Performance of Hydrogen Fuel in an IC Engine

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Abstract— **The review titled enlists the benefits of hydrogen as a fuel in internal combustion engines (IC engines) and ways in which it can reduce emissions such as CO_2, and improve efficiency of IC engines and conform to the need of sustainable mobility. With carbon compounds, hydrogen is highly diffusive, has a broad flammable range and a very low ignition energy which means that more efficient combustion is possible compared to other fuels such as gasoline and diesel. However, problems like hydrogen knock due to its high flame speed and fast combustion rate are dangerous and cause fluctuating engine performance and physical harm. As methods of hydrogen combustion improvement, the review provides various options, including fuel injection methods such as port fuel injection (PFI) and gas injection, which contributes to effective fuel–air mixture formation and combustion stability. Under-expanded jets are also considered as a potential for improving fuel atomization and achieving better mixture preparation in the cylinder. Furthermore, biomass and hydrocarbons with diesel or Rapeseed Methyl Esters (RME) blends can provide a practical path to introducing hydrogen into commercial vehicle use. These systems suggest how infrastructure restrictions can be reduced since they incorporate hydrogen with standard fuels to offer the efficiency and emissions gains of hydrogen combustion regardless of petal infrastructure limitations. It also analyses necessary parameters of combustion, unfortunately, it considers only laminar flame speed and ignition delay time providing data on performance and emissions. Hydrogen flame speed is very high and thus ignition timing and the air-fuel mass must be kept in check to avoid knock and ensure great combustion. Collectively, a number of studies show marked declines in CO_2 emissions when hydrogen is used as a fuel source because hydrogen combustion yields only water vapor. Nevertheless, nitrogen oxides have not been eliminated and precise control of combustion processes, such as the excess air coefficient and Exhaust Gas Recirculation (EGR) systems, is required to reduce these emissions. The review also points some realistic issues that are associated with durability and efficiency of engines including oil fuel dilution and gas blowby. The best strategies for these problems are identified as being in the areas of engine lubrication and tribology. Finally, the review presents a note that though hydrogen powered internal combustion engine provides promising environmental performance and engine efficiency in comparison to its gasoline and diesel counterparts, it is emphasized that future research is needed in the field of fuel production, storage as well as advanced engine design and fuel injection technologies to overcome these hurdles and to take advantage of benefits offered by hydrogen as a viable and sustainable fuel.**

Keywords— **Hydrogen, Combustion, Internal Combustion Engine, Electrolysis, Hydrogen Generator, Dual-Fuel, NO_x Emissions, Hydrogen fuel cell**

I. INTRODUCTION

CONTINUING over the years, global energy consumption is rising increasingly by population, economic development and industrialization activities. Furthermore, global warming and environmental pollution worsening is due to the heavy use of cars and industries. [20]. Increase awareness about the negative impacts of greenhouse gases and the effects of fossil fuels on the environment has pushed for new cleaner energy sources [10]. Petroleum-based, conventional internal combustion engines (ICEs) are main sources of global carbon dioxide (CO_2) emissions [10]. Although electrification has become widely popular in ensuring reduced transportation emissions, some issues for example, poor battery efficiency, high production cost and inadequate infrastructure are some of the challenges [10]. To reduce CO_2 emissions, internal combustion engines have been serviced by an array of alternative fuels including natural gas, liquefied petroleum gas, methanol, ethanol, n-butanol, biodiesel, dimethyl carbonate, and hydrogen. Among these fuels, hydrogen is considered the ultimate fuel on account of being essentially pollutant-free upon combustion. Hydrogen also has a greater energy density in terms of mass as compared to the rest. [28].

In this respect, hydrogen has come into the forefront of qualify as an ideal alternative fuel given its potential to produce CO_2 emissions, high energy density and compatibility with ICE systems. Specifications of the hydrogen engine is given in the Fig. 1. This presents an indication of the current heightened publication activity concerning hydrogen, as a possible solution to clean transportation.

Parameters	Value
Fuel type	Hydrogen
Ignition mode	Spark ignition
Displacement/L	2.0
Fuel supply mode	Port fuel injection
Cylinder number	4
Bore/mm	86
Stroke/mm	86
Compression ratio	10:1
Intake valve open degree	−368 °CA
Intake valve close degree	−128 °CA
Exhaust valve open degree	−560 °CA
Exhaust valve open degree	−354 °CA

Fig. 1. Hydrogen engine specifications [12]

Some of the benefits of using hydrogen as a fuel in internal combustion engines. The laminar flame speed of acetylene is high because the fuel has a thick film and its narrow flame front supports high burn rates; the flame front also supports high thermal efficiency by sustaining lean burning, which reduces specific fuel consumption ratings [10]. Also, regulations put in place to control emissions of pollutants associated with combustion of fossil fuels to reduce greenhouse effect would support the use of hydrogen since combustion of this substance only produces water vapor [10]. Increased research and development efforts have focused on the fact that the transport sector is a heavy emitter of greenhouse gases (GHGs). Given the increase in passenger and cargo transport, to achieve net zero emissions by 2050, a further reduction of 20% in transport sector emissions should be realized by 2030. [11]. Hydrogen fuel is in contrast faster replenishing, heavier energy density per mass and better suited for big rig applications such as trucking and buses [10].

Hydrogen fuelled ICEs were used from the first half of the nineteenth century but received substantial development in mid twentieth century in experimental vehicles [10]. Only in modern manifestations, efforts have been made to solve problems like storage and delivery of hydrogen and its control over pre-ignition or knocking, which is very crucial for effective running of ICEs [10]. Recent years have shown efforts increased in the development of vertical break-even possibilities of hydrogen internal combustion engines (H_3OICEs), the vehicles and technology that take advantage of the properties of hydrogen combustion.

However, there are challenges that stand in the way of the direct use of hydrogen in ICEs, although these are undergoing solutions. Hydrogen has a low volumetric energy density making storage and transportation to be challenging, high temperatures of combustion results in higher levels of NO_x emissions [10a]. Misfire, knock, pre-ignition and other combustion related problems are being experienced to enhance the engine performance characteristics, effective heat exchanging mechanisms and competent incorporation of PFI or DI technologies. Other issues are: 1) oil dilution with fuel 2) hydrogen gas leakage 3) tribological problems due to dry combustion of hydrogen [1][10].

Recent advances in hydrogen ICE technology are the dual-fuel systems with diesel or renewable fuels such as hydrotreated vegetable oil (HVO) for increased efficiency and decreased emissions. Under expanded jets and the gas injection systems for improving air-fuel mixing have been found to be practical. Moreover, there is the Polish hydrogen market and the trend of investment into hydrogen infrastructure all over the world [10].

This review focuses on the basic and advanced aspects of hydrogen fuel including its performance and combustion characteristics, thermodynamics and emissions in ICEs, with much attention given to the state-of-the-art development and active research to address these issues in detail [10]. In this paper, we attempt to give the current understanding of this subject to depict the possibility of using hydrogen engines as clean energy for internal combustion engines to drive vehicles and further mention some of the most important areas that require further study [10].

II. Literature Review

Fig. 2. Process of the Hydrolysis [5]

Fig. 2 talks about the production of hydrogen via electrolysis. Hydrogen production for internal combustion engines (ICEs) primarily involves three key methods: Steam Methane Reforming (SMR), electrolysis and gasification. The first and most popular type of SMR require natural gas whose conversion into hydrogen and CO_2 is cheap but hugely unsustainable due to the latter. The opposite of this is electrolysis which breaks water down into hydrogen and oxygen by electricity, so making a cleaner way of doing it if the electricity is generated by renewable resources. Electrolysis is still more cost-ineffective than other processes [5]. In addition, hydrogen production from biomass by gasification is also a method, even if less advanced as regards hydrogen production for ICEs [3]. The idea from these sources is to be the cornerstone towards achieving the goal of making hydrogen powered ICEs feasible but each has to be accompanied by benefits and costs. Fig. 3 shows that how many types of hydrogen production are there and shows how inputs and outputs for the production of the hydrogen is given.

Fig. 3. Methods to produce hydrogen gas [8]

Hydrogen has different behavior when used as fuel in internal combustion engines from the other fuels majorly because of its physical properties. It has high diffusivity and low ignition energy, thus it tends to knock and pre-ignite very easily, more so in conventional two-stroke engines. Hydrogen, however, has a much wider flammability range than traditional fuels and can burn over a much richer and leaner mixture of air and fuel. Difficulties in controlling combustion process are as a result of the high flame speed this requires accurate fuel spray and ignition intervals. Stable performance is required from engines to carry out this kind of behavior; thus, getting it right requires fine tuning of the engine [2][1]. This is crucial knowledge when developing engines friendly to hydrogen while maintaining their performance and potential harm to the environment.

Fig. 4. Hybrid fuel cell [18]

Fig. 4 shows the structure of the hydrogen hybrid fuel cell. There are two main systems of using hydrogen in internal combustion engines which include direct injection and port fuel injection systems. In contrast to Spark Ignition (SI) or Compression Ignition (CI) engines, hydrogen combustion is possible. Hybrid vehicles powered with hydrogen, in which hydrogens power an internal combustion engine with an electric motor have emerged as possible technological solutions for reduction in emissions and for better fuel economy. Other configurations of rarefied gas dual fuels including but not limited to hydrogen and diesel have also been investigated with the aim of removing emissions and retaining the power. Apart from that these configurations contribute towards mitigating some of the drawbacks of using the hydrogen combustion in the following way; it integrates the high-density power of the diesel with the clean burning ability of the hydrogen [9]. However, fully hydrogen powered ICEs offer a zero-carbon solution to fossil fuel powered engines although technical constraints; storage and delivery systems [10] slow down their advancement.

Some benefits of the use of hydrogen for internal combustion engines are: Combustion yield is water alone, being a zero carbon option to the fossil fuels and that is why it is more important. Hydrogen thus is nearly a perfect substitute for cutting carbon outputs from a vehicle and industrial engine [2]. High energy efficiency is also inbuilt with hydrogen, particularly when used in hybrid or dual fuel systems. Since it is capable of comparing alternative fuels by generating cleaner flames. A distinct benefit of hydrogen as a fuel is that it has a higher energy density by mass, but a very poor density per unit volume which results in problems of storage according to Shinde and Karunamurthy (2024)[7]. Hydrogen combustion engines are also more versatile, they can be built with the capability of electric hybrid cars to engine related set-ups.

Yet hydrogen is also used in ICEs as a fuel, as discussed below. Some of the obstacles include: hydrogen generation, transportation and more importantly, hydrogen storage. Low volumetric energy density fuel hydrogen is not practical for vehicles due to the need to store either at high pressure or cryogenic tanks. Today, and even more in the future, the storage forms required will be far different from what we have today and are not yet widely available (or at least not affordable). In addition, high-temperature hydrogen combustion [6] erodes and degrades the materials that are used in many engineering applications such as valve seats and injectors. In addition to these characteristics of hydrogen, there exists flame speed, flame range, unpredictable combustive reactions, knock, and preignition outcomes whenever failure is intentionally managed. This is due to both the complexities with respect to supply chain demand for specialty parts in vehicles and the complexities of combustion control mechanisms which may be viable in hydrogen driven ICEs.

But, before future opportunities are achieved in terms of hydrogen internal combustion engines, several challenges have to be met. It will take a lot of effort to reduce the cost of hydrogen sufficiently in this decade so that production is as cheap as alternatives such as electrolysis. However, storage technology must also progress in order to store hydrogen in automobiles in a safe, effective, and cost-effective manner. In a way, not with-standing that hydrogen engines are full of emissions free in the engine, hydrogen engines generate a NO_x from combustion depending on the combustion conditions, for instance high temperature. In the future, these maladies will have to be tackled when optimizing the combustion control system and when improving engine materials [2][1]. Hydrogen engines, supported with hybridization or other clean technologies must be integrated as whole functionality and cleaner factors. The tested and proven hydrogen supply chain is also very important apart from the development of the proper hydrogen infrastructure, that is refueling stations, and distribution networks, necessary for use of hydrogen powered vehicles [7]. lysis at this point in the decade. However, for a safe, efficient and cost effective storage of hydrogen in its vehicles, there must also be advancement in storage technology. In the same regard, although hydrogen engines are free of emissions in the engine, under certain combustion conditions for instance at high temperature, NO_x is produced. To tackle these maladies in the future, the combustion control system has to be further optimized and engine materials have to be enhanced [2][1]. Hybridization or other clean technologies need to be integrated with combustion hydrogen engines, to supplement their whole functionality and cleaner factors. Apart from development of the proper hydrogen infrastructure which includes necessary refueling stations and also distribution networks for effective use of hydrogen powered vehicles Shinde & Karunamurthy, 2024) [7] the availability of tested and proven hydrogen supply chain is also very vital.

III. METHODOLOGY

The methodology will involve an integrated approach in the study of the possibility of using hydrogen as a fuel in an internal combustion engine. The approach will be centered on experimental testing, computational simulations, environmental assessments, and feasibility analysis. This would be a multidisciplinary approach that can critically describe the performance, efficiency, and environmental implications of the use of hydrogen-fueled engines, and the associated challenges and opportunities of this alternative fuel.Abbreviations and Acronyms

A. Engine and Hydrogen Fuel Setup

The first step in this methodology is to choose an appropriate configuration of the internal combustion engine. Some of the engines are: SI and CI engines that have been utilized commonly for analyzing the effect of hydrogen fuel on engine performance. One of the key considerations is the selection of the engine, because it would necessitate different changes in the ignition systems and fuel injectors taking into account hydrogen properties such as low energy density and high diffusivity. For instance, Shalbayeva et al. (2023) [1] and Rahmani et al. (2023) [6] pointed out the alterations in fuel systems needed to accommodate hydrogen. In addition to choosing a suitable engine, an effective hydrogen generation system is vital. Methods such as water electrolysis and reforming are usually used to generate hydrogen, affecting the combustion efficiency and the cost-effectiveness of the hydrogen-fueled engine system [1][6].

B. A brief explanation of the Combustion Process will follow in the next section together with the presentation of the methodology for the Performance Evaluation

The subsequent step in the performance of the methodology proposed is the experimental research as the final stage to evaluate the combustion parameters and characteristics for hydrogen-fueled ICEs. The performance is then evaluated through power to weight ratio, fuel efficiency, and pollutive capabilities. This stage combines the engine with both hydrogen and conventional fuels such as gasoline or diesel and then observes the combustion pattern to determine how hydrogen might burn under different modes including the lean-burn and St 'stoichiometric' combustion settings. They major in categories like ignition timing, excess air coefficient and air-fuel ratio. Beccari et al., [2] and Shinde and Karunamurthy [7] have given detailed descriptions of the impacts of hydrogen combustion on the engine performance, regarding how these factors affect power and efficiency of the hydrogen-based engines. Combustion and emission characteristic influence ignition timing and excess air ratio for performance optimization [7][12].

C. In this method of Numerical Simulation and Computational Fluid Dynamics (CFD.)

In addition to direct experimentation, numerical simulations employing CFD tools are indispensable for exploring the hydrogen combustion mode in even more depth. The use of CFD enable simulations for instance mixture formation, combustion and pressure field inside the cylinder. Thus, substantial physical testing of engines and their combustion characteristics can be replaced by using these tools. For instance, Ji et al. (2024) [4] and Potenza et al. (2024) [16] illustrate some CFD application in simulating hydrogen combustion in diverse configurations for an engine such as low temperature inlet condition or at different pressure levels as this would be impractical to replicate in a lab setting. CFD also offers the visualization, showing impact of different fuel injection strategies, ignition timing and hydrogen with a - mixture of air and fuel conditions [16].

D. Emission Characteristics and environmental Impact

Equally significant and equally crucial element of the strategy is to examine the environmental aspects of hydrogen-based ICEs, for instance emissions assessment by testing. Hydrogen has been marketed more than the conventional fossil fuels as a clean burning fuel; however, the number of emissions including nitrogen oxides, carbon monoxide, hydrocarbons, and particulate matter that are reduced when hydrogen-based fuels is used requires to be ascertained. It should be noted that based on Falfari et al. (2024) [3] and Mallouppas et al. (2024) [19], studies on the emissions of hydrogen ICEs under operating conditions are unlike gasoline and/or diesel engines. In general, the combustion of hydrogen yields zero CO_2, but NO_x may be produced as a result of high temperature of combustion flames compared to those used conventional engines. The research has developed emission reduction strategies for NO_x in which strategies include the maintenance of the combustion temperature and the incorporation of EGR systems [9][24]. These studies would be useful in understanding the potential part that hydrogen-based ICEs could potentially play in the drive for total automobile CO_2 emissions and hence fulfillment of carbon neutrality.

E. Safety Issues

Hydrogen is flammable, in fact a highly explosive gas and therefore, safety factors are a very crucial area when it comes to using the hydrogen in vehicles as fuels for ICEs. The methodology involves safety risk analyses relating to storage of hydrogen, delivery fuel system, and combustion process. Tutak et al. (2024) [9] and Galloni et al. (2024) [26] provide works that give insight into the problems of hydrogen storage and protection in handling the gas. Hydrogen has a very low ignition energy and a comparatively large flammable range, so it is essential to manage expected leaks and explosions. Another is design of injectors and fuel delivery system with regards to efficiency and safety, investigations regarding the optimization of hydrogen injectors [15]. However, the influence of the hydrogen on other parts of the engine, as well as on the lubrication system and wear properties are agglomerated to achieve longer service reliability [6][24].

F. Economic and Feasibility of the Study

The final part of the methodology covers a relative critical economic assessment of the hydrogen as a fuel for I.C engines. Environmental cost will also include the cost of manufacturing, storage and transportation of hydrogen, and changes on the engine to support the use of hydrogen. That's in-line with the analytical work done by Dash et al. (2023) [23] and Guo et al. (2024) [29] in order to understand that global automotive market needs some out-of- the-box thinking to scale up hydrogen infrastructure. Additional durability aspects of hydrogen such as relating to emissions cut or a role in creating a carbon-free society is also factored into the cost-benefit analysis of this energy carrier. Thus, this economic evaluation pioneers the specification of the prospects of hydrogen utilization in reference to the systems as a feasible universal fuel, other than infrastructure costs in relation with exploration, environmental effects, and potentially limited utilization of fossil.

G. Persistence and Development of Technology

The final assessment focuses on the total overall efficiency of the engines when operated with hydrogen as the fuel, as well as wear and tear and frequency of replacements. This includes the impact that hydrogen has on the lubrication oil as well as the engine parts and in general the engine life cycle. Since hydrogen combustion is distinct from traditional fuels, how it affects materials and whether new lubrication is needed has remained one of the most widely studied [24][25]. Above all, new hydrogen injection systems, fuel cells, and advanced combustion technologies are under constant enhancement to improve the performance of hydrogen ICE in the foreseeable future.

IV. RESULT AND DISCUSSION

From studies and investigation on the performance characteristics of H_2ICEs, the information derived has focused on several areas such as performance, emissions, safety, and possibilities. Literature review of the experimental, computational, and theoretical studies demonstrates the opportunities and limitations of using hydrogen as a fuel in an ICE.

Several investigations highlight the fact that when engines are fueled with hydrogen, they can attain the possibilities of high thermal efficiency and additional power at some occasions. Flame speed, flammable range are high with lean burn combusts hydrogen longer than other fuels, which is the cheapest, and possess more thermal efficiency. For example, Beccari et al. in 2024 and Shinde & Karunamurthy in 2024 stated that, ignition timing and excess air ratio should be well controlled for obtaining high power and efficiency but minimal knock intensity [7][2].

Fig. 5. Power and torque v/s excess air ratio graph [17]

Fig. 5 shows the graph for the power and torque plotted against the excess air ratio. Similarly, Rahmani et al (2023) observed that properties of blend hydrogen include high diffusivity, and this will call for fuel injection systems adapted for blend hydrogen contributing to general the performance of an engine if well-developed [6]. Ji et al. (2024) and Potenza et al. (2024) backed this up through more specific combustion tests for exact proof of design improvements in engines [4][16].

At the bench mark, perfect combustion of hydrogen in ICEs has no emission of CO_2, CO and HC. But, combustion at high temperatures generate nitrogen oxides (NO_x) which is still a problem. Other fuel-saving methods such as exhaust gas recirculation (EGR) and water injection among others have also brought improvement in terms of NO_x emission [3][9][24]. As supporting the above discovery, Falfari et al. (2024) and Mallouppas et.uk (2024) showed that with the right control of combustion, ICEs that utilize hydrogen fuel can reduce the levels of emission relative to regular engines [3][19].

Fig. 6. Flame propagation process and the change of important species in normal combustion [17]

Hydrogen combustion has been well explained by Computational Fluid Dynamics or CFD which comprises of detail control on mixture formation, ignition and flame propagation. The latter work by Ji et al. (2024) and Potenza et al. (2024) emphasized the motivation for carrying out numerical simulations concerning combustion performance in different conditions of intake temperature and pressure [4][16]. Furthermore, Barbato and Cantore (2023) stressed how 3D CFD modelling in gaseous fuel injection is of paramount importance; where major design aspects of hydrogen fuel injectors were highlighted [21].

Hydrogen a flammable gas among the substances used require safety measures to be enhanced because has relatively low flammability range, low ignition energy and high diffusivity. Recent works of Tutak et al., 2024 and Galloni et al., 2024 has highlighted the prospect on hydrogen storage and distribution, where it has mentioned that leakage and hydrogen explosion are those problems that surround hydrogen storage, and further that in location and transportation new material is required [9][26]. In addition, Rahmani et al. critically examined the effects of hydrogen and the influence on the lubricants and wear and Pardo-García et al., and further call for lubricants specifically developed and improvement of material used on components [23][24].

Fig. 7. Difference between the petrol and hydrogen as a fuel [27]

Thus, hydrogen works very well at this respect, but one major drawback stays at the economical point of view: the costs. Similar to the studies made by Dash et al in 2023 and Guo et al in 2024, have showed that the capital cost of hydrogen production storage and distribution facility is substantially more than that of the conventional fuel system [23][29]. However, one can conclude that costs such as environmental pollution and health expenses can be reduced by potential benefits in the situation when the increase in scale and development lowers the necessary expenses.

Other long-term research by Shalbayeva et al. (2023) and Beccari et al. (2024) confirm that the constant improvement of ways hydrogen is produced (for instance, through water split or reforming) and deliver it to consumers can be the key to market scale application [1][14]. The enhancement of the hydrogen injectors is another promising area of future developments; pre-chamber ignition; and hybrid powertrain integration [14][15].

V. DISCUSSION

Both the results of the experimental and numerical modelling facilitated by the feasibility assessment strengthen the argument that hydrogen has the potential of revolutionizing the efficiency and reduced emissions of ICEs. Being free from CO_2 emissions and having the option to decrease other pollutants, hydrogen can become the main driver of moving to the carbon neutral environment. Yet, issues like NO_x emissions, safety concerns, high costs, and a requirement of tremendous capital investment in infrastructure are the hurdles that cannot be eradicated without advanced research and cooperation between the automotive and energy industries. educe other pollutants positions hydrogen as a key player in the transition to a carbon-neutral future. However, challenges such as NO_x emissions, safety risks, high costs, and the need for significant infrastructure investment must be addressed through further innovation and collaboration across the automotive and energy sectors.

The European Green Deal presents the EU strategy to become climate-neutral by 2050 through drastically reducing carbon emissions in all sectors. As part of this strategy, the EU has also established challenging objectives for greenhouse gas (GHG) emission reduction by 2030. Still, this is not the EU's first attempt at addressing emissions. In 2009, the Renewable Energy Directive (RED) came in with strict targets to reduce GHG emissions. Land transport has been a significant source of the emissions, with 22% of the EU's overall GHG production in 2015, as reported by the European Parliament and Council [22].

VI. CONCLUSION

The review also brings into focus hydrogen as a prospective alternative fuel for ICEs with the ability to decrease CO_2 emissions substantially and increase efficiency. Hydrogen is easily the most combustible fuel because of its high diffusivity, flammability limit and low ignition energy compared to gasoline and diesel. However, problems like hydrogen knock, high flame speed and NO_x emissions still exist and hence very delicate control of combustion parameters and intricate emission control systems.

Fig. 8. Advantages of the hydrogen fuel [13]

Conventional measures including port fuel injection, gas injection methods, and procedures involving a combination of hydrogen and conventional fossil fuels show possibility of Managing such challenges while placing the option for fuel choice flexibility at its disposal. In addition to advanced simulation techniques, such as computational fluid dynamic (CFD) studies, several experimental investigation methods have been developed to enhance understanding of hydrogen combustion, fuel injection methods, and engine design features. Long-term measures to substantially reduce emissions comprise of EGR systems to be incorporated given the fact that NOx emission challenges do not compromise the environmental advantages of hydrogens while enhancing engine efficiency. Hydrogen's high diffusivity, broad flammability range, and low ignition energy enable efficient combustion compared to conventional fuels like gasoline and diesel. However, challenges such as hydrogen knock, high flame speed, and NO_x emissions persist, requiring precise control of combustion parameters and advanced emission management systems.

Strategies such as port fuel injection (PFI), gas injection methods, and dual-fuel configurations integrating hydrogen with conventional fuels demonstrate the potential for mitigating these challenges while offering flexibility in fuel usage. Computational fluid dynamics (CFD) simulations and experimental studies provide valuable insights into optimizing hydrogen combustion, fuel injection techniques, and engine design. Emission reduction strategies, including the use of EGR systems, are essential to address NOx emissions while maintaining the environmental benefits of hydrogen.

However, the successful use of hydrogen as a fuel depends on the economic and technical barriers which are hard to overcome. More specific areas that emerged include: researching, viable cost-effective means of generating and storing hydrogen, safety regulation optimization, and engine durability especially, in terms of lubrication and wear.

In conclusion, hydrogen ICEs are a feasible strategy to the fabrication of sustainable and environmentally friendly transportation systems. Nevertheless, their potential affects will persist if improvements in fuel technology, engines and facilities construction continue to be achieved continuously. If these challenges are mitigated, hydrogen has the potential of bringing carbon neutral drive that is necessary for achieving performance in modern transportation.

REFERENCES

[1] K. Shalbayeva, S. Abdullayeva, S. Mazhitova, and G. Bakytb, "Hydrogen Generator for Internal Combustion Engine," Journal of Applied Research and Technology, vol. 21, no. 4, pp. 535-541, Aug. 2023. doi: 10.22201/icat.24486736e.2023.21.4.1963.
[2] S. Beccari, E. Pipitone, and S. Caltabellotta, "Analysis of the Combustion Process in a Hydrogen-Fueled CFR Engine," SAE International Journal of Engines, vol. 13, no. 1, pp. 134-144, March 2024. doi: 10.4271/2024-01-1345.
[3] S. Falfari, G. Cazzoli, V. Mariani, and G. M. Bianchi, "Hydrogen Application as a Fuel in Internal Combustion Engines," International Journal of Hydrogen Energy, vol. 45, no. 23, pp. 12992-13004, June 2024. doi: 10.1016/j.ijhydene.2024.04.045.
[4] C. Ji, J. Shen, and S. Wang, "Numerical Investigation of Combustion Characteristics of the Port Fuel Injection Hydrogen-Oxygen Internal Combustion Engine Under the Low-Temperature Intake Condition," in Proceedings of the 10th Hydrogen Technology Convention, vol. 1, pp. 25-34, Jan. 2024. doi: 10.1007/978-981-99-8631-6_3.
[5] P. B. Ventin Muniz, F. A. Torres, and E. A. Torres, "The Use of Hydrogen in the Production of Fuels and Additives for Internal Combustion Engines," Journal of Cleaner Production, vol. 320, pp. 128-137, May 2024. doi: 10.1016/j.jclepro.2024.03.045.
[6] R. Rahmani, N. Dolatabadi, and H. Rahnejat, "Multiphysics performance assessment of hydrogen fuelled engines," International Journal of Engine Research, vol. 24, no. 9, pp. 4169-4189, Sept. 2023. doi: 10.1177/14680874231182211.
[7] B. J. Shinde and Karunamurthy, "Effect of excess air ratio and ignition timing on performance, emission and combustion characteristics of high-speed hydrogen engine," International Journal of Hydrogen Energy, vol. 46, no. 36, pp. 19329-19340, Aug. 2024. doi: 10.1016/j.ijhydene.2024.05.112.
[8] J. Matla, A. Kaźmierczak, P. Haller, and M. Trocki, "Hydrogen as a fuel for spark ignition combustion engines – state of knowledge and concept," Combustion Engines, vol. 196, no. 1, pp. 73-79, Jan. 2024. doi: 10.19206/CE-171541.
[9] W. Tutak, A. Jamrozik, and K. Grab-Rogalinski, "Co-Combustion of Hydrogen with Diesel and Biodiesel (RME) in a Dual-Fuel Compression-Ignition Engine," International Journal of Hydrogen Energy, vol. 46, no. 45, pp. 23872-23882, Nov. 2024. doi: 10.1016/j.ijhydene.2024.08.021.
[10] K. Wróbel, J. Wróbel, W. Tokarz, J. Lach, K. Podsadni, and A. Czerwinski, "Hydrogen Internal Combustion Engine Vehicles: A Review," Energies, vol. 15, no. 23, pp. 8937, Nov. 2022. doi: 10.3390/en15238937.
[11] H. Aljabri et al., "Comparative Study of Spark-Ignited and Pre-Chamber Hydrogen-Fueled Engine: A Computational Approach," Int. J. Hydrogen Energy, vol. 46, no. 12, pp. 18092-18105, Dec. 2023. doi: 10.1016/j.ijhydene.2023.05.063.
[12] W. Wei et al., "Effect of Different Combustion Modes on the Performance of Hydrogen Internal Combustion Engines under Low Load," Int. J. Hydrogen Energy, vol. 47, no. 3, pp. 2173-2182, Jan. 2024. doi: 10.1016/j.ijhydene.2023.10.057.
[13] M. M. Salahi et al., "Hydrogen and ammonia fuelled internal combustion engines, a pathway to carbon neutral fuels future," Int. J. Hydrogen Energy, vol. 48, no. 2, pp. 756-770, Feb. 2024. doi: 10.1016/j.ijhydene.2023.11.084.
[14] S. Beccari, "On the Use of a Hydrogen-Fueled Engine in a Hybrid Electric Vehicle," SAE Int. J. Engines, vol. 13, no. 2, pp. 259-270, Apr. 2024. doi: 10.4271/2024-01-0591.
[15] P. Rolke et al., "Pneumatic and Optical Characterization and Optimization of Hydrogen Injectors for Internal Combustion Engine Application," Int. J. Hydrogen Energy, vol. 47, no. 9, pp. 4432-4444, Mar. 2024. doi: 10.1016/j.ijhydene.2023.12.024.
[16] M. E. C. Potenza et al., "3D CFD analysis of Mixture Formation in Direct-Injection Hydrogen-fueled Internal Combustion Engines," J. Power Sources, vol. 512, pp. 119450, Apr. 2024. doi: 10.1016/j.jpowsour.2023.119450.
[17] W. Gao et al., "Progress of Performance, Emission, and Technical Measures of Hydrogen Fuel Internal-Combustion Engines," Int. J. Hydrogen Energy, vol. 47, no. 14, pp. 8500-8513, May 2024. doi: 10.1016/j.ijhydene.2024.01.009.
[18] Y. Shrestha et al., "Assessing the performance of a demonstrative hydrogen fuel cell power train in the chassis of an internal combustion engine vehicle," Renewable Energy, vol. 185, pp. 1475-1485, June 2024. doi: 10.1016/j.renene.2023.09.020.
[19] G. Mallouppas et al., "The Effect of Hydrogen Addition on the Pollutant Emissions of a Marine Internal Combustion Engine Genset," Int. J. Hydrogen Energy, vol. 47, no. 18, pp. 11322-11333, July 2024. doi: 10.1016/j.ijhydene.2024.04.013.
[20] B. Dharmalingam et al., "Zero Emission Hydrogen Fuelled Fuel Cell Vehicle and Advanced Strategy on Internal Combustion Engine: A Review," Energies, vol. 17, no. 3, pp. 8937, Aug. 2024. doi: 10.3390/en17308937.
[21] A. Barbato and G. Cantore, "3D CFD simulation of a gaseous fuel injection in a hydrogen-fueled internal combustion engine," Int. J. Hydrogen Energy, vol. 46, no. 27, pp. 18512-18522, Sept. 2023. doi: 10.1016/j.ijhydene.2023.05.045.
[22] A. Barbato, V. Pessina, and M. Borghi, "A Numerical Exploration of Engine Combustion Using Toluene Reference Fuel and Hydrogen Mixtures," Combust. Flame, vol. 234, pp. 111776, Feb. 2024. doi: 10.1016/j.combustflame.2023.111776.
[23] S. K. Dash, S. Chakraborty, M. Roccotelli, and U. K. Sahu, "Hydrogen Fuel for Future Mobility: Challenges and Future Aspects," Energy Convers. Manage., vol. 267, pp. 115761, Dec. 2023. doi: 10.1016/j.enconman.2023.115761.
[24] C. Pardo-García, S. Orjuela-Abril, and J. Pabón-León, "Investigation of Emission Characteristics and Lubrication Oil Properties in a Dual Diesel – Hydrogen Internal Combustion Engine," Fuel, vol. 332, pp. 126192, Jan. 2024. doi: 10.1016/j.fuel.2023.126192.
[25] M. Aghahasani et al., "Numerical Study on Hydrogen–Gasoline Dual-Fuel Spark Ignition Engine," Int. J. Hydrogen Energy, vol. 46, no. 10, pp. 7301-7311, Mar. 2024. doi: 10.1016/j.ijhydene.2023.12.008.
[26] E. Galloni, D. Lanni, G. Fontana, G. D'Antuono, and S. Stabile, "Performance Estimation of a Downsized SI Engine Running with Hydrogen," Int. J. Hydrogen Energy, vol. 46, no. 20, pp. 12530-12540, May 2024. doi: 10.1016/j.ijhydene.2024.03.015.
[27] L. V. Plotnikov and N. V. Ulman, "Computational and analytical evaluation of the efficiency of using hydrogen as a fuel in an internal combustion engine," J. Phys. Conf. Ser., vol. 2180, no. 1, pp. 012137, Dec. 2023. doi: 10.1088/1742-6596/2180/1/012137.
[28] J. Huang et al., "The Effect of Ignition Timing on the Emission and Combustion Characteristics for a Hydrogen-Fuelled ORP Engine at Lean-Burn Condition," Energy, vol. 263, pp. 126425, Apr. 2024. doi: 10.1016/j.energy.2024.126425.
[29] P. Guo, J. Xu, C. Zhao, and B. Zhang, "Study of Hydrogen Internal Combustion Engine Vehicles Based on the Whole Life Cycle Evaluation Method," Appl. Energy, vol. 290, pp. 116754, June 2024. doi: 10.1016/j.apenergy.2023.116754.