Review of The Performance, Emission, And Challenges Faced by Hydrogen-Powered Internal Combustion Engines

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***Abstract*—** Hydrogen-powered internal combustion engines (ICEs) provide an encouraging proposal to reduce vehicular emissions and improve energy efficiency. These engines are characterized by enhanced thermal efficiency and lower emissions of CO2 and NOx compared to traditional fossil fuel-powered engines, aligning them with stringent global environmental regulations. However, the broader adoption of hydrogen ICEs is hindered by several challenges. Key areas among these are the advancement of effective hydrogen storage solutions and fuel delivery systems, along with the establishment of a robust infrastructure for hydrogen production and distribution. Additionally, technical challenges such as the risk of pre-ignition, backfiring, and maintaining consistent performance under variable engine loads present significant obstacles. Overcoming these challenges is essential for successfully integrating hydrogen ICEs into the automotive sector. Addressing these issues will enable the pervasive use of hydrogen as a sustainable vehicle fuel and significantly reduce the automotive industry’s environmental footprint.

***Keywords*—** *Hydrogen-powered; emissions; developments; technical challenges; sustainable.*

I. INTRODUCTION

Hydrogen fuel stands at the forefront of the shift towards sustainable energy solutions, addressing the urgent need to mitigate the environmental impacts of conventional fossil fuels. Recognized for its high energy content and the cleanest combustion of any fuel—emitting only water vapor—hydrogen offers a promising route to decarbonizing multiple sectors, particularly transportation [1]. This paper explores hydrogen's role as a major substitute fuel, its integration into IC-Es, the technological advancements enabling its use, and the challenges it faces toward widespread adoption.

Hydrogen stands as the most prevalent element in the universe and presents a highly efficient solution as a sustainable energy source. Its deployment in dual-fuel engines, particularly spark ignition (SI) engines, underscores its potential to reduce reliance on traditional fossil fuels [2] while mitigating environmental pollution. Hydrogen optimizes combustion performance and significantly reduces emissions compared to conventional gasoline engines when used in conjunction with gasoline in dual-fuel engines. These engines harness hydrogen as their primary fuel, boosting thermal efficiency, especially during low and partial loads. However, they face the hurdle of heightened NOx emissions stemming from elevated combustion temperatures. This challenge can be addressed with technologies like Exhaust Gas Recirculation (EGR), which has demonstrated substantial reductions in NOx emissions [3].

Moreover, the integration of hydrogen in ICEs supports the transition to greener transportation by leveraging existing engine technologies. This pragmatic approach not only fosters the adaptation of current infrastructures but also paves the way for incremental advancements towards [4] fully sustainable energy systems [5]. Hydrogen’s role in future transportation is further endorsed by its inclusion in various strategic energy plans, which reflect its potential to meet stringent emission standards and contribute to the transition to low-carbon energy systems [6].

Hydrogen's substantial energy content and clean combustion characteristics render it an appealing choice for diminishing greenhouse gas emissions and lessening reliance on fossil fuels. Hydrogen-fuelled ICEs offer efficiencies comparable to traditional engines but have the advantage of emitting no CO2 or harmful pollutants when the hydrogen is produced from renewable sources [7]. The adaptation of existing ICEs to run on hydrogen involves several technological challenges, including modifications to the fuel injection system to accommodate hydrogen’s low ignition energy and high diffusivity. Additionally, adjustments in engine timing are required to manage hydrogen's high flame speed, which can cause pre-ignition and knocking, potentially detrimental to engine performance [8].

The distinctive characteristics of hydrogen, including its broad flammability range and rapid flame speed, facilitate the adoption of lean burn and super-charged technologies. This, in turn, boosts the efficiency and performance of ICEs while simultaneously curbing emissions.[9]. As technology evolves, these engines could serve as a transitional technology towards a more sustainable automotive sector, bridging the gap until full electrification becomes feasible [10].

However, challenges remain, particularly in terms of hydrogen storage and the higher NOx emissions resulting from hydrogen's high combustion temperatures. Innovative approaches such as advanced combustion strategies are being explored to address these challenges, aiming to optimize hydrogen engines for commercial viability and environmental compatibility[8]. Despite these hurdles, the deployment of hydrogen technology in vehicles is progressing, with advancements that include improved engine efficiencies and reduced pollutant emissions [11].

In current study revolves around the prospect of hydrogen as a game-changing energy transporter for the automotive sector is immense, ongoing research and development are crucial to overcoming the existing challenges hindering its extensive implementation. The integration of hydrogen technology in internal combustion engines not only supports sustainable energy goals but also leverages decades of combustion engine development for a smoother transition to greener alternatives. Hydrogen’s increasing momentum as a clean and sustainable alternative in the energy sector positions it as a key player in achieving broader energy security [12] and environmental sustainability goals [13]. As research progresses, the integration of hydrogen technologies in public and private transport sectors becomes more viable, paving the way for a greener future.

II. HYDROGEN'S ATTRIBUTES RELATIVE TO OTHER FUELS IN ICES

Hydrogen fuel is distinguished in the energy sector by its high energy content and unique combustion properties. Being the most elementary and prevalent element in the universe, hydrogen offers several advantages over traditional hydrocarbon fuels, especially in terms of environmental impact and efficiency. When used as a fuel, hydrogen's primary emission is water vapor, effectively eliminating the release of carbon dioxide and other greenhouse gases associated with fossil fuels. This characteristic makes it an appealing option for reducing global carbon emissions and combating climate change.

TABLE I. SUMMARIZES THE KEY PROPERTIES OF HYDROGEN FUEL [14–19]

Sl No	*Property*	*Value*	**Notes/Comments**
1	Molecular Weight	2.016 g/mol	Lightest of all gases
2	Energy Content	33.33 kWh/kg	Highest per mass-energy content of common fuels
3	State at Room Temp.	Gas	Requires compression or liquefaction for storage
4	Boiling Point	-252.87°C	Extremely low, complicates storage
5	Density	0.08988 g/L (at STP)	Very low, affects storage and transport requirements
6	Flammability Limits	4% to 75% in air	Wide range, highly flammable
7	Autoignition Temp.	500°C	Higher than gasoline
8	Adiabatic Flame Temp.	~2045°C	Higher than most common fuels
9	Diffusivity	0.61 cm^2/s	High, mixes quickly with ambient air

However, hydrogen also presents challenges, especially when considering storage and transportation, attributed to its low density and high flammability. Innovations in hydrogen storage, such as compression and liquefaction, or the development of chemical hydrides for hydrogen binding, are critical to making its use more practical across diverse applications, encompassing transportation and power generation. These advancements are essential for harnessing hydrogen's potential as a sustainable energy source.

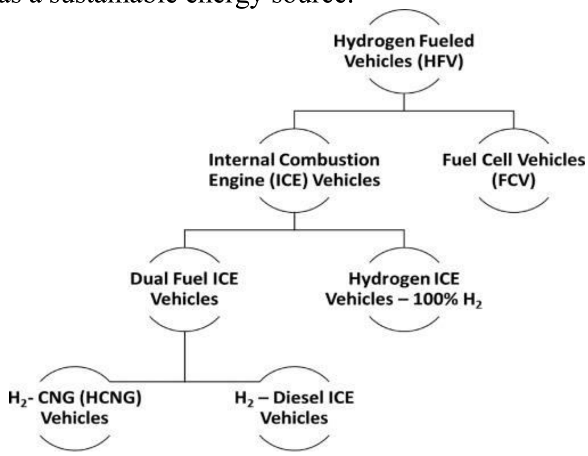

Figure I: Distribution of hydrogen-fueled-vehicles [20]

III. Hydrogen-Spark Ignition Engines

Hydrogen has emerged as a hopeful option for alternative fuel in spark-ignition (SI) engines, thanks to its numerous advantageous properties including Quick flame propagation, minimal ignition requirements, and a broad range of operations. This thorough assessment evaluates the potential of hydrogen in powering SI engines, focusing on its combustion characteristics, emission reduction capabilities, and injection system configurations. The review explores various methods of introducing hydrogen into SI engines such as carburetion method induction (CMI), port fuel injection (PFI), and direct injection (DI), and assesses the attributes related to performance and emissions of hydrogen-fuelled SI engines compared to traditional hydrocarbon-fuelled engines. Additionally, it examines recent advancements in engine combustion systems to align with changing the prospect of hydrogen as an environmentally friendly and effective fuel for spark-ignition engines, paving the way for sustainable transportation solutions.

In recent times, there has been a burgeoning interest in hydrogen as a viable alternative fuel for spark-ignition (SI) engines. Hydrogen offers several advantages over conventional hydrocarbon fuels, including faster flame propagation, lower ignition energy, and a wider operating range. These characteristics render hydro-gen an appealing choice for enhancing combustion efficiency and mitigating detrimental emissions in SI engines. However, the successful integration of hydrogen into SI engines [21, 22] requires careful consideration of various factors, including combustion characteristics, injection system configurations, and emissions control strategies. This review provides an in-depth analysis of the potential of hydrogen in powering SI engines, with a focus on recent advancements and prospects.

One of the major benefits of hydrogen-fuelled SI engines is their competency to achieve ultra-lean combustion, resulting in lower flame temperatures and decreased heat transmission to the engine walls [23]. This leads to improved engine efficiency and lower emissions of nitrogen oxides (NOx), a major contributor to air pollution [24]. Additionally, hydrogen-powered SI engines exhibit lower emissions of harmful pollutants relative to traditional hydrocarbon-fuelled engines [25]. Earlier investigations have demonstrated that hydrogen engines primarily emit NOx and particulate matter (PM), with NOx emissions being higher because of the elevated combustion temperatures associated with hydrogen combustion [26]. However, by optimizing the air-fuel ratio, it becomes feasible to diminish combustion temperatures and NOx emissions in hydrogen-powered SI engines [27].

The successful integration of hydrogen into SI engines requires efficient injection systems that can effectively transport the fuel to the combustion chamber. Three main injection system configurations are commonly used: carburetion method induction (CMI), port fuel injection (PFI), and direct injection (DI)[28]. In CMI systems, hydrogen is instigated into the intake manifold before the throttle valve, where it is mixed with the incoming air [29]. PFI systems, on the other hand, involve spraying the fuel directly into the intake manifold, either at a single point or multiple points near the intake valve of each cylinder [30]. DI systems, the most advanced of the three, incorporated with a high-pressure injector inject the fuel directly into the combustion chamber, allowing for precise control over the fuel-air mixture [31]. DI systems offer several advantages, including reduced time lag, enhanced transient response, and improved thermal efficiency [32]. Numerous studies have highlighted that direct injection (DI) can notably enhance thermal efficiency in hydrogen-fuelled spark-ignition (SI) engines [33].

Comparing the attributes related to performance and emissions of hydrogen-fuelled spark-ignition (SI) engines with traditional hydrocarbon-fuelled engines is essential for evaluating their potential as a viable alternative. Hydrogen-powered SI engines demonstrate superior performance, especially under part-load conditions, due to their higher hydrogen combustion velocity and improved combustion efficiency [33]. Additionally, hydrogen-fuelled engines emit virtually no hydrocarbons or carbon monoxide, with negligible quantities of these pollutants generated by the evaporation and combustion of lubricating oil on the engine cylinder walls [21]. However, NOx emissions from hydrogen-fuelled SI engines may surpass those from petrol-fuelled engines due to the elevated combustion temperatures linked with hydrogen combustion [27]. Strategies for reducing NOx emissions, such as optimizing the air-fuel ratio and employing advanced emissions control technologies, are essential for maximizing the environmental benefits of hydrogen-fuelled SI engines [23].

Considerable endeavours have been undertaken to improve engine combustion systems in line with advancing emission and fuel economy regulations. Recent advancements in engine technology, such as variable valve timing, cylinder deactivation, and turbocharging, have contributed to improving combustion efficiency and reducing emissions in hydrogen-fuelled SI engines [34]. Additionally, advancements in fuel injection technology, such as the development of high-pressure direct injection (HPDI) systems, have enabled more precise control over the fuel-air mixture, further enhancing engine performance and efficiency [29]. Moreover, research endeavours aimed at optimizing engine operating parameters, such as compression ratio and ignition timing, have yielded encouraging outcomes in enhancing thermal efficiency and curbing emissions in hydrogen-fuelled spark-ignition (SI) engines [24].

Hydrogen presents significant promise as a clean and efficient fuel for spark-ignition engines. Its advantageous characteristics, including rapid flame propagation, minimal ignition energy requirements, and broad operating range, make it an attractive alternative to traditional hydrocarbon fuels. By optimizing combustion processes, employing advanced injection systems, and implementing emission control strategies, hydrogen-fuelled SI engines can offer significant environmental benefits, including reduced emissions of harmful pollutants and improved fuel efficiency. Additional research and development efforts are necessary to address current obstacles and unlock the full potential of hydrogen as a sustainable fuel for transportation.

IV. Hydrogen Compression Ignition Engines

Type your main text in 10-point Times New Roman, single-spaced and justified. Do not use double-spacing. Hydrogen presents itself as a compelling option for improving both the efficiency and environmental friendliness of compression ignition (CI) internal combustion engines when used as a diesel fuel additive. Injecting small amounts of hydrogen into compression ignition engines offers a range of benefits across various aspects, primarily attributed to its exceptional diffusivity and combustion characteristics. Hydrogen injection improves the uniformity of mixing within the diesel spray stream, leading to more efficient combustion, leading to more thorough blending with air. This phenomenon substantially diminishes the formation of unwanted byproducts like hydrocarbons, carbon monoxide, and carbon dioxide during the combustion process [21–25]. The combustion chamber remains relatively free from these harmful emissions, with trace amounts being generated only through the partial combustion of lubricating oil [26, 27].

In hydrogen-fuelled CI engines, the design of both the engine structure and the injector is critical. The injector plays a pivotal role in controlling the pressurization level of hydrogen injected into the combustion chamber, influencing combustion dynamics and emission profiles[23, 24, 28]. While hydrogen cannot independently sustain combustion in CI engines due to the requisite compression temperature, the integration of a glow plug[29] enables efficient ignition [30].

Dual-fuel engines offer an alternative approach, wherein hydrogen serves as the primary fuel and is introduced into the intake air or carburettor, with diesel fuel used to ignite the mixture. The pilot fuel generally accounts for 10–30% of the total fuel, while hydrogen contributes the majority of the energy. [31].

Nitrogen oxides (NOx) present a notable challenge in dual-fuel compression ignition engines powered by hydrogen, akin to their impact in spark ignition (SI) engines. Exhaust gas recirculation (EGR) emerges as a formidable strategy for NOx reduction, albeit with trade-offs. EGR dilutes the intake charge's oxygen content, thereby lowering NOx emissions. However, escalating EGR levels lead to a substantial decrease in volumetric efficiency, with a notable 15% reduction compared to systems without EGR [32]. Furthermore, in hydrogen dual-fuel setups, employing Exhaust Gas Recirculation (EGR) may increase particulate emissions, resulting in smoke levels akin to conventional CI engines [33].

Introducing liquid water into the combustion chamber provides an additional method for reducing NOx emissions. Water injection not only helps suppress knocking combustion and premature ignition but also cools the charge and re-tards the combustion rate, akin to the effects of EGR[34–36]. However, water injection into the intake manifold inevitably decreases the engine's volumetric efficiency, necessitating a balanced approach to emission control and performance optimization [36].

In summary, while hydrogen holds immense promise as a diesel fuel additive for CI engines, its effective integration necessitates a comprehensive understanding of combustion dynamics, injector design, and emission control strategies. Continued research and development in this domain are vital for realizing the full potential of hydrogen-enhanced CI engine technology in advancing sustainable transportation.

V. Emissions

Hydrogen holds significant promise in revolutionizing combustion processes In internal combustion engines (ICEs), hydrogen exhibits distinctive traits and the potential to merge the combustion characteristics of both spark ignition (SI) and compression ignition (CI) systems. This essay provides a comprehensive analysis of hydrogen's advantages, challenges, and potential solutions in automotive combustion, drawing on a range of scholarly references.

Hydrogen's versatility lies in its capability to integrate predominantly premixed combustion akin to SI engines with the primarily diffusion-type combustion characteristic of CI engines[37–39]. In spark ignition (SI) engines, hydrogen is partially injected early and ignited by the spark plug, creating a homogeneous premix, while the remaining portion is directly injected into the flame for subsequent combustion stages [40, 41]. This dual-phase injection strategy offers precise control over combustion, enabling significant reductions in CO2 emissions and minimizing knocking, especially during diffusion combustion phases.

Moreover, hydrogen combustion concepts encompass a spectrum of approaches, incorporating both spark ignition utilizing homogeneous premix and compression ignition techniques. Spark-ignited hydrogen engines utilizing premixed homogeneous charges offer the potential for 100% CO2 reduction, albeit with challenges in power density, fuel efficiency, and transient performance. The choice between low-pressure and high-pressure hydrogen combustion concepts affects injection pressures and storage systems, with implications for energy efficiency and system complexity.

Designing hydrogen-fuelled direct injection (DI) combustion systems presents several challenges. These include limitations in mass flow rate due to injector size constraints, difficulties in achieving homogenization and stratification, and the need to address hydrogen's higher diffusivity compared to gasoline. Strategies to enhance efficiency involve developing inhomogeneous combustion processes, such as stratified or diffusive combustion, and optimizing injection parameters.

Hydrogen combustion strategies must also address NOx emissions, primarily stemming from high combustion temperatures and mixture homogeneity issues[11]. Lean burn operation and the implementation of exhaust gas recirculation (EGR) are effective approaches for reducing NOx emissions, though they may come with compromises in engine performance and thermal efficiency. [11]. Fine-tuning equivalence ratios and integrating EGR mechanisms are essential for balancing emission control and engine efficiency.

The integration of hydrogen with gasoline in a dual-fuel concept shows promise in enhancing performance and reducing emissions[11]. Direct injection of hydrogen into the combustion chamber, combined with gasoline port injection, offers advantages in reducing backfire and optimizing combustion efficiency. Past efforts focused on building the hydrogen economy have laid the groundwork for hydrogen-enriched combustion, leading to increased output and reduced dependence on conventional fuels.

However, significant research gaps persist in fully realizing hydrogen's potential in automotive applications. Further investigations are needed to address unexplored areas and optimize hydrogen utilization for automobiles. Recent studies have demonstrated satisfactory results in using hydrogen-gasoline blends to improve performance and reduce emissions, underscoring the importance of ongoing research and development efforts.

NOx emissions pose a prominent hurdle in hydrogen-fuelled engines, largely stemming from elevated combustion temperatures and combustion chamber conditions [11]. Lean burn operation, with equivalence ratios ranging from 0.4 to 0.6, offers an effective strategy for NOx reduction, balancing emissions, and engine stability. However, operating at equivalence ratios below 0.4 may lead to misfiring and increased NOx emissions.

Additionally, employing exhaust gas recirculation (EGR) presents an opportunity to quench combustion chamber temperatures and reduce NOx formation [11]. EGR serves not only to diminish NOx emissions but also to improve thermal efficiency by decreasing heat dissipation through the combustion chamber walls. Additionally, EGR implementation can diminish hotspots within the combustion chamber, lowering the likelihood of backfire [11].

Hydrogen combustion offers a compelling pathway for optimizing automotive engines, with the potential to revolutionize combustion processes and reduce environmental impact. Despite challenges in combustion control, emissions management, and system integration, ongoing research and development efforts are advancing hydrogen's viability as a clean and efficient fuel source for automobiles. By addressing these challenges and leveraging hydrogen's unique properties, the automotive industry can unlock significant opportunities for sustainable transportation.

VI. CHALLENGES FACED

Hydrogen engines offer a promising avenue for achieving sustainable transportation, but they face numerous challenges ranging from technical limitations to infrastructure and safety concerns. This paper delivers a thorough analysis of these challenges, exploring issues related to combustion, materials, infrastructure, and more. Additionally, it discusses ongoing research efforts aimed at addressing these challenges to unlock the unleashing the complete potential of hydrogen as a clean energy source for transportation.

Recent research in the field of engine technology highlights several critical areas of interest. Notably,[42] has focused on knock resistance and its significant impact on engine performance, detailing how this phenomenon can affect combustion characteristics. To address engine knock, strategies such as ignition timing adjustments and water injection have been explored by [43] as viable methods to mitigate this issue, demonstrating the importance of precise control over combustion conditions.

In terms of materials compatibility, [44] researchers have investigated the challenges posed by hydrogen embrittlement and its detrimental effects on engine components. This issue underscores the necessity for research into materials that exhibit improved hydrogen compatibility, with ongoing [45] efforts directed toward developing such materials.

Fuel injection and storage also present significant challenges, particularly in the context of hydrogen-powered engines. Discussions [46] have centerer around the precise injection requirements and the persistent issue of hydrogen leakage, highlighting the need for advancements in this area. Additionally, studies have [47] addressed storage options and their limitations, emphasizing concerns related to tank design and safety that are crucial for the effective use of hydrogen as a fuel source. These studies collectively highlight the continuous endeavours aimed at improving the efficiency and safety of engine systems using alternative fuels.

VII. CONCLUSION

The transition towards sustainable mobility has become imperative in addressing environmental concerns and reducing carbon emissions. Hydrogen fuel has emerged as a promising alternative, offering zero environmental impact and attracting significant interest from the automotive industry. This comprehensive review explores the potential of hydrogen fuel across various transportation sectors, focusing on hydrogen internal combustion engines (ICEs) and the dual fuel approach in spark ignition (SI) engines.

Hydrogen's clean energy profile makes it an attractive option for vehicle development, promising improvements in engine efficiency and emissions reduction. Its combustive qualities offer advantages, but careful engine design is required to mitigate issues such as anomalous combustion. Despite challenges, hydrogen-powered ICEs have the potential to significantly contribute to alternative, environmentally friendly road mobility solutions and help meet CO2 neutrality targets.

Modifying internal combustion engines for hydrogen fuel poses several challenges, necessitating engine subsystems and component modifications. These include injection, ignition, cylinder heads, pistons, and aftertreatment systems. Addressing these modifications is paramount for optimizing engine performance and curbing emissions.

The paper discusses the dual fuel approach, combining hydrogen with gasoline in SI engines, to enhance engine performance while minimizing emissions. However, challenges such as abnormal combustion and the need for further research persist. Understanding the combustion dynamics and optimizing fuel injection strategies are essential for maximizing the benefits of the dual fuel concept.

Hydrogen-powered vehicles face challenges related to infrastructure development, combustion irregularities, and emissions reduction. Overcoming these challenges requires ongoing research and innovation, including the optimization of combustion processes and the development of supportive infrastructure. Utilizing renewable energy sources for hydrogen production is essential for achieving widespread adoption and realizing the full potential of hydrogen fuel for sustainable mobility.

Hydrogen fuel holds immense promise for advancing sustainable mobility and reducing carbon emissions in the transportation sector. Despite challenges, ongoing research and innovation are paving the way for the widespread adoption of hydrogen-powered vehicles. By addressing technical challenges, optimizing engine performance, and developing supportive infrastructure, hydrogen fuel has the potential to revolutionize transportation and contribute significantly to a greener future.

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