hydrogen in an internal combustion engine [16]

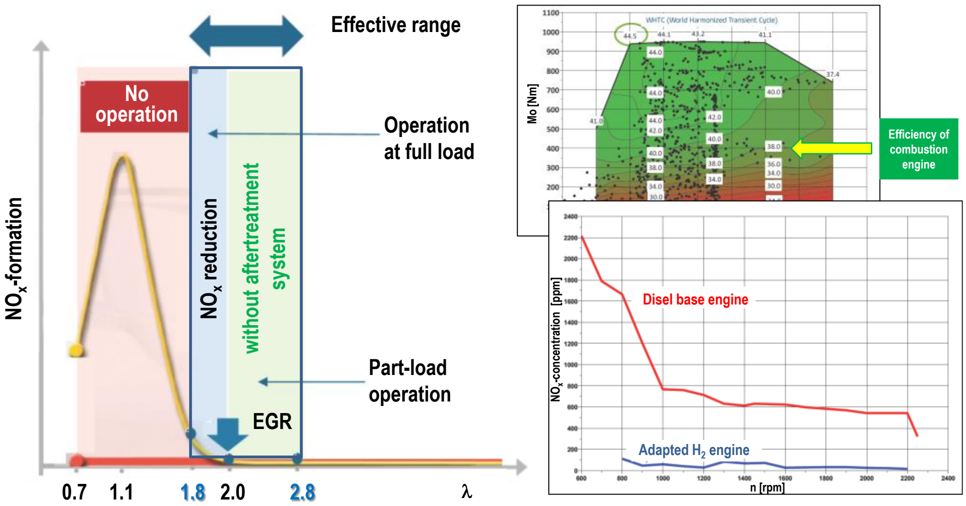


Fig. 16. Hydrogen injection and combustion in an internal combustion engine [33]

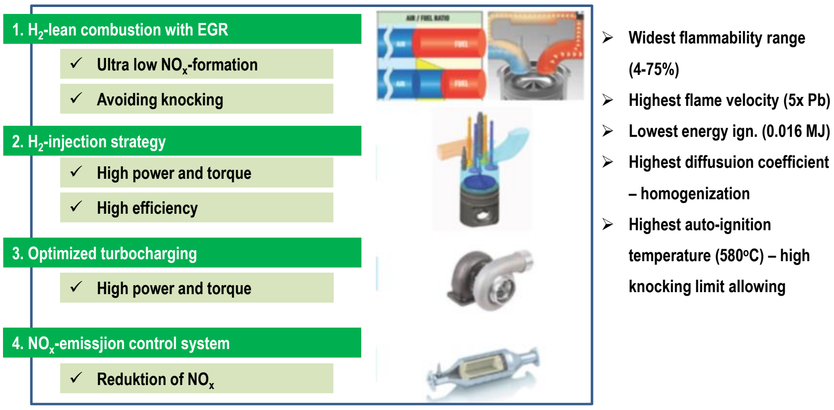


Fig. 17. Hydrogen combustion process in a combustion engine [33]

lues have been observed when supplying the engine with hydrogen. With increasing engine rotational speed, the NO concentration in the diesel exhaust gases decreases, while it remains almost constant in the hydrogen-powered engine, at about 6 times lower concentration level.

Combustion systems in piston engines have been adapted for the combustion of hydrogen. This solution results in a wide range of hydrogen flammability and a high combustion rate, about 5 times greater than the combustion of gasoline. Ignition requires very small amounts energy, and at the same time a high diffusion coefficient is achieved, which favors the formation of homogeneous mixtures. Low emission of nitrogen oxides and high resistance to engine knock was achieved by using a relatively large share of recirculated exhaust gases in the engine. This made it possible to lower the maximum combustion temperature as a result of limiting flame propagation in the cylinder. Other systems allowing for optimal hydrogen combustion have been shown in Fig. 17.

Combustion of hydrogen in an internal combustion engine requires a direct or indirect injection system to supply the hydrogen fuel (Fig. 18). Direct injection improves combustion quality resulting in better torque characteristics. The mean value of the rated power was found to increase by about 20% with the concentration of nitrogen oxides remaining at a constant value. The specific exhaust emission of nitrogen oxides related to the engine power will be lower as the engine power increases in such a scenario.

Increasing the engine power with direct hydrogen injection typically increases the concentration of nitrogen oxides. A significant reduction in their emission at the cost of a slight reduction in engine power can be achieved by using an exhaust gas recirculation system. Adequate fuel injection and ignition control (usually ignition delay) further reduces NO creation in the combustion chamber. Another step in NO exhaust emission reduction can be achieved by using exhaust aftertreatment systems. As a consequence, adoption of direct hydrogen injection can be expected to contribute to increasing engine power while reducing the exhaust emissions of nitrogen oxide.

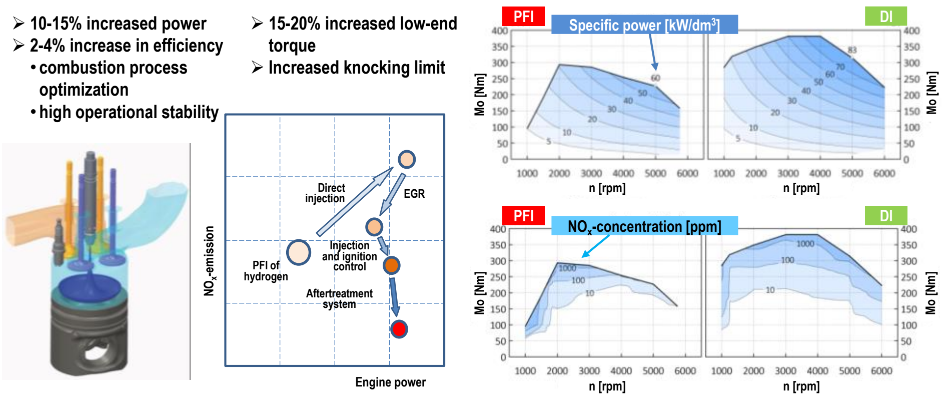


Fig. 18. Solutions for direct and indirect injection of hydrogen in a combustion engine [8, 28]

Combustion engines supplied with hydrogen fuel are used by Keyou. Modernized Deutz engines were chosen for this modification. Zero-emission heavy-duty combustion engines are defined as engines whose exhaust emissions are below 1 g CO_2/kWh (proposed in the EC Regulation No 595/2009). The vehicles shown in Fig. 19 are equipped with internal combustion engines with a stroke volume of 7.8 or 13.5 dm³ (for those equipped with PFI systems) or 15 dm³ (for those equipped with the DI – 40 t truck system).

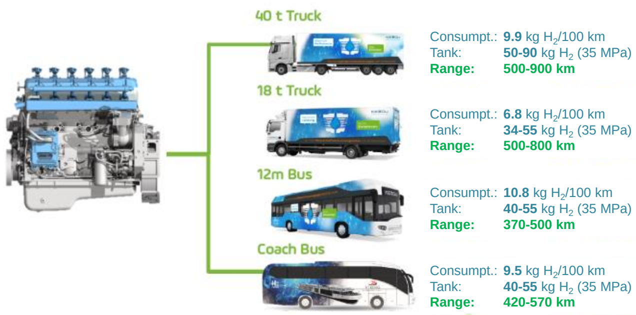
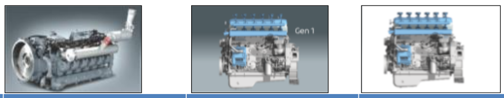


Fig. 19. Hydrogen for transport applications [33]

These vehicles consume approximately 10 kg of H_2 per 100 km. The minimum range of the vehicles is over 350 km while running on 35 MPa hydrogen tanks. Improving the design of hydrogen-powered engines increases their operational indicators. Changing the fuel injection method (indirect injection replaced with direct injection) not only increases the engine power, but also increases the torque. Changing the fuel delivery method not only increases the operational indicators of the engine, but also reduces the fuel consumption, which ultimately results in an increased efficiency of the entire drive unit (Fig. 20). A direct injection engine can mostly run at an air excess ratio of $\lambda > 2$. The exhaust emissions are, therefore, very low. A comparison with a compression ignition engine (the first value with diesel fuel, the second with hydrogen) shows significantly lower exhaust emission values (in g/kWh) for: CO_2 – 1.0:0.08; NO_x – 0.46:0.04; PM: 0.01:0.002; HC: 0.16:0.01 and CO: 4:0.01. Such low emission values indicate an exhaust emission reduction at a factor of 10 from a hydrogen-powered engine as compared to a diesel-powered engine.



Engine	MAN H2676 UH01 (2006)	DEUTZ TCG7.8 PFI	DEUTZ TCG7.8 DI
No. of cyl.	6	6	6
Vss	12.8 dm³	7.8 dm³	7.8 dm³
Charging	Natural aspirated	Turbocharged	Turbocharged
Ne	150 kW	180 kW	210 kW (+130% power)
Mo	760 Nm	950 Nm	1100 Nm
Combustion	Stoichiometric	Lean	Lean
NO_x-reduction	Tree-way catalyst	EGR + H_2 SCR	EGR + H_2 SCR
H_2-consumption	21.6 kg H_2/100 km	10.7 kg H_2/100 km	9.7 kg H_2/100 km (–60%)

Fig. 20. Development of hydrogen powered engines [33]

5. Conclusions

The use of hydrogen in internal combustion engines is an alternative to the combustion of fossil fuels (gasoline, diesel oil). The use of hydrogen makes it possible to significantly reduce the exhaust emissions of not only carbon dioxide, but also other components of the exhaust gas.

Hydrogen as a fuel for the internal combustion engines (ICE):

a) is used in demonstration vehicles such as passenger cars, trucks and buses (engines displacement about 1.5–15 dm³),

b) is used in ICE with small displacement and power, does not make it suitable for railway applications at present.

The use of hydrogen as a fuel for vehicles to be converted into power in fuel cells also enables further propagation of hydrogen in vehicle propulsion systems and the transport sector. It should be noted that 1 kg of hydrogen produces 33 kWh of energy, while that value from fossil fuels is 2.4 times lower. This difference in energy potential indicates the desirability of using hydrogen-based propulsion systems and of hydrogen as fuel in means of transport. Contemporary alternative fuel supply projects indicate an increased interest in propulsion systems using fuel cells as well as hydrogen-powered internal combustion engines.

Nomenclature

CcH_2	crio/compressed hydrogen
CCS	carbon capture storage
CCU	carbon capture utilization
CH_2	compressed hydrogen (CGH_2)
CI	compression ignition
CNG	compressed natural gas
DI	direct injection
EGR	exhaust gas recirculation
GHG	greenhouse gas
GLT	gas-to-liquid
HC	hydrocarbons
HCCI	homogeneous charge compression ignition
IMEP	indicated mean effective pressure
LH_2	liquefied hydrogen
Li-Ion	lithium-ion battery
LNG	liquefied natural gas
LPG	liquefied petroleum gas
Mo	engine torque
Ne	engine power
NO	nitrogen oxide
PFI	port fuel injection
PM	particulate matter
RCCI	reactivity controlled compression ignition
SCR	selective catalysts reduction
SI	spark ignition
TJI	turbulent jet ignition
Vss	displacement
λ	air excess ratio

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