International Journal of Research and Review
Volume 11; Issue: 4; April 2024
Website: www.ijrrjournal.com
Review Paper *E-ISSN: 2349-9788; P-ISSN: 2454-2237*

Prospective Study of the Main Internal Combustion Engines Running on Hydrogen: State of the Art

Gédéon Marlein DAHOU[1], David G. F. ADAMON[2], Tognon Clotilde GUIDI[3]

[1]Engineering and Mathematical Sciences Laboratory, Graduate School of Science, Technology, Engineering and Mathematics, Abomey, Benin.
[2,3]Processes and Technological Innovations of the High National Institute of Industrial Technology, Lokossa, Benin

Corresponding Author: G. Marlein DAHOU

DOI: https://doi.org/10.52403/ijrr.20240426

ABSTRACT

Several studies have revealed the high GHG emissions of the road sector compared with other sectors. One alternative is to replace fossil fuels with others that are less harmful to the environment. Hydrogen is positioned as an adaptable solution for existing engines, especially internal combustion engines. This article presents an analysis of internal combustion engines and the different fuels used to date. In addition, the properties of hydrogen, and the current state of research into the use of hydrogen in internal combustion engines, are discussed. After a presentation of the properties of hydrogen, it goes on to describe the hydrogen combustion process, the possible anomalies caused by its properties, and a few possible modifications for adapting an internal-combustion engine to hydrogen, initially using either gasoline or diesel.

Keywords: Hydrogen - Engine design - Combustion - Sustainable development - Vehicle

INTRODUCTION

The final decade for achieving the 2030 Sustainable Development Goals has begun. The acceleration of global warming means that mitigation measures must be found in all sectors that emit greenhouse gases (GHGs). The transport sector is responsible for massive global emissions of CO_2 [(1)] with 25% of emissions [(2)]. Decarbonizing road transport is important for achieving long-term climate change mitigation targets [(3)]. All solutions to decarbonize our energy systems are welcome. The transport sector would have to choose between two solutions: the design of purely electric cars, or the design of engines using biofuels. A major drawback to the development of first-generation fuels, which are produced from crops traditionally grown for food, is that they compete with food crops[(4)].

Hydrogen is a clean, sustainable energy carrier. It is one of the energies of the future. Most studies on its use as a fuel focus on hybridization experiments with other biofuels. With the aim of reducing greenhouse gas emissions, while seeking an alternative to the depletion of fossil resources, several studies have identified several gases, including hydrogen, as fuels that could be used in the automotive sector to replace conventional fuels such as gasoline and diesel [(5,6)]. Its use in the automotive sector is based on two main technologies: the fuel cell and the hydrogen-powered internal combustion engine [(7)].

The internal combustion engine has benefited from continuous development for over a century and still shows potential for optimization. However, several key fuel cell technologies remain immature and costly, and therefore cannot be applied on a large scale in the short term[8], On the other hand, there are a multitude of internal combustion engines that can be converted to run on hydrogen. What's more, the hydrogen engine has a considerable advantage over the fuel cell in terms of low cost [7] which is driving interest in directing research towards the use of hydrogen as a fuel in internal combustion engines.

Several studies have demonstrated the efficiency of hydrogen in an internal combustion engine when added to various biofuels and fossil fuels. Simulations have been carried out to understand its combustion, without mixing, in engines dedicated to conventional fuel, and to identify the causes of probable abnormal combustion. Some studies have revealed multiple advantages of its use as a fuel in an engine: high flame propagation speed - low lean burn limit - short quenching distance [9].

The current challenge is to switch to an engine running essentially on hydrogen.

Today, it's much more common to find cars running on gasoline/gasoline bi-fuel than on gas alone. The gases used are natural gas, biogas and, much more recently, hydrogen.

The following lines present the state of research into hydrogen, and its use as a fuel in internal combustion engines.

LITERATURE REVIEW

The impact of the use of internal combustion engines running on conventional fuels is prompting the community to look for alternative solutions, either in terms of the type of engine or the type of fuel that could have less impact.

For *Towoju and Ishola*, the solution of using electric vehicles to reduce CO_2 emissions is a mistaken idea [10]. Their study showed that, based on life-cycle assessment, the CO_2 emission values of these vehicles are close to those emitted by the much-maligned internal combustion engines, based on one kilometre of road. Indeed, according to available data, the source of electricity production to power these electric vehicles is of fossil origin. Until electricity production becomes green, the electric vehicle cannot be considered green. For them, finding an alternative fuel to fossil fuels will undoubtedly lead to a drastic reduction in CO_2 emissions. Still, the mere adoption of the electric vehicle means producing more electricity.

For *Leach et al.*, the focus should be on improving internal combustion engines in order to reduce their environmental impact, considering that 99.8% of world transport uses internal combustion engines [11]. To achieve this, the technologies exist for post-treatment to ensure that exhaust pollutant levels meet today's most stringent emission requirements, and for the implementation of other technologies such as hybridization and lightweighting, which could reduce fuel consumption by 50% compared with the current average.

As shown by Woo et al., the use of a three-way catalytic converter for a petrol engine, and a diesel particulate filter (DPF) and a lean NO_x trap (LNT) as aftertreatment devices for a diesel engine, considerably reduces emissions [12].

The use of hydrogen as a fuel in internal combustion engines has been the subject of much research. Compared with gasoline and diesel, hydrogen requires lower ignition energy and features a wider flame range and faster combustion speed. This makes it an ideal fuel for internal combustion engines [13]. Mastering the parameters of its influence on internal combustion engines is the key to putting a vehicle using hydrogen as a fuel on the road.

The review by *Algayyim et al.* examines in detail the promising properties of hydrogen that enhance its suitability as a fuel, including its high diffusivity, high laminar flame speed, high auto-ignition temperature, among others [14]. These favorable characteristics for use in an engine include low ignition energy, rapid flame propagation and a wide operating range. However, the use of hydrogen is not without its challenges. The two main drawbacks are its high NO_x emission rate and the challenges associated with its storage and transport due to its gaseous state at ambient temperature and pressure. The review proposes solutions to significantly reduce NO_x emissions and effectively mitigate the phenomenon of pre-ignition in the engine. One suggested approach is the direct introduction method, involving the transfer of liquid hydrogen from a cryogenic cylinder to a heat exchanger via a pump, causing vaporization, followed by injection of cold hydrogen into the engine. Part of the study demonstrates that hydrogen is best suited to gasoline engines. The review also identifies challenges such as storage and knocking, while exploring the opportunities associated with using hydrogen as a fuel.

Akal et al. also confirm that the use of hydrogen as a fuel is more appropriate for gasoline engines, given hydrogen's high auto-ignition temperature [(15)]. Having studied the addition of hydrogen to other fuels (Diesel - LPG - Petrol), their study indicates that the addition of hydrogen to other types of fuel improves engine performance and energy efficiency, notably by reducing fuel consumption. In addition, it was found that, due to the specific structural characteristics of engines, those running on gasoline are more likely to derive significant benefits from the use of hydrogen.

Zhu et al. have shown that an excess of hydrogen for an excess coefficient between 1.04 and 1.08, increases engine power and significantly reduces emissions of NO_x [(16)]. However, an excess above a coefficient of 1.08 leads to a reduction in performance due to excess unburned hydrogen. The three-dimensional (3 - D) simulation model was based on the CONVERGE combustion model. The combustion model adopted is SAGE.

Zhenzhong et al. studied the abnormal combustion of the hydrogen internal combustion engine on the basis of hydrogen injection parameters [(17)]. The study reveals that both the flow of hydrogen into the combustion chamber and the angle of injection have an influence on combustion abnormality. They show that a hydrogen injection angle that is too small is more likely to cause a sharp rise in temperature, thus leading to pre-ignition, and a hydrogen injection angle that is too large will reduce the partial velocity of hydrogen along the inlet axis, thus leading to flashback. A hydrogen injection angle of 45° and an injection flow rate of 4.96 kg/h guarantee normal combustion conditions.

Sébastien Verhelst *confirms that the challenge for internal combustion engines is to eliminate abnormal combustion in hydrogen engines due to flashback and pre-ignition* [(18)]. Abnormal combustion is combustion that does not result from the normal propagation of a spark-ignited flame: pre-ignition and knocking[(19)]. After establishing a list of design features enabling the proper operation of hydrogen spark-ignition engines, the author presented a model of hydrogen combustion in the engines developed, validated based on experimental results from the conversion to hydrogen operation of 03 engines.

Diéguez et al. have shown that a small addition of methane (5-20% vol.) to hydrogen in a combustion engine intended to run on pure hydrogen, ensures operation with air-fuel ratios (k) closer to stoichiometric conditions, with a reduced risk of combustion anomalies in the engine [(20)]. This air-fuel ratio (k) has proved to be one of the most influential operating variables on engine performance, due to its marked effect on combustion temperature. In fact, a higher ratio to avoid knocking reduces specific emissions of nitrogen oxides, with a negative effect on engine performance.

Sáinz D et al. have demonstrated the feasibility of converting a gasoline-powered commercial vehicle into a bi-fuel car, i.e. using hydrogen and gasoline[(21)]. The main modifications concern the machining of the intake manifold and the incorporation of a new programmable electronic control unit to manage hydrogen operation. The bi-fuel vehicle's performance confirmed the superiority of hydrogen operation over petrol in terms of thermal efficiency and fuel consumption, with an estimated consumption of 1 kg of hydrogen per 100 km at an average speed of 90 km/h.

Furthermore, Arana et al. have shown a significant increase in noise levels outside a hydrogen-powered car [22].

Sopena et al. ran a gasoline internal combustion engine on hydrogen by modifying the original engine [23]. The main modifications involved the intake manifold, gas injectors, oil cooler and electronic management unit. The established engine control parameters enabled safe operation of the hydrogen engine without knocking, backfire or pre-ignition, with reasonably low NO_x emissions, improved braking torque of 63 Nm at 3800 rpm and maximum braking power of 32 kW at 5000 rpm.

Hamada et al. show that an optimized injection technique can prevent combustion anomalies in the hydrogen engine, with direct injection of the hydrogen avoiding the flashback phenomenon [24]. This is also confirmed by *Kang-da et al.* [7], and *Verhelst* [25]. The results of the experimental study show that the richer mixture condition produces higher pressure trends at all points tested. The mixture exhibited a faster rate of increase in combustion rate due to the increased flame speed.

Having obtained the same result on the reduction of abnormal hydrogen combustion through the use of direct injection, the study by *Aggarwal et al*. reveals that recirculation of 25 to 30% of the exhaust gases eliminates flashbacks [6]. If this technique is combined with water injection into the intake manifold, NO_x emissions can be reduced by 50%. In addition, crankcase ventilation is recommended, given that hydrogen exhaust gases are made up of water vapour and could cause several problems.

Wallner et al. also demonstrate that direct injection of hydrogen into the engine offers many degrees of freedom for optimizing the injection strategy to minimize individual losses and NO_x [26].

This was confirmed by Yaodong et al. on the reduction of NO_x and CO emissions, but in the case of adding hydrogen to gasoline [27]. Indeed, adding hydrogen to gasoline in an internal combustion engine, makes stable combustion possible, and an excess air coefficient of 1.5, increases effective thermal efficiency, and significantly reduces NO_x et CO emissions.

Gammaidoni et al.'s study of the effect of injection timing and air-fuel ratio shows that operation of the hydrogen engine with an air-fuel ratio $\lambda = 3$ gives very high combustion efficiency, in the case of port injection [2]. However, despite the reduction in combustion efficiency of the direct-injection engine, improvements are obtained by advancing the timing of the start of injection towards the end of the intake stroke. Simulations for these studies were carried out using the commercial CFD software CONVERGE, version 3.0 for solving the unstable Reynolds-Averaged Navier Stokes (U-RANS) equations, and combustion was modeled with the mixed approach, using SAGE as the chemical solver. Recall that a port injection engine is a type of internal combustion engine equipped with a fuel injection system where fuel is injected directly into the engine's intake manifold, also known as the intake port. This type of injection is commonly used in modern gasoline engines.

In contrast to *Gammaidoni et al*. the study by *Zhenzhong et al*. shows that delayed ignition combined with water injection into the intake manifold can control the phenomenon of flashback, although this solution is not without its drawbacks [28]. As pre-ignition and flashback are two major drawbacks to hydrogen combustion in an engine, their study shows that one can be transformed into the other, and that each of them is mutually beneficial. Electronic control software designed for this purpose, programmed in the C language, is used to control ignition delay and water injection. Before ignition, the results of pre-ignition and quench detection determine whether pre-ignition or backfire control is required. If so, the intensity of pre-ignition and flashback detected is used to calculate the degree of elimination required. The ignition advance angle is then adjusted accordingly, depending on the degree of elimination of pre-ignition and flashback. This study presents an approach to achieving normal combustion in the hydrogen-powered engine.

Zhenzhong et al. have highlighted the negative impact of water injection on the cylinder and lubrication system, while proposing an alternative [(28)], while *Duan et al.* are considering another alternative to water injection to eliminate flashback [(8)]. This is a strategy for optimizing the timing and pressure of hydrogen injection to run a backfire-free hydrogen engine with improved power output. This was demonstrated by experiments on a 2.0 L atmospheric four-cylinder gasoline engine converted to a HICE port fuel injection system. Their study shows that an extremely small or extremely large starting angle of the hydrogen injection valve results in a significantly higher-than-normal maximum pressure and rate of pressure rise inside the inlet. These conditions are considered typical signs of flashback. The absence of flashback can be observed when the starting angle of the hydrogen injection valve is within a medium range, between 258°CA and 378° CA (CA crankshaft angle), and the air-fuel ratio is 0.65.

Although direct injection of hydrogen into the cylinder avoids abnormal combustion, it does result in non-premixed hydrogen combustion. In fact, direct injection into the engine does not allow the hydrogen to premix with the air prior to combustion. Thus, studies by *Thawko and Tartakovsky* have shown that combustion of non-premixed hydrogen in an internal combustion engine can lead to increased particulate formation, significantly higher than when burning hydrocarbon fuels [(29)]. These particles are classified as the main risk factor for environmental mortality by the World Health Organization.

The studies by *Guanting Li et al.* propose a new type of injection mode: direct injection of fractionated hydrogen [(30)]. This new mode of injection can form a controlled stratified condition of hydrogen that could make combustion more complete and faster. By adding an early spray to form a more homogeneous mixture, direct injection of fractionated hydrogen can not only help form a flame core to make combustion stable but can also accelerate the rate of combustion throughout the combustion process.

Shine and k. in reviewing the various advances in the field of hydrogen internal combustion engines (H2ICE), presented insight into the physical, chemical and combustion properties of hydrogen as well as engine design requirements, recent trends in hydrogen engine and vehicle development strategies [(31)]. The study presents 22 requirements for the design of a hydrogen-powered internal combustion engine, including requirements relating to air intake system volume and geometry, oxygen sensor, flame trap, hydrogen sensors to detect hydrogen gas build-up in the vehicle and engine area, and so on. It should be noted that hydrogen's low density limits its power output. The direct injection strategy is presented as a solution to this problem.

Meng et al. carried out a comparative study of the operation of a hydrogen-powered reciprocating internal combustion engine and a Wankel rotary engine, both of which are used to running on gasoline [(32)]. The study shows that hydrogen occupies a larger volume of the intake volume, around 30%, sharply limiting the amount of fuel entering the combustion chamber. Experimentation with reciprocating-piston internal combustion engines shows flashback production at 2500 rpm. The study also reveals that in hydrogen-fuelled internal combustion engines, knocking is generally caused by rapid, unstable combustion of the hydrogen and spontaneous combustion of the final gas, which is several times more intense than the former.

Bakar et al. experimentally analyzed the performance and combustion/emission characteristics of a diesel engine using hydrogen in bi-fuel mode [(33)]. The addition of hydrogen for a quantity of 21.4 l/min to diesel resulted in a better efficiency of 34.9%, reduced combustion time, more stable combustion, and significantly reduced *CO*, CO_2, and smoke concentration. The engine, using diesel and hydrogen simultaneously, underwent no major modifications. In addition to diesel, for low loads (5 Nm and 10 Nm), hydrogen enrichment tends to reduce NOx emissions. However, hydrogen enrichment beyond a certain limit led to knocking, and limits engine operation. The study did not address the unique use of hydrogen as a fuel in the diesel engine.

Yadav et al. also found that a hydrogen-enriched diesel engine gives maximum efficiency at around 70% of full load, whereas when running on diesel, these values approach 80% of full load [(34)]. They also claim that the combustion characteristics of hydrogen are almost like those obtained with diesel. Slightly higher values of peak cycle pressure and the same values mean that the effective pressure indicates a higher lag period and a lower cetane number for hydrogen compared with diesel fuel.

Sun et al. in their study present the coefficient of variation of indicated mean effective pressure (COV_{imep}) as the main parameter for assessing combustion stability in an engine because it describes, according to the literature, the overall characteristics of combustion pressure as a function of engine power [(13)] . This parameter was studied by them, to evaluate cycle variations in a port-injected hydrogen internal combustion engine. It is recalled that hydrogen engines are influenced by many factors, such as engine speed, air-fuel ratio, ignition advance angle and hydrogen injection timing. The study shows that in port injection, the air-fuel ratio influences the (COV_{imep}) than the ignition advance angle.

In addition, the use of calculation codes makes it possible to model the engine and discern the behaviour of each of its components.

For example, *Mezher* studied the characterization of the dynamic behaviour of the intake circuit of a supercharged internal combustion engine, as opposed to natural aspiration, using a transfer matrix [(35)]. The study described the dynamic behaviour of pressure waves at the intake of a supercharged internal combustion engine. Only the charge-air cooler was modelled.

Phenomenological modelling of the combustion chamber during valve crossing was studied by *Jannoun* to estimate the fraction of residual gas in the combustion chamber [(36)]. The model chosen was Benson's in the AMESim simulation software. The study estimated the residual gas content in the combustion chamber of a gasoline engine experimentally and by simulation. The study reveals that a better estimate of the combustion chamber content is obtained with the Hybrid model with mass transfer.

A predictive model for lean hydrogen combustion in a spark-ignition internal combustion engine has been implemented by *Krebs et al*. The model can reproduce the effects of abnormal combustion phenomena that accompany the use of hydrogen inside internal combustion engines [(37)].

Babayev et al. have further investigated the hydrogen combustion cycle in a diesel engine, highlighting several distinct aspects of direct hydrogen combustion compared with a conventional diesel engine [(38)]. This analysis was achieved through the development of a CFD (Computational Fluid Dynamics) model using the CONVERGE CFD solver. This model focuses on the unique characteristics of hydrogen, using a numerical method adapted to accurately reproduce the H_2 direct injection phenomenon.

MATERIALS & METHODS

The literature review was carried out by searching for articles on internal combustion engines in general, and on hydrogen-powered engines in particular. Then, those dealing with the operation of these engines with hydrogen, and highlighting the various problems linked to their operation, in particular abnormal combustion of hydrogen inside the engines, were selected. Similarly, articles proposing solutions to the various problems encountered by hydrogen-powered engines were also selected.

The articles consulted came mainly from the Sciences direct platform, and google scholar, and were published between 1990, and 2024. The following graph shows the proportion of articles read by year of publication.

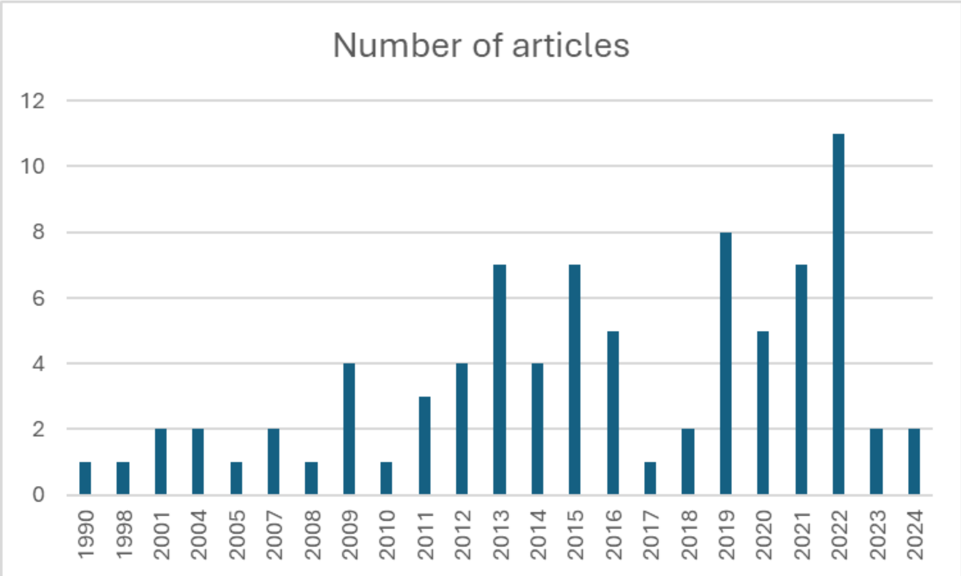


Figure 1 : Number of publications read by year of publication.

HYDROGEN

Hydrogen is a basic material for the chemical industry [39]. Hydrogen is an energy carrier in the sense that although hydrogen (H) is one of the most abundant elements on Earth, it is not available in a pure state in nature. It is only found in combined form (in water H_2O, in hydrocarbons C_nH_m, etc.). Hydrogen therefore must be produced, and energy expended, before it can be used to produce energy. We therefore speak of an energy carrier rather than an energy source [40].

1. Different ways of producing hydrogen

There are many ways to produce hydrogen. Hydrogen can be produced from fossil fuels or from renewable sources.

The first category, involving fossil fuels, includes hydrocarbon reforming and pyrolysis methods. In the hydrocarbon reforming process, the chemical techniques used are steam reforming, partial oxidation and autothermal steam reforming.

The second category includes processes that produce hydrogen from renewable resources, either biomass or water.

Hydrogen can also be produced by reforming biogas. The most important aspect of its production from biogas is the use of catalysts insensitive to carbon and sulfur content [41].

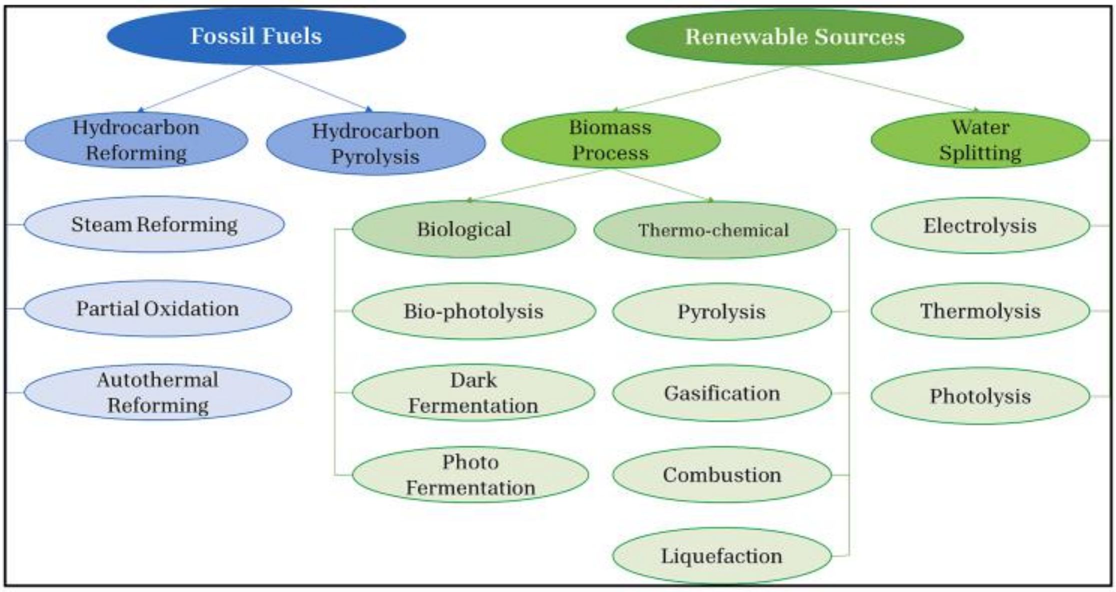


Figure 2 **: Hydrogen production methods** [14, 42]

2. Hydrogen's Properties

Hydrogen is the smallest of all the elements in the periodic table, measuring just 10-15 meters, and can diffuse rapidly in air: air diffusion coefficient 0.61 cm²/s (four times faster than natural gas: diffusion coefficient 0.16), which is a positive factor for safety.

Hydrogen is colourless, odourless, tasteless and non-corrosive, and has the advantage of being particularly energetic: 1kg of hydrogen releases around three times more energy than one kg of gasoline [5].

With a density of 0.0695 at 20°C and 101.3 kPa, the hydrogen molecule is the smallest and lightest in nature. As a result, it diffuses rapidly through the air and concentrates at the highest level in a confined area[43].

The properties of hydrogen are presented in the table below.

Table 1 Thermodynamic properties of hydrogen, methane and gasoline (generally accepted literature values) [44]

Property	Hydrogen	Methane	Fuel
Molecular weight (g/mol)	2.016	16.043	~107
Gas density at NTP (g/m^3)	83.764	651.19	4400
Heat of combustion (low) (*kJ/g*)	119.93	50.02	44.5
Heat of combustion (high), (*kJ/g*)	141.86	55.53	48
Specific heat $(C)_p$ of NTP gas, (*J/g/K*)	14.89	2.22	1.62
Viscosity of NTP gas, g cm^{-1} S^{-1}	0.0000875	0.000110	0.000052
Specific heat ratio (v) of NTP gas	1.383	1.308	1.05
Gas constant (R) cm^3 atm^{-1} g^{-1} K^{-1}	40.7030	5.11477	0.77
Diffusion coefficient in air NPT cm^{-2} S^{-1}	0.61	0.16	0.005

Hydrogen's wide flammability range compared with all other fuels means that it can be burned in an internal combustion engine on a wide range of air-fuel mixtures. The advantage of this is that hydrogen can operate on a lean mixture, i.e. one in which the quantity of fuel is less than the theoretical, stoichiometric, or chemically ideal quantity required for combustion with a given quantity of air. This is why it's relatively easy to start a hydrogen engine [45].

Its auto-ignition temperature exceeds that of methane, making it particularly suitable for spark ignition and unsuitable for compression ignition [(18)].

Table 2 Combustion properties of hydrogen, methane, and gasoline[(44)]

Property	Hydrogen	Methane	Gasoline
Flammability limits in air, vol%	4.0 à 75.0	5.3 à 15.0	1.0 à 7.6
Stoichiometric volumetric fraction (in air)	29.53	9.48	1.76
Minimum ignition energy in air (mJ)	0.02	0.29	0.24
Auto-ignition temperature (K)	858	813	501 à 744
Flame temperature in air (K)	2318	2148	2470
NTP air combustion rate,cm s^{-1}	265 à 325	37 à 45	37 à 43
Air quench gap NTP, cm	0.064	0.203	0.2
Percentage of thermal energy radiated from the flame to the environment, (%)	17 à 25	23 à 32	30 à 42
Mass diffusivity in air (cm^2/s)	0.63	0.2	0.08
Standardized flame emissivity (2000 k, 1 ATM)	1	1.7	1.7
Flammability limits (equivalence ratio)	0.1 à 7.1	0.53 à 1.7	0.7 à 3.8

Hydrogen's higher diffusivity is a strong plus point in engine application due to its ability to mix [(42)].

INTERNAL COMBUSTION ENGINES

Basically, from a thermal point of view, the internal combustion engine is a heat engine that releases thermal energy from the combustion of fuel [(46)].

Internal combustion engines are engines in which the system is renewed at each cycle and is in contact with a single heat source (the atmosphere) [(47)]. Internal combustion means that combustion takes place inside the engine [(48)].

An internal combustion engine can be distinguished according to the mechanism used to achieve the thermodynamic cycle, the number of thermodynamic cycles, and the combustion mode.

This study is concerned with piston capsulism engines [(49)].

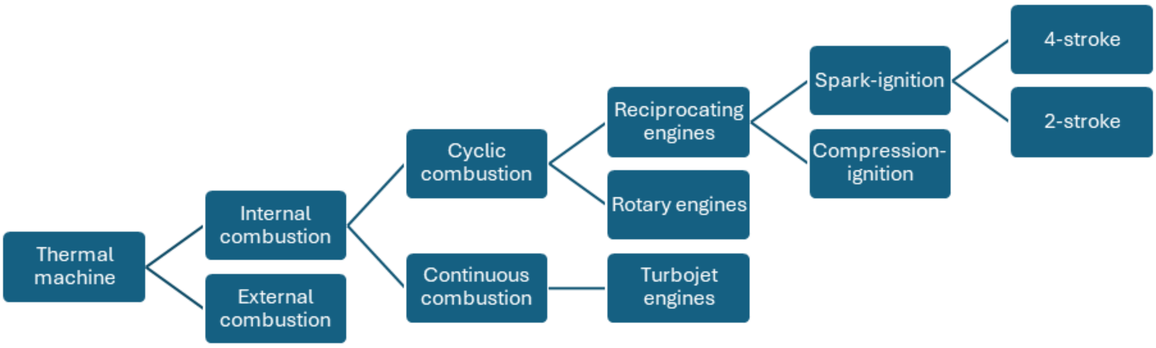


Figure 3 : Thermal engines [(48)]

1. Four-stroke engine operating principle

The four-stroke engine corresponds to two crankshaft revolutions which group together the four strokes. The intake phase is when the piston descends, the intake valve opens and fresh air rushes into the cylinder. The compression phase is when the intake valve closes, and the piston rises. The air or fresh charge is compressed and heats up considerably. For diesel engines, when the piston reaches about 9/10ths of its stroke, a quantity of fuel is injected. Expansion phase: when the valves are closed, the mixture of air and fuel in the cylinder is under pressure, and the temperature is high

enough for the mixture to ignite, creating excess pressure that pushes the piston down.
Exhaust phase: the exhaust valve opens, and the piston moves upwards, expelling the burnt gases into the exhaust system. In the case of a four-cylinder engine, each of the pistons performs the four phases described above and is offset by 180° in relation to the other pistons, following the 1342 firing order. So, while the first piston is at the end of the compression phase, the third is at the end of the intake phase and beginning of compression, the fourth is at the end of the exhaust phase and beginning of intake, and the second is at the end of the explosion phase and beginning of exhaust [50].
Correct engine operation depends on the quality of the fuel-combustion mixture introduced into the internal combustion engine.
For physicists, the nature of the flame is the cornerstone of the work. In a combustion engine, the flame is a premixed flame, whereas in a diesel engine, the flame is a succession of premixed flames, followed by rapid and then slow diffusion.
For chemists, combustion in the engine is a rapid oxidation reaction. It is governed by kinetics and chemical equilibrium. Each reaction has a rate of progression linked to the species involved [50].
A normal volumetric ratio is of the order of 1:20 for a diesel engine (compared with 1:10 for a petrol engine) [51].

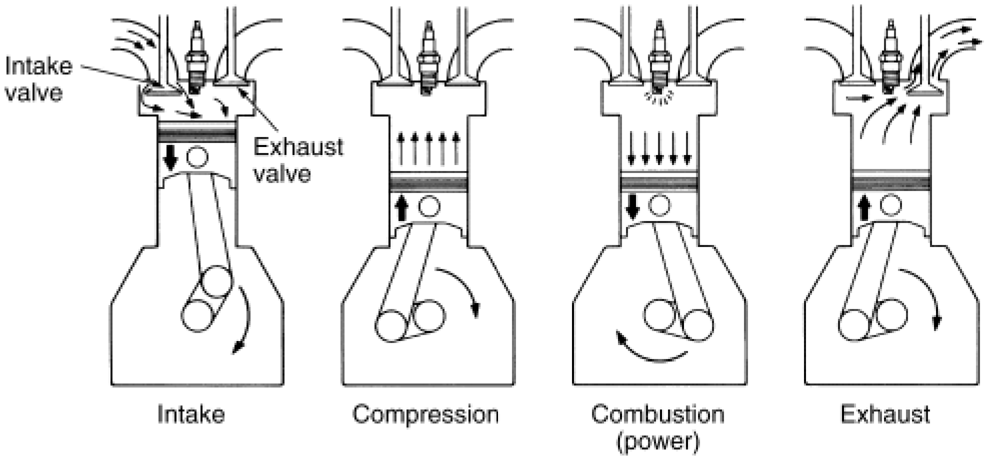


Figure 4 : Presentation of the four strokes of an internal combustion engine [52]

2. Structure of an internal combustion engine

Overall, the components of spark-ignition engines are similar to those of diesel engines. The combustion chamber consists of a cylinder, usually stationary, closed at one end and into which a piston slides. The reciprocating motion of the piston alters the volume of the chamber between the inner face of the piston and the closed end of the cylinder. The outer face of the piston is coupled to a crankshaft by a connecting rod. The crankshaft transforms the reciprocating motion of the piston into rotary motion. In multi-cylinder engines, the crankshaft has a cranked part, the crank pin, associated with each connecting rod [50, 53].

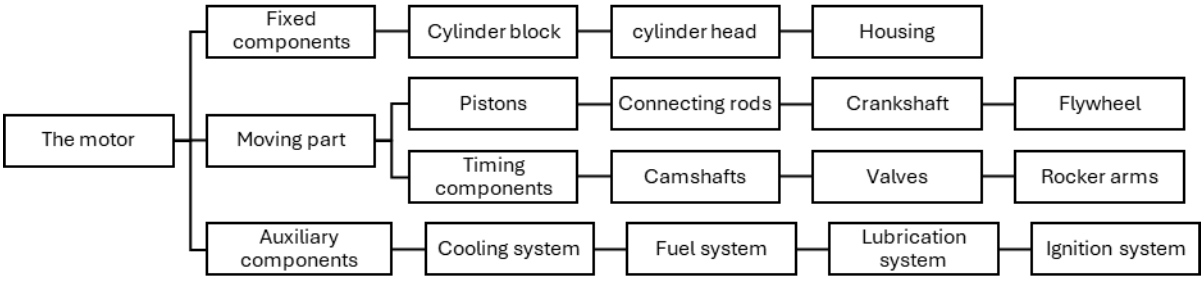
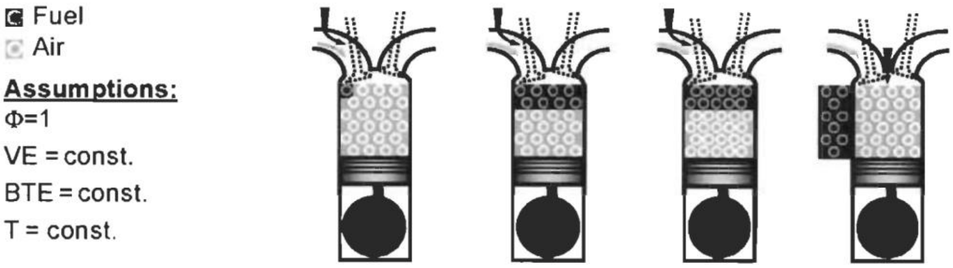


Figure 5 : Main components of a reciprocating engine [48]

3. Hydrogen engine

Internal combustion engines can also run on fuels other than petrol and diesel. These include biofuels and hydrogen. The choice of operating cycle depends on the nature of the fuel. Running the hydrogen engine in the diesel cycle is highly advantageous, as it delivers high power density and improved efficiency. But for hydrogen, it is difficult to reach the auto-ignition temperature of hydrogen under conventional compression ratio conditions, hence the preference for the spark-ignition engine over the diesel type. The formation of the gas mixture has an impact on the engine's power density. Hydrogen engines are generally gasoline engines with modified injection systems and electronic control units. The power density of hydrogen engines varies according to how the mixture is formed [54].



Fuel	Gasoline	H_2	H_2	H_2
Mixture formation	*external*	*external*	*external cryogenic*	*internal*
Mixture temperature [K]	293	293	210	293
Mixture calorific value [MJ/m³]	3.6	3.0	4.15	4.22
Power potential [%] (compared to gasoline)	100	82	115	117

Figure 6 : Influence of mixture formation on charge potential [54]

In Figure 6, the concept of mixture formation changes the engine's power density in comparison with a gasoline engine. Three types of hydrogen/air mixture formation are compared with gasoline. The indirect injection system (the mixture is formed outside the combustion chamber like that of petrol) has a lower power potential than petrol (82%). When the hydrogen is cooled, the power potential rises to 115%. But this technique is complicated by the need to cryogenine the hydrogen. The direct injection system, where the mixture is formed inside the combustion chamber, is the best in terms of power potential (117%), but the process is difficult to implement.

The indirect injection system is the most widely used, as it is easier to implement and can be applied to a gasoline-powered machine with a simple change of fuel, as in the case of dual-fuel machines. At present, there are three main lines of research aimed at improving hydrogen engines. The first is to study the possibility of operating with the diesel cycle. This will improve power potential and efficiency. The second focuses on direct hydrogen injection, which is the best option for operation with the petrol cycle. The third axis is based on improving the indirect injection system already in use, to make it more efficient.

3.1 Operating principle

The hydrogen engine doesn't change the operating principle of 4-stroke engines, only a few things:

- The fuel introduced into the cylinders is gaseous (hydrogen).
- Hydrogen is highly sensitive to auto-ignition (same principle as diesel engines, which operate on auto-ignition).
- Combustion is about six times faster than gasoline.
- The hydrogen engine generates just water vapor H_2O and NO_x (of nitrogen oxides) and heat, not CO_2

The hydrogen internal combustion engine, transforms the chemical energy resulting from the explosive reaction between dihydrogen and dioxygen into mechanical energy [55].

$2H_2 + O_2 = H_2O$ + energy

The mechanical energy generated powers a piston, like the operation of a gasoline or diesel engine. However, due to the characteristics of hydrogen, adjustments are required to take account of its gaseous state, propensity for self-ignition, increased combustion rate and corrosive potential. Adjustments are also required to reduce nitrogen oxide (NO_x) emissions resulting from the oxidation of atmospheric nitrogen [55].

3.2 Different components

Hydrogen engines use the same components as natural gas engines.

The use of hydrogen in a car requires a tank. Here, hydrogen is stored in a cylinder at a pressure of 200 to 700 bar. This requires a solenoid valve to release the hydrogen from the storage tank.

A Vapo regulator is used to reduce the hydrogen pressure from 200 to 700 bar to 30 to 60 bar, thus bringing the fuel from its storage pressure to its operating pressure. The gas enters through the inlet chamber, and its pressure (30 to 60 bar) is indicated by a manometer/flowmeter.

Other experiments have shown, with the use of a pressure regulator, which would maintain the pressure at 9 bars in the pipe connecting the gas bottles to the accumulator, and another at the inlet of the accumulator to reduce the pressure to 3 bars, which is the operating pressure of the hydrogen injectors [21].

The injectors deliver hydrogen to the combustion chamber at a pressure of between 30 and 60 bar. Injection takes place at an injection angle of 45° and an injection rate of 4.96 kg/h, since they guarantee normal combustion conditions, i.e. 59.21 m^3/h.

3.3 Hydrogen injection system in the combustion chamber

Three types of injection systems can be found in hydrogen engines:

Port Injection System: This system feeds fuel directly to the intake manifold through all intake ports, eliminating the need for single-point concentration. At the start of the intake phase, hydrogen is introduced into the intake manifold, making conditions less critical and minimizing the risk of pre-ignition. There are two types of port injection system: electronic fuel injector and constant fuel injector [(6)].

Direct injection system: In this system, fuel is injected while the intake valve is closed, thereby preventing flashback and avoiding premature ignition during the intake phase [(6)].

Central injection system: This system uses a carburettor to create an air-fuel mixture to inject into the engine, providing a simple method of supplying hydrogen to the engine. Using this system has two main advantages for a hydrogen engine: on the one hand, the required hydrogen supply pressure is relatively low compared to other methods, and on the other hand, gasoline engines can be easily converted to hydrogen engines as most use central injectors or carburettors [(6)].

3.4 Advantages of hydrogen engines

Hydrogen engines offer the following advantages:

- Faster combustion speed.
- Wider range of flames.
- Thermal efficiency.
- Low fuel consumption.

3.5 Disadvantages of hydrogen engines

The limitations of hydrogen engines can be enumerated as follows:

- High resistance to auto-ignition.
- Operating range was limited.
- High NO_x emissions.
- Abnormal combustion due to flashback and pre-ignition.
- Rattling.

The small quench gap of hydrogen explains why it's harder to extinguish a hydrogen flame than a gasoline flame. This is because hydrogen flames move closer to the cylinder wall than other fuels before extinguishing. The shorter extinguishing distance plus of hydrogen increases the tendency to flashback, since the flame of a hydrogen-air mixture passes more easily through a nearly closed intake valve than a hydrocarbon-air flame [(45)].

In addition, the low ignition energy of hydrogen is a source of pre-ignition and flashback problems, since hot gases and hot spots on the cylinder can serve as ignition sources [(45)].

3.6 Summary of the advantages and disadvantages of different gas engines

The following table summarizes the advantages and disadvantages of the various gas engines.

Table 3 : Advantages and disadvantages of different gas engines

Engine type	Fuel type	Advantages	Disadvantages
Natural gas engine	Natural gas (NG)	Good calorific value (GCV=10 kwh/Nm3) Can be used directly in spark-ignition and modified diesel engines. Better ecological balance Satisfactory, albeit limited, range in: 1m3 of compressed gas at 200 bar gives a bus a range of around 400 km No soot formation during combustion (no calamine formation) No soot formation during combustion (no soot formation during combustion (no soot formation during combustion (no soot formation during combustion), Enables lean-burn engine operation thanks to its	Natural gas engines require a precise metering system to limit emissions. Injecting or inducting natural gas into the intake manifold affects volumetric efficiency, as the fuel gas replaces air. The 2.2% lower mass ICP and 17.2% higher stoichiometric ratio of natural gas to petrol also affect engine power. Overall, the combination of these three factors results in a 10-15% reduction in power compared with gasoline engines of the same size. Exhaust gases contain unburned methane hydrocarbons. Engine performance is reduced by around 10%,

		wider flammability range.	compared with petrol engines.
LPG engine	Liquefied Petroleum Gas	More consistent engine torque at low revs thanks to homogeneous LPG-air mixture Quieter engine operation Low vibration LPG combustion without deposits (scale) Dust-, lead- and sulphur-free exhaust gases. Better ecological balance	Approx. 5% power loss at high rpm 15 to 20% lower fuel consumption Reduced carbon monoxide emissions Slight drop in power compared to a gasoline vehicle. Fuel tank often housed in place of spare wheel. Higher fuel consumption than a diesel vehicle on short journeys
Biogas engine	Methane	Produces fewer toxic pollutants. Saves fuel.	The problems of biogas engines are: Slow combustion speed. Severe post-combustion. Exhaust temperature is high. And the heat load is heavy and so on. Need for well-cleaned gas
Hydrogen engine	Hydrogen	Faster combustion speed Wider range of flames Thermal efficiency Lower fuel consumption	High resistance to auto-ignition Short ignition delay Operating range was limited. Increases emissions of NO_x Abnormal combustion due to flashback and preignition Rattling

Combustion

Combustion refers to a rapidly evolving chemical reaction accompanied by the emission of light and a significant release of heat: the flame [56].

The fuel fed into the cylinder is a mixture of air and fuel.

The fuels most used in internal combustion engines (gasoline and diesel fuels) are mixtures of many different hydrocarbon compounds obtained by refining petroleum or crude oil. These fuels are mainly made up of carbon and hydrogen (generally around 86% carbon and 14% hydrogen), although diesel fuels can contain up to around 1% sulphur. Other fuels of interest are alcohols (which contain oxygen), gaseous fuels (natural gas and liquefied petroleum gas) and simple hydrocarbon compounds (e.g. methane, propane, isooctane), which are often used in engine research [57].

Air contains nitrogen, but when the products are at low temperature, nitrogen is not significantly affected by the reaction. Consider the complete combustion of a general hydrocarbon fuel of average molecular composition C_mH_n with air. The overall equation for complete combustion is [57] :

$$C_mH_n + (m + n/4)\,(O_2 + 3.773\,N_2) \longrightarrow mCO_2 + n/2\,H_2O + 3.773\,(m + n/4)\,N_2$$

There are 03 different types of combustion [56]:

Homogenous: oxidizer and fuel are premixed in each ratio. Examples: spark-ignition engine, blowtorch.

Heterogeneous: combustion takes place at the boundary between oxidizer and fuel. Oxidizer and fuel can be either or both: solid, liquid, or gaseous.

Stratified: oxidizer and fuel are premixed in a variable ratio between a value allowing ignition and the ratio characterizing the presence of pure oxidizer. **Example**: stratified charge engine.

1. Conditions of ignition of a gaseous mixture

A reactive medium can be defined by three parameters: the pressure of the medium P, the absolute temperature of the medium T and the composition of the fuel mixture. If any of these parameters falls below a critical value, the oxidation process is slow, which means that live combustion (with flame) cannot be initiated. The reaction itself will not take place. If all three parameters reach values above the critical thresholds, the fuel may self-flame. The reaction process goes into overdrive. When such self-ignition is not de facto ensured by the nature of the fuel, as in the case of gasoline, external activation energy is supplied to the reactive system to initiate combustion [58].

1.1 Minimum temperature

There is a minimum temperature T_i at which combustion begins: this is the ignition temperature. It is around 870°K (600°C) for common gases (H_2, CH_4, CO, …)

It can be of the order of 700°K up to 900°K in engine conditions such as diesel. For combustion to propagate, the amount of heat released locally by oxidation must raise the temperature of neighbouring layers of the mixture to a temperature equal to T_i [(58)].

Table** Error! No text of specified style in document.**-4 : Examples of flammability temperatures [(58)]

Designation	T_i (°K)
Hydrogen (H_2,)	840
Methane (CH_4)	850
Ethane (C_2H_6)	760
Propane (C_3H_8)	750
Butane (C_4H_{10})	750

1.2 Flammability limits L_s and L_i

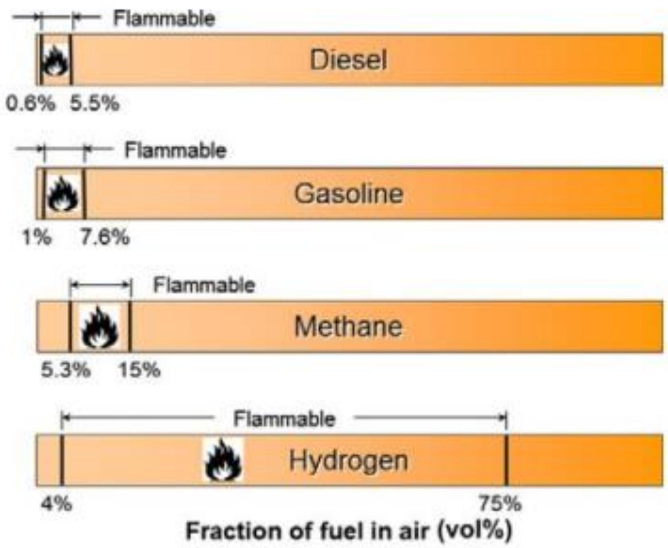


Figure 7 : Comparison of flammability limits for typical motor fuels [(59)]

Gas-phase combustion only takes place when the quantity of reactive mixture prepared (fuel/fuel) is sufficient to initiate combustion [(58)].

If the quantity of fuel is high, only a fraction of it is burnt, and the rest does not react due to a lack of O_2. However, if the amount of oxidizer is high, the amount of heat released may be insufficient for the reactive charge to reach ignition temperature.

Hydrogen has the advantage of being flammable in a proportion of 4 to 75% by volume in a mixture with oxygen [(59)].

Note: L_s and L_i vary according to the initial temperature of the mixture.

2 Abnormal combustion in a hydrogen engine

Three (04) abnormal combustion regimes are encountered in hydrogen engines:

- Knock, a self-ignition in the end-gas region resulting in explosion resonance on the walls of the combustion chamber and piston, is rare in hydrogen engines, compared with gasoline engines.
- Pre-ignition, an uncontrolled ignition induced by a hot spot, premature for spark ignition [(18)] ;
- Flashback, a premature ignition of the air-hydrogen mixture during the intake stroke.

- and auto-ignition of the unburned mixture.

2.1 Pre-ignition

Pre-ignition in hydrogen engines is a complex process influenced by the nature of the fuel, the temperature and pressure conditions in the cylinder, and the characteristics of the air-fuel mixture.

In fact, due to the nature of hydrogen, with its low ignition threshold and rapid combustion, it can ignite prematurely at hot spots in the combustion chamber, even before the spark plug is due to ignite. This phenomenon is intensified when the intake and exhaust valves remain open simultaneously, promoting contact between the new mixture and the hot exhaust gases. As engine temperature rises, so does the temperature of the fuel particles in the cylinder, aggravating the risk of pre-ignition (15)[, 28).]

In addition, pre-ignition is influenced by the changing pressure and temperature in the cylinder. If spontaneous combustion conditions are reached before ignition, the mixture may ignite prematurely. This premature combustion triggers an intense chain reaction, rapidly increasing the pressure and temperature in the cylinder. As a result, the rate of mass combustion increases, leading to a further rise in pressure and temperature.

2.2 Flashback

Flashback, a major problem associated with the use of hydrogen in engines, results from various conditions and interactions within the system. It occurs when a mixture of hydrogen and air ignites uncontrollably in the combustion chamber or intake manifold. This ignition can be triggered by hot spots in the combustion chamber or on the intake valve, and is often accompanied by pre-ignition, particularly under rich mixture or high-speed conditions [(15,] (28).

When the intake valve is not yet closed during the intake process, the flame in the cylinder can propagate into the intake manifold, causing it to ignite. Flashbacks can also occur due to gas residues in the mixture, resulting in delayed combustion and flame propagation from previous cycles [(15, 28)].

These backfires compromise the normal operation of the hydrogen engine, leading to reduced power, poorer fuel economy and even engine shutdown. To avoid these undesirable situations, adjustments must be made to the ignition system and the air-fuel mixture[(15, 28)].

It should be remembered that flashback in hydrogen engines is a complex phenomenon influenced by factors such as mixture composition, temperature, and pressure in the combustion chamber, as well as the design of the intake and ignition system. Its effective management is essential to ensure stable and safe operation of the hydrogen engine.

2.3 Knocking

The phenomenon of knocking, also known as engine knocking, occurs when the hydrogen-air mixture ignites spontaneously in front of the flame front after compression. This rapid ignition creates pressure waves in the rest of the mixture, leading to an excessive rise in temperature and pressure in the cylinder walls. The result is a reduction in engine power and an increase in harmful emissions.

The formation of knocking can be influenced not only by the amount of hydrogen introduced into the cylinder, but also by the spraying method. To avoid this phenomenon, it is essential to maintain the correct compression ratio and mixing ratio.

Introducing water or nitrogen into the mixture in the cylinder can also help prevent knocking [(15)].

2.4 Hydrogen in internal combustion engines

It's easier to adapt a gasoline engine to the use of a gaseous fuel. A comparative study between gasoline and diesel engines fuelled by hydrogen shows that hydrogen's high auto-ignition temperature makes it more suitable for gasoline engines than for diesel engines [(14)].

The unique use of hydrogen in internal combustion engines has demonstrated that hydrogen has a high resistance to auto-ignition [(60)]. Its ignition delay is short, and effective pressure is higher than that of diesel, with glow plug ignition. Its use in a single-cylinder diesel engine revealed that its operating range was limited [(60)].

However, its use with diesel showed that the engine could achieve higher thermal efficiency than diesel fuel under high engine load conditions. In addition, NO_x emissions at higher loads are increased compared with conventional diesel fuel. When used in a 4-stroke engine, the thermal efficiency of the engine decreases at every load condition, as the flame speed of hydrogen is nine times faster than that of diesel fuel, and the additional heat flux increases, leading to higher heat loss.

The use of small quantities of hydrogen, up to 10%, with biofuels did not affect the engine's steady-state operation. In addition, hydrogen increases emissions due to high combustion rates. Combustion time was reduced and ignition delay, maximum pressure rate and peak pressure increased [(60)].

CONCLUSION

Internal combustion engines have undergone several evolutions, from the use of gasoline, or diesel as a liquid fuel, to the use of gaseous fuels such as natural gas and LPG.

Today, climate change requires us to seek more sustainable solutions that are more protective of the environment.

The objective of this review is to present major studies on the use of hydrogen as a fuel in internal combustion engines, while highlighting the problems related to its use in engines.

Hydrogen offers favourable properties for its use in internal combustion engines. However, it is important to control certain phenomena such as flashbacks, pre-ignition, and self-ignition, which can occur given the properties of hydrogen. Furthermore, its storage should be studied, depending on the pressure, and the quantity to be stored.

This overview demonstrates that it is possible to run an internal combustion engine on hydrogen. This would be possible by controlling normal hydrogen combustion and a secure means of storage.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: The authors declare no conflict of interest.

REFERENCES

1. Suttakul P, Wongsapai W, Fongsamootr T, Mona Y, Poolsawat K. Total cost of ownership of internal combustion engine and electric vehicles: A real-world comparison for the case of Thailand. Energy Reports. nov 2022;8:545-53.
2. Gammaidoni T, Miliozzi A, Zembi J, Battistoni M. CFD analysis of hydrogen mixing and combustion in internal combustion engine: Evaluation of premixed and DI methods. Case Studies in Thermal Engineering. févr 2024;104072.
3. Morfeldt J, Davidsson Kurland S, Johansson DJA. Carbon footprint impacts of banning cars with internal combustion engines. Transportation Research Part D: Transport and Environment. juin 2021;95:102807.

4. Tarabet L, Loubar K, Lounici MS, Hanchi S, Tazerout M. Eucalyptus Biodiesel as an Alternative to Diesel Fuel: Preparation and Tests on DI Diesel Engine. Journal of Biomedicine and Biotechnology. 2012;2012:1-8.
5. Maamri R. MODELING AND EXPERIMENTATION OF COMBUSTION ENGINES OPERATING WITH DIFFERENT SUBSTITUTE FUELS AND BLENDS. :286.
6. Aggarwal A, Yadav S, Singh K, Singh Verma A, Chhabra S. Study of utilization of hydrogen as fuel in internal combustion engine. Materials Today: Proceedings. 2022;64:1211-6.
7. Wang K da, Sun B gang, Luo Q he, Li Q, Wu X, Hu T, et al. Performance optimization design of direct injection turbocharged hydrogen internal combustion engine. Applications in Energy and Combustion Science. déc 2023;16:100204.
8. Duan J, Liu F, Sun B. Backfire control and power enhancement of a hydrogen internal combustion engine. International Journal of Hydrogen Energy. mars 2014;39(9):4581-9.
9. Gao J, Wang X, Song P, Tian G, Ma C. Review of the backfire occurrences and control strategies for port hydrogen injection internal combustion engines. Fuel. janv 2022;307:121553.
10. Towoju OA, Ishola FA. A case for the internal combustion engine powered vehicle. Energy Reports. févr 2020;6:315-21.
11. Leach F, Kalghatgi G, Stone R, Miles P. The scope for improving the efficiency and environmental impact of internal combustion engines. Transportation Engineering. juin 2020;1:100005.
12. Woo SH, Jang H, Lee SB, Lee S. Comparison of total PM emissions emitted from electric and internal combustion engine vehicles: An experimental analysis. Science of The Total Environment. oct 2022;842:156961.
13. Sun B gang, Zhang D sheng, Liu F shui. Cycle variations in a hydrogen internal combustion engine. International Journal of Hydrogen Energy. mars 2013;38(9):3778-83.
14. Algayyim SJM, Saleh K, Wandel AP, Fattah IMR, Yusaf T, Alrazen HA. Influence of natural gas and hydrogen properties on internal combustion engine performance, combustion, and emissions: A review. Fuel. avr 2024;362:130844.
15. Akal D, Öztuna S, Büyükakın MK. A review of hydrogen usage in internal combustion engines (gasoline-Lpg-diesel) from combustion performance aspect. International Journal of Hydrogen Energy. déc 2020;45(60):35257-68.
16. Zhu H, Zhang Y, Liu F, Wei W. Effect of excess hydrogen on hydrogen fueled internal combustion engine under full load. International Journal of Hydrogen Energy. août 2020;45(39):20419-25.
17. Yang Z, Wu J, Yun H, Zhang H, Xu J. Diagnosis and control of abnormal combustion of hydrogen internal combustion engine based on the hydrogen injection parameters. International Journal of Hydrogen Energy. avr 2022;47(35):15887-95.
18. Verhelst S. A Study of the Combustion in Hydrogen-Fuelled Internal Combustion Engines. 2004.
19. Trapy J. Spark ignition engine. Engineering Techniques, Mechanical Engineering treatise. :20.
20. Diéguez PM, Urroz JC, Marcelino-Sádaba S, Pérez-Ezcurdia A, Benito-Amurrio M, Sáinz D, et al. Experimental study of the performance and emission characteristics of an adapted commercial four-cylinder spark ignition engine running on hydrogen–methane mixtures. Applied Energy. janv 2014;113:1068-76.
21. Sáinz D. Conversion of a commercial gasoline vehicle to run bi-fuel (hydrogen-gasoline). International journal of hydrogen energy. :9.
22. Arana M, Martín RS, Urroz JC, Diéguez PM, Gandía LM. Acoustic and psychoacoustic levels from an internal combustion engine fueled by hydrogen vs. gasoline. Fuel. juin 2022;317:123505.
23. Sopena C, Diéguez PM, Sáinz D, Urroz JC, Guelbenzu E, Gandía LM. Conversion of a commercial spark ignition engine to run on hydrogen: Performance comparison using hydrogen and gasoline. International Journal of Hydrogen Energy. févr 2010;35(3):1420-9.
24. Hamada KI, Rahman MM, Abdullah MA, Bakar RA, A. Aziz AR. Effect of mixture strength and injection timing on combustion characteristics of a direct injection hydrogen-fueled engine. International

Journal of Hydrogen Energy. mars 2013;38(9):3793-801.
25. Verhelst S. Recent progress in the use of hydrogen as a fuel for internal combustion engines. International Journal of Hydrogen Energy. janv 2014;39(2):1071-85.
26. Wallner T, Matthias NS, Scarcelli R. Influence of injection strategy in a high-efficiency hydrogen direct injection engine. SAE Int J Fuels Lubr. 30 août 2011;5(1):289-300.
27. Du Y, Yu X, Wang J, Wu H, Dong W, Gu J. Research on combustion and emission characteristics of a lean burn gasoline engine with hydrogen direct-injection. International Journal of Hydrogen Energy. janv 2016;41(4):3240-8.
28. Yang Z, Wang L, Zhang Q, Meng Y, Pei P. Research on optimum method to eliminate backfire of hydrogen internal combustion engines based on combining postponing ignition timing with water injection of intake manifold. International Journal of Hydrogen Energy. sept 2012;37(17):12868-78.
29. Thawko A, Tartakovsky L. The Mechanism of Particle Formation in Non-Premixed Hydrogen Combustion in a Direct-Injection Internal Combustion Engine. Fuel. nov 2022;327:125187.
30. Li G, Yu X, Shi W, Yao C, Wang S, Shen Q. Effects of split injection proportion and the second injection timings on the combustion and emissions of a dual fuel SI engine with split hydrogen direct injection. International Journal of Hydrogen Energy. avr 2019;44(21):11194-204.
31. Shinde BJ, K. K. Recent progress in hydrogen fuelled internal combustion engine (H2ICE) – A comprehensive outlook. Materials Today: Proceedings. 2022;51:1568-79.
32. Meng H, Ji C, Xin G, Yang J, Chang K, Wang S. Comparison of combustion, emission and abnormal combustion of hydrogen-fueled Wankel rotary engine and reciprocating piston engine. Fuel. juin 2022;318:123675.
33. Bakar RA, Widudo, Kadirgama K, Ramasamy D, Yusaf T, Kamarulzaman MK, et al. Experimental analysis on the performance, combustion/emission characteristics of a DI diesel engine using hydrogen in dual fuel mode. International Journal of Hydrogen Energy. mai 2022;S0360319922016998.
34. Yadav VS, Sharma D, Soni SL. Performance and combustion analysis of hydrogen-fuelled C.I. engine with EGR. International Journal of Hydrogen Energy. avr 2015;40(12):4382-91.
35. Mezher H. Characterization of the dynamic behavior of an admission circuit. Impact on filling a supercharged internal combustion engine. :251.
36. Jannoun P. Experimental characterization and 0D/1D modeling of the quantity of residual gases in a spark ignition engine. :197.
37. Krebs S, Biet C. Predictive model of a premixed, lean hydrogen combustion for internal combustion engines. Transportation Engineering. sept 2021;5:100086.
38. Babayev R, Andersson A, Dalmau AS, Im HG, Johansson B. Computational characterization of hydrogen direct injection and nonpremixed combustion in a compression-ignition engine. International Journal of Hydrogen Energy. mai 2021;46(35):18678-96.
39. Ahmed B. PRODUCTION OF HYDROGEN BY A MICROBIAL ELECTROSYNTHESIS (ESM) PROCESS. :77.
40. D. TIGREAT. Hydrogen production techniques and associated risks. 2008.
41. Kumar R, Kumar A, Pal A. Overview of hydrogen production from biogas reforming: Technological advancement. International Journal of Hydrogen Energy. sept 2022;47(82):34831-55.
42. Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. Renewable and Sustainable Energy Reviews. janv 2017;67:597-611.
43. Das L. Hydrogen engines: A view of the past and a look into the future. International Journal of Hydrogen Energy. 1990;15(6):425-43.
44. Das LM. Hydrogen-fueled internal combustion engines. In: Compendium of Hydrogen Energy [Internet]. Elsevier; 2016 [cité 12 oct 2023]. p. 177-217. Disponible sur: https://linkinghub.elsevier.com/retrieve/pii/B9781782423638000074
45. Lanz W. Module 3: Hydrogen Use in Internal Combustion Engines. Hydrogen Fuel. 2001;

46. Salam S, Choudhary T, Pugazhendhi A, Verma TN, Sharma A. A review on recent progress in computational and empirical studies of compression ignition internal combustion engine. Fuel. nov 2020;279:118469.
47. BENSAOUCHA S. DETECTION OF FAULTS AND REPAIR OF CYLINDER HEADS. 2015.
48. BOUSBAA H. Internal combustion engines. 2015.
49. Id H. Thermodynamic cycles of thermal machines. :154.
50. Radouane L, Abdelhakim H, Madani M. Study and design of a four-stroke internal combustion engine. :101.
51. Rouba B. Study of heat engines. 2014.
52. Brady RN. Internal Combustion (Gasoline and Diesel) Engines.
53. GHERBAL A, SADAOUI N. Gasoline engine maintenance.pdf. 2019.
54. LAMOUSSA JK. IDENTIFICATION, OPTIMIZATION AND CONTROL OF A HYDROGEN GENERATOR IN A HYBRID ELECTRIC VEHICLE. 2015.
55. Mohammed B, Malika T. Study of the mechanical and energy performances of a hydrogen automobile engine.
56. BARBE S, BEN ABDEL JAOUED H, HAMZAH MA, LI G, OFIALA M, DIOUARA M, et al. MODELING THE COMBUSTION OF A PETROL ENGINE. 2011.
57. Heywood JB. Internal combustion engine fundamentals. New York: McGraw-Hill; 1988. 930 p. (McGraw-Hill series in mechanical engineering).
58. BENCHERIF M. Internal Combustion Engines, Combustion and Carburetion Elements. 2018.
59. Verhelst S, Demuynck J, Sierens R, Scarcelli R, Matthias NS, Wallner T. Update on the Progress of Hydrogen-Fueled Internal Combustion Engines. In: Renewable Hydrogen Technologies [Internet]. Elsevier; 2013 [cité 12 oct 2023]. p. 381-400. Disponible sur: https://linkinghub.elsevier.com/retrieve/pii/B9780444563521000167
60. Gheorghe D, Tutunea D, Bică M, Gruia A, Calbureanu M. Hydrogen a new fuel for internal combustion engines. IOP Conf Ser: Mater Sci Eng. 1 sept 2019;595(1):012032.

How to cite this article: Gédéon Marlein DAHOU, David G. F. ADAMON, Tognon Clotilde GUIDI. Prospective study of the main internal combustion engines running on hydrogen: state of the art. *International Journal of Research and Review*. 2024; 11(4): 231-250. DOI: *https://doi.org/10.52403/ijrr.20240426*

******