Article citation info:
Stępień Z. Analysis of the prospects for hydrogen-fuelled internal combustion engines. Combustion Engines. 2024;197(2):32-41. https://doi.org/10.19206/CE-174794

Zbigniew STĘPIEŃ

Combustion Engines
Polish Scientific Society of Combustion Engines

Analysis of the prospects for hydrogen-fuelled internal combustion engines

ARTICLE INFO

Received: 5 October 2023
Revised: 15 October 2023
Accepted: 3 November 2023
Available online: 6 November 2023

Hydrogen, as a zero-emission fuel, makes it possible to build a piston combustion engine that can be qualified as a drive for a "Zero Emission Vehicles", in terms of CO_2 emissions. Thus, a hydrogen-powered piston combustion engine may be a future transitional technology for powertrains, especially in trucks and off-road vehicles, competitive with both electric drives and fuel cells. The article presents a multi-directional analysis of the prospects for the development and dissemination of hydrogen-powered internal combustion piston engines in motor vehicles. The current interest of the automotive industry in hydrogen-powered internal combustion engines, the current state of their development and the challenges that need to be overcome were presented. Various conditions that will determine their future in Europe were also indicated.

Key words: *piston combustion engine, hydrogen, fuel injection, combustion process, hydrogen combustion engines, exhaust emissions*

1. Introduction

Climate protection has long become a priority topic in the activities of many political groups in the world. New regulations, standards, norms and directives related to counteracting the broadly understood degradation of the natural environment are being introduced or tightened continuously. Concerns about combustion engines exacerbating climate change have become a public and political topic. Impartial assessments of the actual impact of combustion engine emissions on climate change are necessary, taking into account the enormous progress that has been made in reducing all standardized exhaust emissions from combustion piston engines (Euro 1–Euro 6; Euro 7). To achieve national and EU climate goals and meet the successively stricter regulations on reducing exhaust emissions from road and off-road vehicles, it became necessary to both significantly increase the energy efficiency of their power units and move away from fossil fuels. As part of the adopted action plan called the Green Deal, the European Union has set itself the goal of achieving net zero greenhouse gas emissions by 2050. The intermediate goal is to reduce their emissions by 55% by 2030 compared to the reference year of 1990. Therefore, the entry of EU Regulation 2019/1242 into force, the targets for reducing CO_2 emissions of the vehicle fleet by –15% by 2025 and –30% by 2030 (compared to 2019 levels) became permanent legislation for truck manufacturers in the EU. Currently, the automotive industry is looking for and developing various solutions for power units with zero or very low CO_2 emissions and at the same time reducing emissions of harmful, regulated and not yet regulated exhaust gas components. So far, a rapid development of electric drive units, an increase in interest in fuel cells and the possibility of using various alternative, pro-ecological fuels such as hydrogen, ammonia and others have all been observed. This raises the question of what role combustion engines will play in the coming decades and whether they can meet future environmental requirements through the use of alternative, non-hydrocarbon fuels [20, 22]. It is worth remembering the basic advantages of combustion engines over electric drives and fuel cells, the most important of which are: resistance to environmental conditions, including fuel and air pollution, low demand for rare earths and precious metals, and well-established development and production practices [4, 32].

Hydrogen has the potential to become a sustainable fuel of the future, to reduce global dependence on fossil fuel resources, and can also be used as an ecological fuel with zero CO_2 emissions because it does not contain carbon. Hydrogen is the most common element in the world, as an energy carrier it has the highest specific energy of 33 Wh/g and a calorific value of 120 MJ/kg. The energy per unit of mass stored in hydrogen is approximately 2.6 times greater than that of gasoline. However, hydrogen requires about four times more volume to store than gasoline when stored as a liquid, and about 19 times more volume when stored in gas form. Although hydrogen does not occur freely in nature, it can be produced using various processes, the most popular of which are steam reforming of natural gas or biomass gases, coal gasification and water electrolysis. The use of hydrogen as a fuel in vehicles powered by an internal combustion engine (H2ICE) or fuel cells (FC) is currently a promising direction for the future of the transport sector. The use of hydrogen as a fuel for piston combustion engines would make it possible to almost completely eliminate CO_2 emissions. In addition, emissions of toxic substances such as carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM) can be reduced to very low (trace) levels. This is because these emissions will only arise from the combustion of lubricating oil entering the engine's combustion chambers. The only exhaust component that may be produced in notable amount during hydrogen combustion in the engine is nitrogen oxides (NO_x). However, they can be reduced almost to zero through a properly designed exhaust aftertreatment system, without increasing secondary emissions such as N_2O and NH_3 [7, 11, 34]. Consequently, H2ICE may play the role of a transitional technology in the development of propulsion systems, especially in trucks and off-road vehicles, at least until fuel cells become technologically advanced, easy to use and fully profitable. In the medium term, a hydrogen-powered internal combustion engine may provide a competitive alternative to electric powertrains until a sufficient amount of fully renewable electricity is available. In turn, hybrid drive systems with a hydrogen combustion engine are a real alternative to electric drives and fuel cells, both from the point of view of CO_2 emission equivalent and the total cost of production and long-term use [27, 31]. In addition to advantages in terms of efficiency and driving range, this leads to attractive functional synergies and additional degrees of freedom in terms of design and operating strategies that need to be taken into account. Hydrogen can also be used as admixtures with hydrocarbon fuels or as alternative fuels such as ammonia [34]. Despite extensive work already being carried out on the use of both pure hydrogen and its mixtures with other fuels to power piston combustion engines, further actions are necessary to optimize the design changes of the piston combustion engine, in particular its fuel supply system and combustion processes allowing the full use of the properties of hydrogen. There are several manufacturers currently interested in introducing hydrogen-powered internal combustion piston engines into production that have announced their current status of work on such drive units (Table 1).

Table 1. List of manufacturers currently exploring new H2ICE technologies [13, 17, 18, 23]

Manufacturer	Status of work
JCB	Start of production announced
MAN	
PUNCH - Torino	
Toyota	
Deutz	
DAF	Ongoing development
Kawasaki	
Yamaha	
Daimler	
Cummins	
Liebherr	
MTU	
Hongqi	Research announced
Ford	
Volvo	
Scania	
Great Wall	
Caterpilar	

The article was motivated by the intention to present the current interest and plans of the automotive industry in the field of hydrogen-powered internal combustion engines, the challenges facing their further development and to analyze the prospects for using such engines in the future.

2. Advantages of H2ICE – future possibilities

The use of hydrogen as a standalone fuel or as an admixture with another fuel (e.g. hydrocarbon, synthetic or alternative) is considered possible in both SI (spark ignition) and CI (compression ignition) engines. Hydrogen as a fuel is characterized by several favorable properties enabling high efficiency of the combustion process. The most important of these properties are [31]:

- Wide range of flammability

Compared to hydrocarbon fuels, the flammability range of hydrogen is very wide, it ranges from 4 to 76% of the volume content in air [9, 21, 28] (these values are for example 1–7.6% for diesel oil, and 0.6–5.5% for gasoline). This property allows the engine to run on a very lean mixture. This, combined with the complete combustion of hydrogen, allows for greater fuel savings and optimization of the combustion process in terms of reducing NO_x emissions thanks to a lower combustion temperature. Moreover, lower heat losses through the walls of the combustion chamber make it possible to achieve higher thermal efficiency of the engine [5].

- High rate of combustion

The combustion rate of a hydrogen-air mixture is approximately seven times faster than a mixture of air and any hydrocarbon fuel. As the combustion rate increases, the actual curve of the indicator graph approaches the ideal one. This means that an increasingly higher thermodynamic efficiency can be achieved [1]. When using a stoichiometric mixture, the hydrogen engine comes closest to the ideal thermodynamic cycle, and the propagation speed of the hydrogen flame is almost an order of magnitude greater than that of the gasoline flame [19]. Making the combustion mixture more lean reduces the speed of flame propagation. The speed of flame propagation and its adiabatic temperature have a significant impact on the thermal efficiency of the engine, the stability of the combustion process and the level of emissions (especially NO_x) [9, 19, 28].

- High stoichiometric air-to-fuel ratio

The stoichiometric air-to-fuel (A/F) mass ratio for complete combustion of hydrogen in air is approximately 34.4:1, which is significantly greater than that of gasoline (14.7:1) or diesel (14.5:1) [9, 19, 28].

- Very low energy of ignition

The ignition energy of the hydrogen-air mixture is only 0.02 mJ, which is very low compared to a mixture of gasoline with air or diesel fuel with air, which both require 0.24 mJ. Such low ignition energy creates a risk of premature, uncontrolled ignition and flame returning to the engine intake duct. Such premature ignition may be initiated by particles of unburned lubricating oil in the fuel-air mixture, hot spots in the combustion chamber resulting from the formation of deposits, hot electrodes of the spark plug, etc. [13, 28].

- High auto-ignition temperature

The auto-ignition temperature of hydrogen fuel is high compared to hydrocarbon fuels (853 K compared to ~623 K for gasoline and ~520 K for diesel oil). Thus, it is difficult to ignite the hydrogen-air mixture through compression in the engine cylinder and an external ignition source is usually required. Therefore, the auto-ignition temperature is an important factor in determining the engine's compression ratio, which is related to the temperature of the compressed mixture. The possibility of increasing the compression ratio makes it possible to increase the engine thermal efficiency. On the other hand, the high auto-ignition temperature of hydrogen makes it difficult to achieve auto-ignition in a diesel engine [1, 13, 28].

– Small distance of flame quenching from the cylinder wall

The quenching distance is the shortest distance from the inner wall of the cylinder at which the flame is quenched. In the case of hydrogen, the flame-quenching distance is 0.64 mm, while for gasoline it is 2 mm. Thus, it is more difficult to extinguish a hydrogen flame compared to other fuels. This creates the possibility of hydrogen burning in narrow gaps, such as between the piston and the cylinder, or retreating into the intake channel when the intake valve is not yet fully closed [1, 13, 28].

– High diffusivity

Hydrogen is characterized by a very high diffusivity, which means that its ability to disperse in the air is much greater than that of gasoline. This is beneficial from the point of view of the combustible mixture quality in the engine, as it facilitates the rapid creation of a homogeneous mixture of fuel and air. Moreover, if hydrogen leaks, it quickly dissipates in the surrounding air. In this way, the potential hazards of hydrogen leaks can be at least partially avoided or minimized [9, 19, 28].

– High octane number (~130)

This makes hydrogen more resistant to knocking combustion even when burning in very lean mixtures.

The interest in H2ICE has been increasing in recent years due to significant progress in optimizing their power and combustion processes, which allow for a significant increase in their thermal efficiency while reducing NO_x emissions [25]. This was graphically presented (Fig. 1) by the relationships between the air-fuel ratio (AFR), mean effective pressure, thermal efficiency and NO_x emission [2, 25]. The operation of H2ICE in the stoichiometric mixture range is unfavorable because at high engine load, the onset of knocking combustion occurs at lower BMEP values, while the thermal efficiency is low and NO_x emissions are quite high due to high cylinder temperatures. With high excess air coefficients (with very lean mixtures, AFR = 2.0–2.5), high thermal efficiency and low NO_x emissions can be achieved at the same time, (Fig. 1 – area in green dashed line). However, in this range of the excess air ratio, the combustion process slows down significantly, the stability of the combustion process becomes difficult to maintain and control, and NO_x emissions increase in transient engine operating states [2, 25]. All in all, the operation of the engine in the indicated range of the excess air coefficient has more advantages than disadvantages and is currently a direction for further work in the optimization of the H2ICE combustion process [2, 10, 15, 16, 23, 25, 35].

Overall, the research and development work carried out so far has shown that the combustion process of a lean hydrogen-air mixture with the selective addition of exhaust gas recirculation (EGR) is the basis for achieving competitive operational parameters for the H2ICE. This combustion process allows obtaining high torque at low engine speeds, high specific engine power, maximum thermal efficiency and low NO_x emissions [3, 24]. The stoichiometric mixture combustion process, due to the high laminar flame speed, high isentropic exponent and high adiabatic combustion temperature, favors the formation of nitrogen oxides (NO_x) [3, 24, 25]. Moreover, hydrogen combustion is characterized by short flame quenching distances, which causes the hydrogen flame to burn close to the walls of the combustion chamber. As a consequence, heat losses increase, which in turn leads to a reduction in engine efficiency [25]. Lowering the temperature in the combustion chamber y using a leaner combustible mixture counteracts these phenomena. Lean mixture combustion requires a large amount of intake air, which necessitates the use of a high compression ratio to obtain high engine efficiency [12].

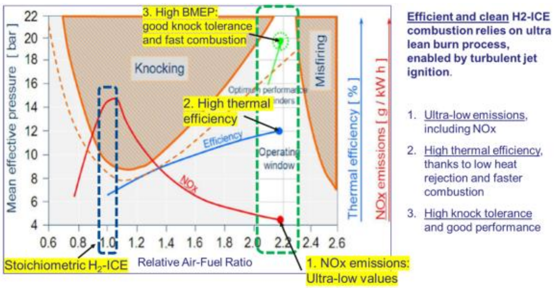


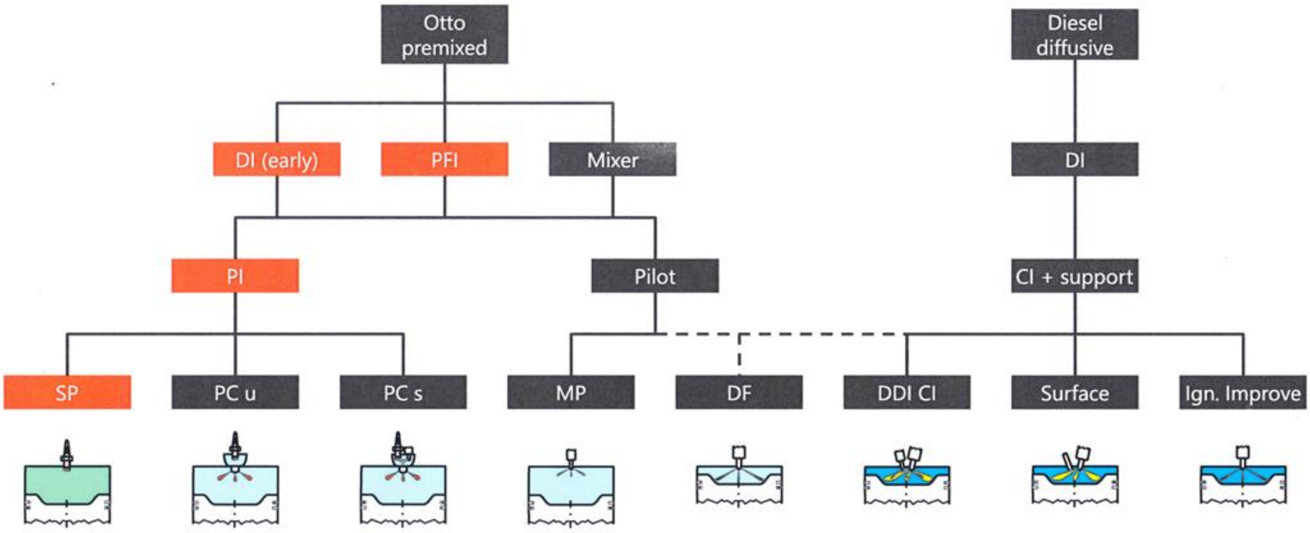
Fig. 1. Visualization of the relationships between the parameters involved in optimization of the combustion process in H2ICE [16, 17]

ICE can be divided into two groups based on the employed injection strategy: engines with indirect injection, i.e. with fuel injection into the intake manifold (PFI – port fuel injection or MPI – multi-point injection) and engines with direct injection (DI – direct injection). These two groups can be further divided into categories according to the ignition strategy [18, 36]. The divisions in question along with specific solutions were presented in Fig. 2 [18].

Injecting fuel into the intake port of each cylinder (ahead of the intake valves) has the advantage of providing a longer homogenization and mixing period for the mixture. At the same time, the turbulence generated at the intake valve ensures a high level of mixture homogeneity. In addition, lower injection pressures (~10 bar) can be used, which simplifies the injection system. However, with the transition to hydrogen fueling, problems may arise when using PFI. These include pre-ignition, knocking and flashback into the intake system due to low ignition energy and the low hydrogen flame quenching distance.

Moreover, the injected hydrogen displaces a significant amount of air from the air intake system, which significantly reduces the amount of specific power obtained and engine efficiency [32, 34]. PFI reduces the filling of the cylinder. The reduction in volumetric efficiency depends largely on the air-fuel ratio. This efficiency decreases the more the leaner the mixture becomes. At a typical relative air-fuel ratio of λ = 2, the air dose in the cylinder is reduced by approximately 20% due to the presence of hydrogen. As a result, this incentivizes a further increase in boost pressure.

Moreover, the injected hydrogen displaces a significant amount of air from the air intake system, which significantly reduces the amount of specific power obtained and engine efficiency [32, 34]. PFI reduces the filling of the cylinder. The reduction in volumetric efficiency depends largely on the air-fuel ratio. This efficiency decreases the more the leaner the mixture becomes. At a typical relative air-fuel ratio of λ = 2, the air dose in the cylinder is reduced by approximately 20% due to the presence of hydrogen. As a result, this incentivizes further increase in boost pressure.



DI: Direct Injection; PFI: Port Fuel Injection; CI: Compression Ignition; PI: Positive Ignition; DDI CI: Dual Direct Injection Compression Ignition; Ign.: Ignition; DF: Dual Fuel; MP: Micro Pilot; SP: Spark Plug; PC u: Pre Chamber unscavenged; PC s: Pre Chamber scavenged

Fig. 2. Possible combustion strategies that can be employed in a H2ICE [18]

In the case of direct injection (DI) of fuel into the engine cylinder, the injection begins immediately after the intake valve closes, which should completely prevent the occurrence of dangerous phenomena such as reverse ignition due to the return of the flame from the combustion chamber into the intake channel. In addition, pre-ignition can be prevented because the exposure time of the hydrogen mixture to the so-called "hot spots" is shortened. Moreover, hydrogen is injected directly into the combustion chambers, which avoids the problems of limiting the engine's specific power due to the displacement of air by the injected hydrogen. The disadvantage of DI is the shorter time afforded to homogenize the air-fuel mixture before the start of the combustion. The probability of knocking combustion occurring increases as a consequence of this. However, direct injection enables the implementation of other combustion processes, including stratified combustion.

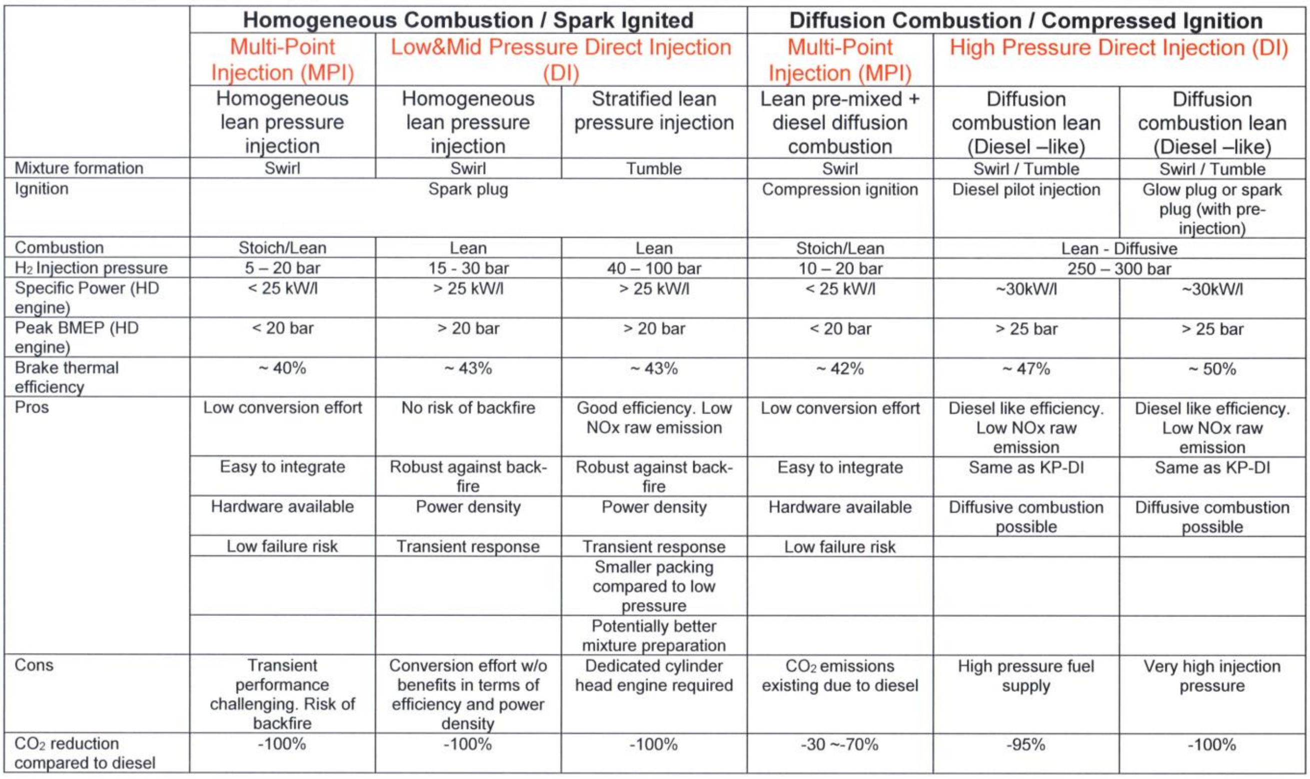
It is also possible to use a multiple injection strategy with controlled, variable fuel injection timing. Direct fuel injection requires a much higher injection pressure compared to indirect injection (PFI) [37].

H_2 combustion concepts in ICE can be divided into spark ignition combustion with a homogeneous pre-mixed chargé, and compression ignition combustion (Table 2). Spark ignition H2ICE using a pre-mixed homogeneous air-fuel mixture enables 100% CO_2 reduction, when ignoring trace emissions from burnt lubricating oil or SCR reagent. The main operation and performance challenges of the spark ignition H2ICE are specific power, fuel economy and transient performance. For low-pressure mixture concepts, only a moderate hydrogen injection pressure is needed and there is no need to use any additional compression systems. Thus, hydrogen can be supplied to the fuel injection system directly from the hydrogen storage pressure tanks. High-pressure mixture concepts, on the other hand, require a hydrogen injection pressure level of 250–300 bar. Therefore, an additional compression system becomes necessary to be able to utilize the maximum capacity of the hydrogen storage system [6].

In terms of low-pressure mixture concepts, multi-point fuel injection (MPI) combined with spark ignition is considered the most cost-effective solution. Good mixture formation, and therefore low NO_x emissions, partially compensate for the disadvantage of needing a higher boost pressure [14] (Table 2). In the case of MPI type indirect injection, a higher boost pressure is required if the same excess air ratio "λ" is to be maintained as in case of direct injection. Based on the concept of low-pressure mixture creation using direct injection (LP-DI) and spark ignition, the high calorific value of the created combustible mixture allows for obtaining a high BMEP. Currently, this mixture formation concept and combustion process is of greatest interest to researchers and manufacturers developing technologies related to H2ICE engines [30] (Table 2) [6, 14, 37]. To achieve the greatest specific power value, the lowest specific fuel consumption and the greatest stability in engine transient operating conditions, diffusion combustion (similar to diesel fuel) is indicated as the most appropriate (Table 2). To initiate a stable hydrogen ignition, it is beneficial to use pilot diesel fuel injection. However, to fully use the potential of the emission-free energy carrier hydrogen, it would be necessary to replace diesel fuel as the source of ignition initiation [30, 31].

To sum up, the greatest advantage of the DI fuel supply system is the increase in the efficiency of filling the combustion chambers and the reduction of work related to the pushing of the air-fuel mixture through the engine cylinders. Furthermore, with DI, higher torque can be achieved in the lower engine speed range as well as helping to avoid knock combustion and other irregularities in the process. These benefits are counterbalanced by the high technical difficulties associated with integrating the DI system in the case of H2ICE. Currently, this technology is still not fully developed yet and very expensive. The PFI system, on the other hand, is a well-known technology and ready for use in H2ICE. In this case, the components are available and very advanced, which allows the rapid development of new H2ICE engines, but with limited potential for optimization.

Table 2. Comparison of different mixture formation, ignition and combustion concepts in H2ICE [6, 14, 33]



	Homogeneous Combustion / Spark Ignited			Diffusion Combustion / Compressed Ignition		
	Multi-Point Injection (MPI)	Low&Mid Pressure Direct Injection (DI)		Multi-Point Injection (MPI)	High Pressure Direct Injection (DI)	
	Homogeneous lean pressure injection	Homogeneous lean pressure injection	Stratified lean pressure injection	Lean pre-mixed + diesel diffusion combustion	Diffusion combustion lean (Diesel –like)	Diffusion combustion lean (Diesel –like)
Mixture formation	Swirl	Swirl	Tumble	Swirl	Swirl / Tumble	Swirl / Tumble
Ignition	Spark plug			Compression ignition	Diesel pilot injection	Glow plug or spark plug (with pre-injection)
Combustion	Stoich/Lean	Lean	Lean	Stoich/Lean	Lean - Diffusive	
H_2 Injection pressure	5 – 20 bar	15 - 30 bar	40 – 100 bar	10 – 20 bar	250 – 300 bar	
Specific Power (HD engine)	< 25 kW/l	> 25 kW/l	> 25 kW/l	< 25 kW/l	~30kW/l	~30kW/l
Peak BMEP (HD engine)	< 20 bar	> 20 bar	> 20 bar	< 20 bar	> 25 bar	> 25 bar
Brake thermal efficiency	~ 40%	~ 43%	~ 43%	~ 42%	~ 47%	~ 50%
Pros	Low conversion effort	No risk of backfire	Good efficiency. Low NOx raw emission	Low conversion effort	Diesel like efficiency. Low NOx raw emission	Diesel like efficiency. Low NOx raw emission
	Easy to integrate	Robust against back-fire	Robust against back-fire	Easy to integrate	Same as KP-DI	Same as KP-DI
	Hardware available	Power density	Power density	Hardware available	Diffusive combustion possible	Diffusive combustion possible
	Low failure risk	Transient response	Transient response	Low failure risk		
			Smaller packing compared to low pressure			
			Potentially better mixture preparation			
Cons	Transient performance challenging. Risk of backfire	Conversion effort w/o benefits in terms of efficiency and power density	Dedicated cylinder head engine required	CO_2 emissions existing due to diesel	High pressure fuel supply	Very high injection pressure
CO_2 reduction compared to diesel	-100%	-100%	-100%	-30 ~-70%	-95%	-100%

The biggest disadvantage of the PFI injection system is the limited engine efficiency. Another significant disadvantage of this system is the possibility of the combustion process not taking place as intended. Therefore, the PFI system can be used in the first vehicle prototypes and then quickly enter the market as a low-cost solution [18, 30].

Achieving the intended, competitive performance of the H2ICE engine at full load with the maximum permissible NO_x emissions from the engine (< 10 g/kWh), requires a high excess air ratio (~1.9) at full load. State-of-the-art single-stage engine boost systems can meet these requirements under standard ambient and steady-state operating conditions. However, in the case of specific boundary conditions of the lean hydrogen combustion process, specific designs of the turbocharging system are required for this type of engine and its application. They can differ significantly from the existing systems in terms of complexity (Fig. 3). The combination of low exhaust gas enthalpy and high boost requirements in lean combustion concepts leads to the need for dedicated and particularly precise matching of the compressor and turbine compared to conventional engine boost systems. In addition, the turbine design must ensure a high potential for exhaust gas recirculation. To fully exploit the potential of such an H_2 combustion process, especially in direct injection concepts, it is crucial to ensure not only the appropriate design of the H_2 injection system [3], but also the engine boost system. With boost pressures required to achieve a mean effective pressure (BMEP) above 20 bar, single-stage boost systems quickly reach their limits. Therefore, more specialized boost systems are required, where some selected configurations were identified (Fig. 3) [7].

For example, the PFI H2ICE has proven that in addition to the 50% greater mass flow, a 90% higher boost pressure is required compared to a regular turbocharged petrol engine. This is something that a single-stage supercharging system cannot provide over a wide range of engine operating conditions. In this case, a two-stage boost system with a variable geometry turbocharger becomes necessary.

In the case of the H2ICE engine, trace amounts of CO, CO_2, HC and particulate matter resulting from the combustion of the engine lubricating oil, as well as urea injection in the case of an SCR catalytic converter, are expected to be found in the exhaust gases. Additionally, secondary emissions such as NH_3 and N_2O can form in the exhaust aftertreatment system itself and should be taken into account. However, NO_x emissions are the most difficult to reduce. As previously stated, this emission is strongly dependent on the excess air coefficient of the combustion mixture (so-called raw emissions), while the structure and effectiveness of the exhaust aftertreatment system depend on the composition of the exhaust gases, their temperature and mass flow rate [1]. Although exhaust gas aftertreatment systems and their components used in engines powered by conventional fuels, such as three-way catalytic converters (TWC), active and passive SCR and NO_x adsorbers, may be taken into account, in the case of engines powered by hydrogen they will not only have to be specially adapted to the composition and temperatures of hydrogen exhaust gases – but also to the required durability and operational reliability. Therefore, their design, and in particular the materials from which they are made, will have to be adapted to the different requirements of H2ICE [31].

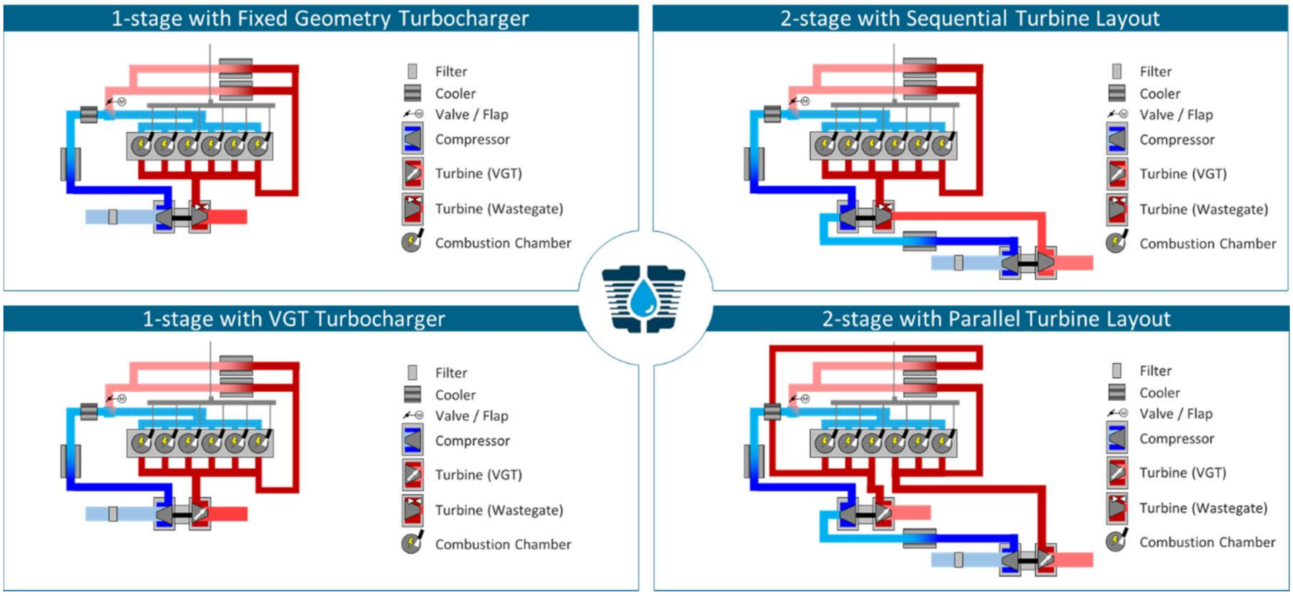


Fig. 3. Engine boost system concepts envisioned for H2ICE [7]

Figure 4 shows various concepts of exhaust gas aftertreatment systems for hydrogen-powered engines.

A different basic engine structure and a different excess air coefficient "λ" of the combusted hydrogen-air mixture were also taken into account [29, 30].

3. Disadvantages of H2ICE – challenges

A major disadvantage of H2ICE engines is their tendency to promote the formation of nitrogen oxides during combustion, especially when striving to obtain high specific power. In this case, the air-fuel ratio must be reduced to stoichiometric, leading to high NO_x emissions. A significant reduction in raw NO_x emissions, without the need to apply exhaust aftertreatment systems, requires an excess air coefficient of approximately $\lambda > 2.5$ to achieve the NO_x emissions level that would be compliant for passenger cars with the expected EU7 emission standards. This directly necessitates the use of a very high boost pressure and, consequently, engines that must be fundamentally resistant to high peak combustion pressure [30]. At the same time, the higher maximum combustion pressure, due to the laminar combustion speed being almost 6 times greater compared to liquid gasoline, causes greater mechanical stress and higher friction losses. Currently, most gasoline engines that have the structural properties to be used for H2ICE do not meet this requirement. Furthermore, very efficient and expensive turbocharging systems are needed, which must provide both sufficient air mass flow and boost pressure at low exhaust gas enthalpy levels. Otherwise, a significant reduction in engine specific power and very moderate torque levels would have to be accepted as the trade-off. Reducing boost pressure requirements can be achieved to some extent by a combination of diluting the combustible mixture with both air and external EGR. Operating the engine on a stoichiometric mixture without a combustion moderator (EGR and/or water injection) leads to irregular combustion processes [30].

The creation of NO_x reaches its peak at an excess air ratio of approximately $\lambda = 1.2$. With a leaner mixture, the combustion temperature decreases, which reduces the amount of NO_x produced. Lean combustion requires a large amount of intake air, which requires a high compression ratio to achieve the desired engine efficiency. Moreover, in this case the combustion speed decreases, which negatively affects the engine's efficiency. Hydrogen combustion is subject to anomalies such as engine knock, pre-ignition and ignited mixture backdraft. These anomalies pose problems when measuring downstream emissions because each anomaly can lead to changes in peak temperatures and emissions, making steady-state measurements challenging. An effective method of controlling combustion anomalies is to create a mixture. Direct injection (DI) after closing the intake valves can eliminate backdraft. However, the disadvantage of this method of fuel injection is the shorter homogenization time of the mixture, which means that locally areas with richer fuel content may create potential knocking combustion nodes as well as serve as sources of NO_x formation [27]. Another problem is the small quenching distance of the burning hydrogen flame from the wall, which results in increased wall heat losses, which leads to a reduction in the overall engine thermal efficiency [7].

Adapting the ICE for hydrogen fuel requires numerous changes to be made, the type and scope of which depends on the engine that is used as the basis for the hydrogen powered engine (spark ignition engine, compression ignition engine powered by diesel oil or natural gas) [6, 30, 34]. Generally, the cylinder head must usually be changed due to variable thermomechanical loads and high stresses resulting from the irregular combustion processes. These irregular processes cannot be avoided in certain H2ICE operating points. They also cause temperature and pressure fluctuations in critical areas of the engine head, such as valves or valve seats, which can lead to reduced lifespan due to fatigue. Elements of the crank system must also be adapted to the frequent occurrence of irregular combustion processes [6]. The exhaust gases of a hydrogen engine contain much more water vapor compared to the exhaust gases of an engine powered by hydrocarbon fuel. Not only exhaust gas

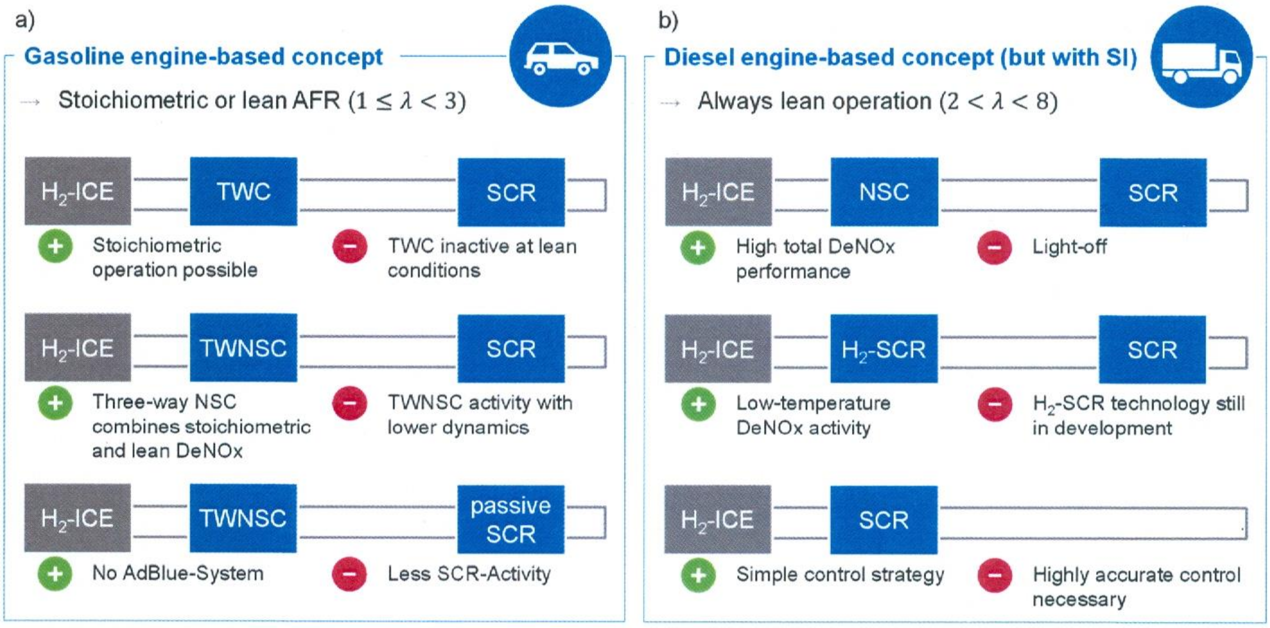


Fig. 4. Aftertreatment system layout for (a) the gasoline engine-based concept including stoichiometric operation and (b) the HD diesel engine-based concept at always lean conditions [29]

aftertreatment systems must be adapted to the increased water content in flue gases, but engine structural elements in contact with exhaust gases must also be adapter due to the higher corrosion risk [6].

Moreover, water entering the oil can accelerate the degradation processes and loss of lubricating properties. Therefore, managing the water content in the engine crankcase proves to be yet another challenge to be solved with H2ICE. It is also necessary to develop an efficient, reliable crankcase ventilation system, since a large amount of unburned hydrogen may penetrate through it, which could otherwise lead to an explosion hazard. At the same time, the piston ring assembly should minimize oil entry into the combustion chamber because, as explained earlier, oil droplets are a potential source of emissions of carbon oxides, hydrocarbons and particulates, as well as a pre-ignition source. To sum up, in recent years, great progress has been made in the development of hydrogen-powered internal combustion engines, significantly improving their performance by using direct hydrogen injection into the combustion chambers and optimizing the organization of the combustion process and turbocharging. However, the operation and popularization of internal combustion engines powered by hydrogen fuel are still associated with several challenges, especially in terms of improving reliability, which must be addressed and solved in the course of their further development. These concern maintaining low lubricating oil consumption, further optimization of hydrogen fueling processes and combustion strategy, including counteracting premature fuel ignition. Greater attention should also be paid to the harmful effects of hydrogen on metals and their alloys (hydride formation, hydrogen embrittlement, cracking caused by hydrogen leakage, and formation of hydrogen bubbles). Another challenge is the very low lubricity of hydrogen, which causes premature wear of elements that come in contact with it, such as intake valves and engine valve seat seals, injector needles and their seats (loss of airtightness), etc. Problems related to the engine lubrication system and the lubricating oil itself also require solutions. As the oil is quickly diluted with a large amount of water released from the hydrogen combustion process [30, 31].

4. Opportunities for H2ICE

Climate protection is becoming an increasingly political issue, which results in far-reaching environmental protection regulations, in particular covering economic sectors using piston combustion engines. Concerns about the impact of combustion engines on climate change have become a publicly politicized subject. Impartial assessments of the actual impact of combustion engine emissions on climate change are necessary, taking into account the enormous progress that has been made in reducing all standardized exhaust emissions from combustion piston engines (Euro 1–Euro 6; Euro 7).

In addition to the currently rapidly developed and popularized electric (battery-powered) vehicle drives and drives using fuel cells, emission-free fuels also offer great opportunities to significantly reduce CO_2 emissions. Among them, hydrogen is given wide recognition as a fuel that does not contain carbon and does not cause CO_2 emissions. Research that has already been carried out showed that H2ICE can become a drive system of the future, especially in the commercial vehicle and off-road machinery sectors, indicating that it can achieve similar levels of performance and efficiency as a modern compression-ignition engine. The criteria that a commercial vehicle must meet to qualify as (ZEV – Zero Emission Vehicles) are set out in EU Regulations 2019/1242 and 2017/2400. In the case of a heavy duty truck, which is outlined to be a vehicle powered by a non-combustion engine, or by an internal combustion engine that emits less than 1 g CO_2/kWh, following Regulation (EC) No 595/2009 and its implementing acts, or under Regulation (EC) No. 715/2007 of the European Parliament and of the Council and its implementing acts (European Parliament, 2019). According to these regulations, the only currently known combustion engine that could feasibly meet the strict EU regulations is a hydrogen-powered combustion engine. It should be remembered that in truck transport the electrification of drive systems is currently still significantly delayed compared to the vehicles of the passenger transport sector. Moreover, hydrogen as an energy carrier still has a higher storage density than batteries [26]. Hydrogen also has a much shorter refueling time than batteries, being much closer to fossil fuel refueling, which makes it more convenient to use than rechargeable batteries. Compared to a fuel cell-based drive system, H2ICE offer the following advantages: much lower purity requirements of hydrogen fuel used to power them, greater durability and longer lifespan, as well as much simpler operation and lower cost of such a drive system [11]. The hydrogen combustion engine is the next logical step in the evolution of a conventional combustion engine and is similar to it in terms of structure, operation and operating conditions. Advanced technological and design modifications, which are now possible, can change the conventional combustion engine into a H2ICE characterized by almost zero CO_2 emissions [17, 30]. Therefore, for heavy commercial vehicles for long-haul applications, H2ICE-based powertrains represent a rapid means to achieve CO_2-free mobility, especially in the short and medium term [27]. Hydrogen-powered internal combustion piston engines can be integrated with electric motors in electrified drive systems (hybrid drive systems). In addition to advantages in terms of efficiency and driving range, this leads to advantageous functional synergies and additional degrees of freedom in terms of design and operating strategies that need to be taken into account.

In 2020, the ACEA HD Expert Group on H2ICE was established and developed the necessary changes and amendments to UN R49 and UN R85 to enable the type approval of hydrogen combustion engines. ACEA experts presented the topic of OICA (Organisation Internationale des Construc-teurs d'Automobiles) in the first half of 2021. This group of experts systematically progressed their work which led to the following documents being presented at the beginning of this year:

- ECE/TRANS/WP.29/GRPE/2023/6 – Working document, joint EC/OICA proposal for a revision of R49 (07 series)
- GRPE 87 30 – Informal update document for ECE/TRANS/WP.29/GRPE/2023/6
- ECE/TRANS/WP.29/GRPE/2023/7 – Working document, OICA proposal to amend R85
- GRPE 87 16 Rev.1 – Informal update document for ECE/TRANS/WP.29/GRPE/2023/7

It is expected that further work by ACEA and OICE will soon lead to the final clarification of the regulations that will enable the full type approval of H2ICE [24].

5. Dangers for H2ICE

So far, hydrogen combustion engines have not yet entered into mass production around the world. This is primarily due to the insufficiently developed hydrogen infrastructure, which is required for all hydrogen-powered vehicles. At the same time, for the use of hydrogen in the transport sector to be sustainable it must be produced using energy from renewable sources. This requires significant development and a large increase in the rate of renewable energy production. Unfortunately, currently, the regions of the world where renewable energy – meaning primarily wind or solar – is available are not the same as the regions where this energy will be most needed [30]. Due to the still high costs of hydrogen and the small number of plants producing hydrogen, especially from renewable sources, hydrogen drive technologies are not yet competitive with conventional technologies, such as vehicles with combustion engines [35]. In practice, there are currently three main barriers that need to be overcome to the deployment of H2ICE-based powertrains in transportation to become economically and technologically viable. The first is the costs of hydrogen production and its delivery, which should be competitive with currently commonly used fuels, such as gasoline and diesel. The cost of hydrogen depends on the process/technology used for its production, the primary energy source and the adopted models of transport, storage and distribution. The second challenge is to develop a new or improved method for storing hydrogen in automotive vehicles to ensure a reasonable driving range. Thirdly, the cost of producing and operating hydrogen vehicles (H2ICE or FCV) should be reduced as a way of improving their life cycle assessment. Moreover, socio-cultural factors also play a significant role in the spread of hydrogen as a fuel in the transport system. Therefore, all information campaigns have a significant impact on the development of hydrogen technologies, especially at this early stage, to increase the awareness of people with low knowledge and have a positive impact on attitudes towards hydrogen vehicles.

The stance of the Council of the European Union, which has so far maintained their distance from this technology, will be of great importance for the development prospects and, above all, the spread of hydrogen-powered internal combustion engines. Currently, the EU is reluctant to diversify powertrains, focusing primarily on electric drives, especially in passenger cars, but not only. Currently, it is difficult to predict whether and to what extent the EU will support the development of power units based on H2ICE.

Conclusions

1. Hydrogen has the potential to become the sustainable fuel of the future, reducing global dependence on fossil fuel resources and significantly lowering automotive emissions.
2. Hydrogen, as a zero-emission fuel, can be used to make a piston combustion engine with zero emissions of CO_2.
3. H2ICE can produce trace CO, HC and particulate emissions solely from the combustion of engine lubricating oil entering the engine's combustion chambers.
4. NO_x emissions caused by H2ICE can be effectively reduced by optimizing the fuel supply and combustion systems (raw emissions) and using a dedicated exhaust aftertreatment system for H2ICE.
5. When high continuous engine power is required in low transient operating conditions, a hydrogen-powered internal combustion engine is a cost-effective approach to

CO_2-free long-distance transport, with a long service life, that relies on tested and proven technology.

6. It is possible to adapt both SI and CI engines to run on hydrogen.
7. In the medium term, a hydrogen drive system may be an alternative to electric drive systems in passenger cars until sufficient availability of fully renewable electricity is achieved.
8. H2ICE-based hybrid powertrains represent a viable alternative to electric and fuel cell drive systems to be used for light commercial vehicles in the medium to long term, both from a CO_2 equivalent and total cost of ownership perspective.
9. The advantage of H2ICE is that this technology can be brought to market relatively quickly, so it can be made available as a technology with minimal delay.
10. The operation of H2ICE presents several specific reliability challenges that will need to be addressed through further development. The already identified challenges concern maintaining low lubricating oil consumption, preventing irregularities occurring in the combustion process and ensuring the adequate durability of structural and operational elements of the engine, which can be caused by low H_2 lubricity and the so-called hydrogen embrittlement of metals.
11. The main challenge preventing the widespread use of hydrogen as fuel in automotive engine units is the limited on-board hydrogen storage technology for vehicles as well as the current scarcity of refueling stations.
12. The further development of H2ICE will require infrastructure and financial resources, which can only be achieved through a significant amount of political support, in particular from the EU.

Acknowledgements

This article was based on my own research work entitled: "Construction of a research stand with a hydrogen-powered internal combustion piston engine. Stage I: Development of assumptions for the construction of a hydrogen-powered engine stand and its power supply infrastructure; number: 1874/TE/21 (TE-5101-549/21) INiG–PIB.

Nomenclature

ACEA	European Automobile Manufacturers' Association
AFR	air fuel ratio
BMEP	brake mean effective pressure
CI	compression ignition
DI	direct injection
ECE	Europe Vehicle Certification & Solutions
EGR	exhaust gas recirculation
EU	European Union
FC	fuel cell
H2ICE	hydrogen internal combustion engine
ICE	internal combustion engine
LP-DI	low pressure direct injection
MPI	multi point injection
OICA	Organisation Internationale des Constructeurs d'Automobiles
PFI	port fuel injection
SCR	selective catalytic reduction
SI	spark ignition
TWC	three way catalyst
UN	United Nations
ZEV	zero emission vehicles

Bibliography

[1] Al-Baghdadi M. An overview of hydrogen as an alternative fuel. Encyclopedia 2020 https://doi.org/10.32545/encyclopedia202006.0003.v1 (accessed on 24.07.2023).

[2] Beatrice C. Technology review for SI ICE based powertrains with 50% brake thermal efficiency. International Workshop on Jan 21st, 2020 – Politecnico di Torino Energy Center.

[3] Bobusch B, Ebert T, Fink A, Nett O. Düse zur oszillierenden Direkteinblasung im H2-Verbrennungsmotor. MTZ Motortechnische Zeitschrift. 2021;82:42-47. https://doi.org/10.1007/s35146-021-0686-5

[4] Candelaresi D, Valente A, Iribarren D, Dufour J, Spazzafumo G. Comparative life cycle assessment of hydrogen-fuelled passenger cars. Int J Hydrogen Energ. 2021;46: 35961-35973. https://doi.org/10.1016/j.ijhydene.2021.01.034

[5] Ciniviz M, Kose H. Hydrogen use in internal combustion engine. International Journal of Automotive Engineering and Technologies. 2012;1(1):1-15. https://dergipark.org.tr/tr/download/article-file/89368

[6] Dreisbach R, Arnberger A, Zukancic A, Wieser M, Kunder N, Plettenberg M et al. The Heavy-Duty Hydrogen Engine and its Realization until 2025Der Nutzfahrzeug-Wasserstoffmotor und seine Umsetzbarkeit bis 2025. 42nd International Vienna Motor Symposium. Vienna 2021.

[7] Ebert T, Leimann D, Maniezki G, Lahni T. Predictive 0D hydrogen combustion simulation. 30th Aachen Colloquium Sustainable Mobility. 2021:1131-1147.

[8] Eichlseder H, Klell M. Wasserstoff in der Fahrzeugtechnik. 2nd Edition. Vieweg+Teubner. 2010.

[9] Faizal M, Chuah LS, Lee C, Hameed A, Lee J, Shankar M. Review of hydrogen fuel for internal combustion engines. Journal of Mechanical Engineering Research and Developments (JMERD). 2019;42(3):35-46. http://doi.org/10.26480/jmerd.03.2019.35.46

[10] Golisano R, Scalabrini S, Arpaia A, Pesce F, Vassallo A, Borgia L et al. PUNCH Hydrogen Internal Combustion Engine & KERS: an Appealing Value-Proposition for Green Power Pack. 42nd International Vienna Motoren Symposium, Vienna 2021.

[11] Huth V, Virnich L, Pfortje A, Pischinger S, Sterlepper S, Wolff T et al. The hydrogen combustion engine as zero impact emission powertrain concept. 30th Aachen Colloquium Sustainable Mobility 2021:1113-1130.

[12] Jincheng L, Dingchao Q, Linghai H, Heyang M, Yingjun G, Yanfeng G et al. FAW high-efficiency zero-emission Miller cycle hydrogen internal combustion engine for carbon neu-

trality. 43rd International Vienna Motor Symposium. Vienna 2022.

[13] Kapus P, Raser B, Arnberger A, Heindl R, Egert M, Kunder N et al. High efficiency hydrogen internal combustion engine – carbon powertrain for passenger car hybrids and commercial vehicles. 43rd International Vienna Motor Symposium. Vienna 2022.

[14] Karim GA. Hydrogen as a spark ignition engine fuel. Int J Hydrogen Energ. 2003;28(5):569-577. https://doi.org/10.1016/S0360-3199(02)00150-7

[15] Klepatz K, Rottengruber H, Zeilinga S, Koch D, Prűmm W. Loss analysis of a direct-injection hydrogen combustion engine. SAE Technical Paper 2018-01-1686. 2018. https://doi.org/10.4271/2018-01-1686

[16] Koch DT, Sousa A, Bertram D. H_2-engine operation with egr achieving high power and high efficiency emission-free combustion. SAE Technical Paper 2019-01-2178. 2019. https://doi.org/10.4271/2019-01-2178

[17] Korn T, Ebert T, Vonnoe M, Tala H, Lang M. Hydrogen engines strong case – new performance benchmarks with hydrogen direct injection. 43rd International Vienna Motor Symposium. Vienna 2022.

[18] Korn T, Nobile RF, Grassinger D. Zero-emission, maximum performance – the latest generation of hydrogen combustion engines. 42nd International Vienna Motor Symposium. Vienna 2021.

[19] Kumar N. Hydrogen use in internal combustion engine. The International Journal of Advanced Culture Technology. 2015;2:87-99. https://doi.org/10.17703/IJACT.2015.3.2.87

[20] Menes M. Program initiatives of public authorities in the field of hydrogenation of the economy in a global perspective, as of the end of 2020. Combustion Engines. 2022;189(2):18-29. https://doi.org/10.19206/CE-142170

[21] Matla J. Possible applications of prechambers in hydrogen internal combustion engines. Combustion Engines. 2022;191(4):77-82. https://doi.org/10.19206/CE-148170

[22] Munshi S, Huang J. The potential for a high efficiency hydrogen engine using Westport Fuel Systems‘ commercially available HPDI fuel system. 42nd International Vienna Motor Symposium. Vienna 2021.

[23] Pauer T, Weller H, Schünemann E, Eichlseder H, Grabner P, Schaffer K. H2 ICE for future passenger cars and light commercial vehicles, 41th International Vienna Motoren Symposium. Vienna 2020.

[24] Richter K, Rost F, Schumacher M. Type approval of H_2 engines update on 87th GRPE Meeting Joint change proposals of EC&OICA for UN R49&UN R85. 87th GRPE Session 11–13 January 2023.

[25] Scalabrini S, Golisano R, Borgia L, Costa N, Fierro E, Pesce F et al. PUNCH H_2-ICE&Flybrid KERS for decarbonizing off-highway applications. 30th Aachen Colloquium Sustainable Mobility. 2021:1079-1112.

[26] Schutting E, Roiser S, Eichlseder H, Lux S, Kleiber S. Hydrogen engine exhaust aftertreatment. 43rd International Vienna Motor Symposium. Vienna 2022.

[27] Sens M, Danzer C, von Essen C, Brauer M, Wascheck R, Seebode J et al. Hydrogen powertrains in competition to fossil fuel based internal combustion engines and battery electric powertrains. 42nd International Vienna Motor Symposium. Vienna 2021.

[28] Srinivasana CB, Subramanian R. Hydrogen as a spark ignition engine fuel technical review. International Journal of Mechanical & Mechatronics Engineering IJMME-IJENS. 2014;14(05):111-117.

[29] Sterlepper S, Fischer M, Claßen J, Huth V, Pischinger S. Energies. 2021;14:8166. https://doi.org/10.3390/en14238166

[30] Stępień Z. A comprehensive overview of hydrogen-fueled internal combustion engines: achievements and future challenges. Energies. 2021;14:6504-6516. https://doi.org/10.3390/en14206504

[31] Stępień Z, Urzędowska W. Tłokowe silniki spalinowe zasilane wodorem – wyzwania. Nafta-Gaz. 2021;12:830-840. https://www.inig.pl/magazyn/nafta-gaz/Nafta-Gaz_2021-12-06.pdf

[32] Verhelst S. Recent progress in the use of hydrogen as a fuel for internal combustion engines. Int J Hydrogen Energ. 2014;39:1071-1085. https://doi.org/10.1016/j.ijhydene.2013.10.102

[33] Virnich L, Durand T, Schaub S, Ghetti S, van der Put D. Powertrain layout optimization to maximize benefits of a H_2 internal combustion engine. 43rd International Vienna Motor Symposium. Vienna 2022.

[34] Virnich L, Lindemann B, Müther M, Schaub J, Huth V, Geiger J. How to improve transient engine performance of HD hydrogen engines while maintaining lowest NO_x emissions. 42nd International Vienna Motor Symposium. Vienna 2021.

[35] Walter L, Sommermann A, Hyna D, Malischewski T, Leistner M, Hinrichsen F et al. The H_2 combustion engine – the forerunner of a zero emissions future. 42nd International Vienna Motor Symposium. Vienna 2021.

[36] Yamane K. Hydrogen fuelled ICE, successfully overcoming challenges through high pressure direct injection technologies: 40 year of Japanese hydrogen ICE research and development. SAE Technical Paper 2018-01-1145. 2018. https://doi.org/10.4271/2018-01-1145

[37] Yip HL, Srna A, Yuen ACY, Kook S, Taylor RA, Yeoh GH et al. A review of hydrogen direct injection for internal combustion engines: towards carbon-free combustion. Appl Sci. 2019;9:4842. https://doi.org/10.3390/app9224842

Prof. Zbigniew Stępień, DSc., DEng. – Performance Testing Department, Oil and Gas Institute – National Research Institute, Poland.

e-mail: *stepien@inig.pl*