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A review of hydrogen combustion and its impact on engine performance and emissions

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The article focuses on the latest research and advancements in the use of hydrogen as a fuel for internal combustion engines. It provides an in-depth analysis of hydrogen's potential to improve combustion efficiency, especially when used in blends with fossil fuels like ammonia and methane. Key findings highlight hydrogen's ability to reduce harmful emissions such as CO, HC, and soot, though it can increase NO_x emissions due to higher combustion temperatures. The article also reviews various hydrogen injection technologies, including direct injection, which outperforms port fuel injection by significantly enhancing power output and fuel efficiency. Moreover, the study emphasizes the need for optimizing hydrogen ratios in dual-fuel engines to balance performance and emissions. These insights underscore hydrogen's role in future decarbonization efforts, with ongoing research focusing on mitigating NO_x emissions while maintaining high efficiency.

Key words: *hydrogen, hydrogen combustion, dual-fuel engines, emission reduction, engine efficiency*

1. Introduction

The combustion of conventional fossil fuels, such as gasoline and diesel, in internal combustion engines, is one of the main sources of air pollutant emissions, negatively impacting human health and the environment. Transportation is a major source of air pollution (Fig. 1), accounting for as much as 15 percent of global greenhouse gases. Emissions of these gases contribute to deteriorating air quality, which in turn increases the risk of respiratory and cardiovascular diseases in humans [11]. In addition, CO_2 emissions are one of the main drivers of global climate change, leading to extreme weather events, rising sea levels, and ecosystem degradation [8].

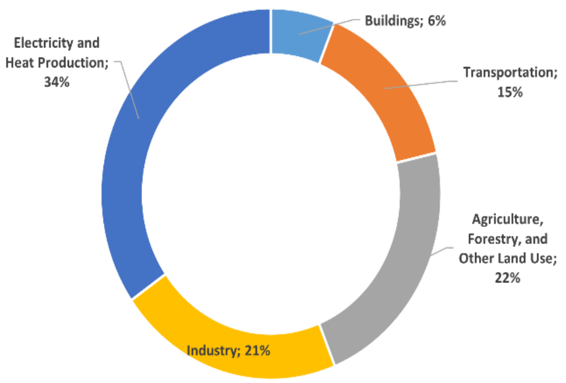

Fig. 1. Global greenhouse gas emissions by economic sector [8]

In response to these challenges, the European Union and other countries worldwide have introduced strict regulations to reduce emissions and promote more sustainable energy sources. EU directives, such as the Euro 7 standard, impose strict emission limits on vehicle manufacturers, forcing the search for alternative propulsion technologies [9]. In this context, hydrogen is gaining importance as a future fuel that can meet stringent emission standards while offering high energy efficiency. Current research on hydrogen combustion in internal combustion engines focuses on optimizing the process to minimize emissions, especially nitrogen oxides, which can be produced at the high combustion temperatures characteristic of hydrogen. Modern technologies, such as direct hydrogen injection and advanced control techniques, make it possible to precisely regulate the combustion process, helping to reduce emissions and improve engine efficiency significantly. In addition, research into the use of hydrogen as a propellant is being supported by international initiatives and policies that support the development of a green economy, putting hydrogen in the spotlight as a key component of future transportation and environmental solutions. This review article highlights the latest developments in this field.

2. Mechanisms and characteristics of hydrogen combustion

In particular, this chapter explores the intricate processes and distinguishing features of hydrogen combustion in internal combustion engines and constant-volume combustion chambers. An analysis of hydrogen combustion kinetics, especially when combined with diesel-pilot fuel, demonstrates the significant impact of injection sequence, timing, and ambient temperature. The injection of diesel before hydrogen delays hydrogen ignition due to the cooling effect caused by diesel-air mixing. In contrast, when hydrogen is introduced initially, the extent of homogenization with air before diesel ignition substantially impacts the spread of combustion. Reduced ambient temperatures cause lean mixes, increasing combustion variability and complicating ignition [6].

To the turbocharger's impact on gas exchange, the combustion duration in turbocharged hydrogen internal combustion engines remains constant and longer at 1500 and 2000 rpm compared to other loads. The peak pressure increase rate remains below 0.25 MPa/°CA under all prevailing conditions. The levels of NO_x emissions exhibit considerable variation by engine speed and equivalence ratio, with the most elevated emissions seen at an air-fuel ratio (λ = = 0.88) at a speed of 2500 rpm [18]. Detonation in hydrogen engines is intricately linked to the spontaneous ignition of an exhaust gas combination and the complex interplay between the flame and pressure waves. Notably, the radicals HO_2 and H_2O_2 play a crucial role in the propagation of flames, particularly in low-temperature reaction zones where they influence the formation of OH. The rapid flame propagation, driven by pressure waves, exacerbates the risks of detonation and emphasizes the need for careful control of combustion dynamics [17]. Through the use of CONVERGE software, advanced chemical reaction pathways of hydrogen-air combustion have been integrated into 3-D engine simulation models. Studies suggest that an excess of hydrogen increases the concentration of OH radicals in the flame zone, accelerating the hydrogen-oxygen reaction and generating higher pressures and temperatures inside the cylinder. These conditions, although increasing electricity production, yet reduce overall efficiency. Moreover, the presence of excess hydrogen generates a decrease in NO_x emissions, specifically NO, due to reduced amounts of O and OH radicals. This information has considerable potential to improve energy efficiency and reduce emissions [34].

Investigation of hydrogen injection in constant-volume combustion chambers that replicate direct injection in compression ignition engines reveals that the ignition delay is very sensitive to ambient temperature, while injection pressure has a negligible effect. Following ignition, the flame travels towards the nozzle, creating a diffusion flame structure, highlighting the significance of environmental variables in direct ignition hydrogen combustion [32].

Investigations on incorporating hydrogen into diesel engines demonstrate that augmenting hydrogen flow rates results in elevated brake specific fuel consumption and thermal efficiency, mostly attributable to accelerated flame speeds. Elevated hydrogen flow rates of 0.80 dm^3/min substantially increase exhaust temperature and NO_x emissions under increased loads. Conversely, emissions of CO, unburnt hydrocarbons and soot are noticeably decreased. The results suggest that it is necessary to meticulously optimize the addition of hydrogen to diesel engines to balance performance and emissions [14]. Experimental studies on hydrogen direct injection engines indicate that cycle-to-cycle variability increases with engine speed but decreases with higher loads. The start of injection timing is critical in influencing cycle variability, especially under low load and high-speed conditions, suggesting that precise injection timing control is crucial for stable operation [16]. An analysis of knocking combustion in a hydrogen-powered engine using a two-stage system with turbulent jet ignition reveals the difficulties in achieving optimal efficiency in hydrogen engines. The investigation manipulated the excess air ratio (λ = 1.25–2.0) while keeping the combustion center constant by employing a single-cylinder engine equipped with a passive pre-chamber. The findings suggest that knocking is present at lower air excess ratios but completely eradicated at λ = 2.0 or above.

An investigation [20] revealed that the pressure oscillation index is a more dependable approach for identifying knock than the Mahle Knock Index, which necessitates repeated modifications depending on engine properties. The timing of hydrogen and diesel injection, along with ambient temperature, plays a crucial role in hydrogen combustion efficiency. Turbocharging and increased hydrogen flow rates enhance performance but also raise NO_x emissions while reducing CO and soot. Controlling knocking in hydrogen engines requires precise management of air ratios and combustion dynamics.

3. Emissions and environmental impact

This section analyzes the emissions and environmental consequences linked to the combustion process of hydrogen and ammonia within internal combustion engines.

A research [5] investigation analyzes the combustion properties and the generation of NO_x in fuel mixes, including H_3-NH_3. The use of H_2 greatly enhances the combustion rate of NH_3, therefore enhancing the overall combustion efficiency. In combustion, H_2 is an accelerant, whereas NH_3 primarily affects the maximum burning velocity. This study reveals that fuel-NO_x substantially impacts total NO_x emissions, while thermal-NO_x is negligible compared to pure H_2-air combustion. The highest levels of NO_x emissions are observed during stoichiometric combustion, while hydrogen facilitates the breakdown of ammonia at an air-fuel equivalency ratio of 1.0.

Another research [4] on NO_x emissions from hydrogen-methane blends used in internal combustion engines. An analytical model utilizing the Zeldovich mechanism was formulated to forecast NO emissions in several scenarios, encompassing the hydrogen-to-methane ratio, equivalency ratio, compression ratio, and engine speed. The model postulates an Otto cycle characterised by immediate combustion, chemical equilibrium at the combustion threshold, and NO generation only during the expansion phase. Results suggest decreased NO levels with lower equivalence ratios and larger compression ratios are observed. Additionally, NO generation takes place soon after the initiation of the expansion stroke, and NO concentration remains mostly unchanged by variations in the H_2/CH_4 ratio in the fuel mixture.

The Life Cycle Assessment approach [1] evaluates the entire life cycle emissions of a hydrogen engine that has been modified from a diesel engine. This engine utilises green hydrogen generated by steam electrolysis and powered by wind energy. The findings indicate that hydrogen engines can decrease greenhouse gas emissions by more than 90% compared to diesel engines. Although the redesign process is accompanied by some emissions, the hydrogen engine exhibits significant environmental advantages and presents an achievable possibility for modifying current internal combustion engines to meet sustainability objectives.

Adding hydrogen to compressed natural gas can reduce CO_2 emissions and improve combustion efficiency without the need for significant engine modifications. Even under transient conditions, hydrogen blends up to 25% demonstrated good engine performance with only a slight increase in NO_x emissions, which can be managed with proper calibration of the air-fuel ratio (λ) [7].

Contrary to the belief that hydrogen combustion leads to zero emissions, non-premixed hydrogen combustion can increase soot formation compared to hydrocarbon fuels. This phenomenon is due to hydrogen's low quenching distance, intense vaporization of lubricant oil, and complex gas-dynamic interactions between oil vapor and the fuel stream, all of which contribute to soot generation [27]. The total PN concentration from this study is shown in Fig. 2.

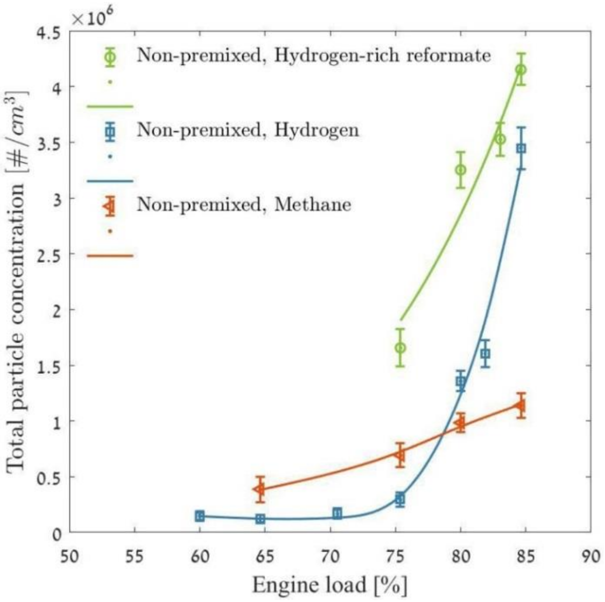

Fig. 2. Total PN concentration with hydrogen, methane, and hydrogen-rich reformate under different engine loads [27]

Hydrogen enhances combustion efficiency in fuel mixtures like hydrogen-ammonia while minimizing NO_x emissions. NO_x emissions are influenced by factors such as equivalence ratios and compression ratios, with stoichiometric combustion producing the highest levels, particularly in hydrogen-methane blends. Additionally, hydrogen engines, especially those converted from diesel and powered by green hydrogen, can reduce greenhouse gas emissions by over 90%, offering significant environmental benefits.

4. Impact of fuel additives on combustion characteristics

This section explores the impact of several fuel additives, with a specific focus on hydrogen, on the combustion properties of internal combustion engines. The primary objective is to improve engine operating efficiency, decrease emissions, and optimize combustion processes by strategically incorporating hydrogen and other additives into various fuel types, such as ammonia and natural gases.

A study [30] on hydrogen internal combustion engines addresses the challenges of low power density and abnormal combustion by evaluating the impact of adding different volumes of ammonia to hydrogen. The results show that ammonia addition extends flame development periods and lowers peak heat release rates, increasing engine power and slightly decreasing thermal efficiency. NO_x emissions are minimally affected by ammonia but increase with delayed ignition timing, highlighting the trade-offs between performance and emissions in hydrogen-ammonia blends.

Article [31] of ammonia and hydrogen mixtures in spark-ignition engines under turbulent conditions reveals that lean flames have more wrinkled structures than stoichiometric and rich flames. Adding hydrogen to ammonia improves flame reactivity and combustion efficiency, enhancing the ratio of turbulent to laminar burning velocities. Notably, hydrogen also alters the chemical pathways for NO formation, resulting in an inverse distribution of NO in flame structures.

Another study [29] explores the performance enhancement of ammonia engines through hydrogen addition and increased inlet air temperatures, ranging from 476 to 551 K. The results reveal that at 476 K, a 30% hydrogen mixture achieves the highest engine power with a combustion knock intensity slightly above 2 MPa/°CA. This optimal mixture minimizes ammonia escape and improves emission performance, supporting the advancement of zero-carbon combustion in ICEs. Another case [29] assesses the impact of blending hydrogen with ammonia on a high-pressure common rail diesel engine operating at 1800 rpm. Nine hydrogen blending ratios (10 to 90%) were tested under two ignition modes.

The study [13] finds that adding ammonia increases ignition delay and flame development periods but reduces the rate of in-cylinder pressure rise. While engine performance remains stable with ammonia addition when ignition timing is adjusted, NO_x emissions increase, indicating ammonia's role as a combustion inhibitor in hydrogen-fueled engines. Adding hydrogen to ammonia improves flame reactivity and combustion efficiency, enhancing the ratio of turbulent to laminar burning velocities. Notably, hydrogen also alters the chemical pathways for NO formation, resulting in an inverse distribution of NO in flame structures.

Figure 3 compares key combustion characteristics of hydrogen and ammonia in terms of combustion efficiency, power output, NO_x emissions, and thermal efficiency. Hydrogen shows superior combustion efficiency and power output performance, as it accelerates flame propagation and increases combustion reactivity. However, ammonia contributes to lower NO_x emissions due to its slower flame development and its role as a combustion inhibitor. On the other hand, ammonia displays slightly lower thermal efficiency than hydrogen, making hydrogen the more efficient fuel overall in high-performance settings.

Effects of varying exhaust gas recirculation rates, spark timings, and engine loads under stoichiometric conditions. Findings indicate that increasing EGR ratios advance brake timing, while adding 10% hydrogen retards it by the same amount. The optimal hydrogen/EGR ratio varies with engine load, suggesting specific blends for different operational conditions to maximize efficiency and minimize emissions [22].

Research [10] on liquid methane gas engines enhanced with hydrogen addresses the low combustion velocity of methane. The results show that hydrogen increases the peak heat release rate and maximum in-cylinder pressure, initially improving indicated thermal efficiency. However, higher hydrogen energy fractions exacerbate detonation tendencies and increase NO_x emissions, suggesting that while hydrogen can enhance methane combustion, its use must be carefully controlled to prevent adverse effects.

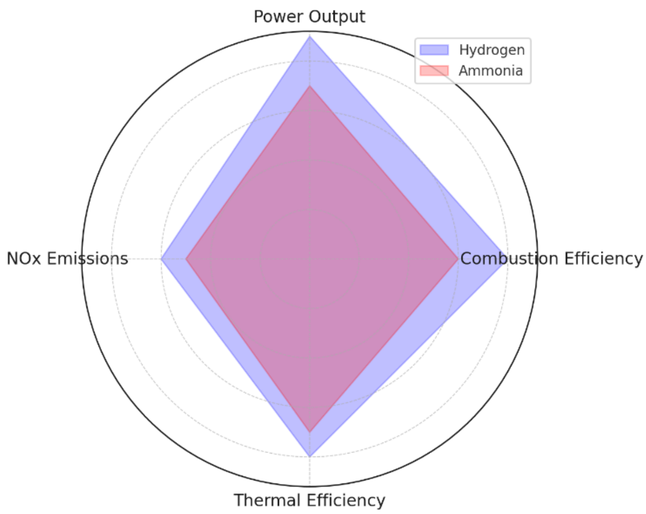

Fig. 3. Comparison of hydrogen and ammonia in combustion based on [30, 31]

Another study on hydrogen addition to gas engines, particularly those using natural gas, highlights how hydrogen accelerates flame propagation and increases combustion efficiency. The research [26] demonstrates that hydrogen boosts the initial spark kernel volume and NO concentrations due to higher combustion temperatures. Additionally, hydrogen improves CO oxidation and reduces HC and soot emissions, enhancing overall energy efficiency and fuel economy, especially in lean burn conditions.

Research on methanol as a fuel for internal combustion engines enhanced with hydrogen demonstrates significant improvements in performance and combustion efficiency, along with reduced emissions. The study [21] finds that hydrogen enrichment, up to 12.5%, increases brake thermal efficiency and brake power, while reducing brake specific energy consumption. However, beyond this enrichment level, performance declines due to reduced volumetric efficiency. Emissions of CO, HC, and CO_2 are significantly reduced, although NO_x emissions slightly increase due to higher combustion temperatures.

Computational fluid dynamics modeling reveals [33] that hydrogen addition increases cylinder pressure and indicates thermal efficiency while significantly reducing HC and CO emissions. However, NO_x emissions rise due to the higher combustion temperatures induced by hydrogen enrichment, presenting a challenge for balancing performance improvements with emission regulations.

The combustion of hydrogen requires precise control over ignition timing to optimize efficiency and reduce emissions. Hydrogen achieves a higher overall efficiency (~48%) compared to methane (~33%) under lean burn conditions, with hydrogen displaying greater sensitivity to ignition angle changes and requiring more advance for optimal combustion [19]. Adding hydrogen to various fuels, such as ammonia and natural gas, significantly enhances engine performance and combustion efficiency while reducing fuel consumption.

However, this improvement comes with a trade-off, as higher combustion temperatures from hydrogen enrichment tend to increase NO_x emissions, despite reducing CO, HC, and soot emissions. Blending hydrogen with ammonia shows promise for achieving near-zero carbon emissions, but managing ignition timing is crucial to minimize the rise in NO_x levels.

Hydrogen and ammonia blend offer a promising solution for reducing carbon emissions and improving combustion efficiency, but they present challenges in managing NO_x emissions and balancing thermal efficiency. These blends require careful ignition timing optimization and air-fuel ratios to maximize performance and minimize environmental impact.

5. Hydrogen injection technologies and strategies

This section explores the advanced technologies and strategies employed in hydrogen injection systems for internal combustion engines. A study compares the performance and emissions of PFI and DI systems in spark-ignited engines using hydrogen, methane, and coke oven gas.

Computational fluid dynamics simulations reveal that DI engines achieve a 40% increase in brake power due to a 30.6% improvement in volumetric efficiency. Additionally, DI systems reduce NO_x emissions by 36% compared to PFI at an optimal air-fuel ratio (λ) of 1.5 with hydrogen. The study also highlights hydrogen's superior performance in reducing fuel consumption – by 71.8% compared to methane and 67.2% compared to coke oven gas (COG) – owing to its higher heating value per unit mass [19]. The significant 71.8% reduction in brake specific fuel consumption observed with Direct injection hydrogen compared to methane (CH_4) is largely attributed to hydrogen's higher lower heating value per mass unit. This higher energy density allows for more power output with less fuel, resulting in greater fuel efficiency. Additionally, the precision of the DI system further enhances this effect by optimizing combustion conditions, reducing fuel losses, and improving thermal efficiency. These results were obtained under optimal air-fuel ratio conditions ($\lambda = 1.5$), which maximized the benefits of hydrogen's superior combustion characteristics.

Investigation [15] into hydrogen direct injection evaluates three mixture formation modes: homogeneous, lean-homogeneous, and lean-stratified charge in a single-cylinder research engine. The results indicate that hydrogen's high heat loss necessitates retarding combustion phasing. Among the modes, Lean-Stratified Charge (LSC) – designed to minimize high-temperature areas near the cylinder wall – achieved the highest indicated thermal efficiency (34.09%) under low load conditions. However, this mode also led to higher nitrogen oxide emissions, demonstrating the trade-offs between efficiency and emissions in hydrogen DI systems.

A study on a 2.0L direct-injection turbocharged hydrogen engine showcases impressive results, achieving 120 kW at 4400 rpm and 340 N·m at 2000 rpm. The engine exhibits a maximum brake thermal efficiency of 42.6% with a slightly lean air-fuel ratio ($\lambda = 1.91$) at 2000 rpm. Additionally, NO_x emissions are reduced by over 99.5% at engine speeds below 2000 rpm, and by about 90% at 4400 rpm, with two-thirds of conditions achieving NO_x levels below 20 ppm using an NH_3-SCR after-treatment system. This study underscores the potential of hydrogen DI systems to deliver high power, efficiency, and near-zero emissions [3].

Further research examines the impact of various injection parameters, such as the hydrogen amount per pulse, dwell time between pulses, and secondary injection pulse width, on engine performance and emissions. The findings suggest that split direct injection improves mixture stratification, leading to more effective and rapid combustion compared to single injection. Optimizing the mass fraction of post-injection and dwell time between injections enhances combustion further, with increased secondary injection pulse width improving engine performance by enriching the mixture around the spark plug. However, while this method reduces HC and CO emissions to near-zero levels, it also produces higher NO_x emissions [25].

Direct injection is more effective for hydrogen engines compared to port fuel injection. DI increases brake power by 40% due to improved volumetric efficiency and reduces NO_x emissions by 36% under optimal conditions. Additionally, DI engines achieve better fuel efficiency, with up to 71.8% lower fuel consumption than methane. Despite some trade-offs with NO_x emissions, DI offers better performance, efficiency, and lower emissions.

6. Dual-fuel and hybrid powertrains with hydrogen

The studies in this chapter examine various strategies for optimizing hydrogen usage in combination with conventional fuels. One study investigates the effect of varying compression ratios on a dual-fuel engine's maximum potential share of hydrogen energy. A numerical model analyses combustion and emission characteristics with hydrogen inducted via port fuel injection. The findings reveal a trade-off between the maximum hydrogen energy share and compression ratio, with the knock-limited maximum hydrogen energy share increasing from 20 to 45% as the compression ratio decreases from 19.5 to 14.5. As the hydrogen energy proportion increases, emissions other than NO_x generally decrease across all compression ratios [24]. The dual-fuel combustion of diesel with hydrogen is also explored, revealing that hydrogen addition increases maximum combustion pressure, heat release rate, and pressure rise rate at full load. While efficiency improves with hydrogen shares up to 25%, engine stability decreases at higher hydrogen content, and NO_x and HC emissions rise significantly. There is a need for careful balance in hydrogen-diesel blends to optimize performance while controlling emissions [12]. Another study [28] focuses on a dual-fuel engine operating on diesel and natural gas, with hydrogen used to enhance the natural gas component. The research shows that hydrogen enrichment improves combustion efficiency, reducing combustion duration by 30% and halving the time to reach 50% of mass fraction burned. However, hydrogen's energy fraction limit is found to be 19%, beyond which engine stability deteriorates due to increased cycle-by-cycle variation and knocking. The research [23] highlights how the injection sequence, timing, and ambient temperature affect combustion. When diesel-pilot is injected before hydrogen, it cools and delays hydrogen ignition. Conversely, injecting hydrogen first allows for better mixing with air, but lean combustion occurs if hydrogen is ignited after its end of injection, especially at lower ambient temperatures. Further research investigates the effects of varying hydrogen flow rates on combustion, performance, and emissions in a dual-fuel diesel engine [2]. Tests at different engine speeds and hydrogen flow rates reveal that certain flow rates significantly impact engine performance and emissions. Specifically, brake thermal efficiency improves at lower flow rates due to reduced combustion length and better phasing, while higher flow rates improve CO, CO_2, and smoke emissions.

Many studies reveal that increasing the hydrogen share in dual-fuel engines enhances combustion efficiency and reduces emissions, but it requires careful balancing to avoid issues like engine instability and increased NO_x emissions. The research highlights the impact of compression ratios, injection timing, and hydrogen flow rates on performance, showing that while hydrogen improves fuel efficiency and lowers emissions, managing its integration is crucial to maintaining engine stability and avoiding combustion-related problems.

7. Conclusion

1. The analysis (Fig. 4) suggests that hydrogen use in direct injection systems can offer significant efficiency gains, with up to 40% improvements in selected engine performance tests.

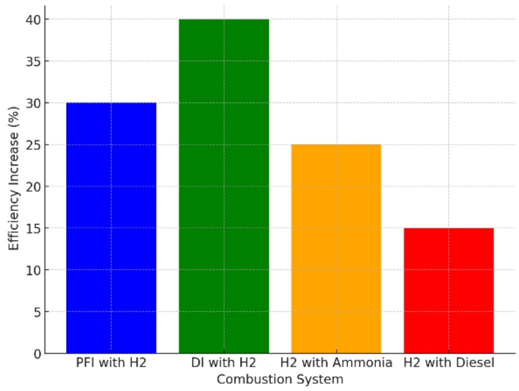

Fig. 4. The increased efficiency is attributed to optimized hydrogen injection parameters and air-fuel ratio control, resulting in improved combustion dynamics [16, 27, 33]

Hydrogen-ammonia blends also provide notable benefits, while hydrogen-diesel mixtures result in a more modest increase in efficiency. These findings suggest that while hydrogen can improve fuel efficiency across different systems, the magnitude of the improvement varies based on the type of combustion system and fuel blend used.

2. **Emission reduction**: Hydrogen combustion, particularly when blended with fossil fuels like ammonia and methane, leads to a substantial reduction in harmful emissions such as CO, HC, and soot. However, the higher combustion temperatures associated with hydrogen can increase NO_x emissions, requiring further research into emission reduction technologies like selective catalytic reduction (SCR) systems.
3. **Dual-fuel engines**: In dual-fuel engines (diesel-hydrogen), adding hydrogen increases combustion pressure and thermal efficiency. However, too much hydro-

gen can lead to engine instability and higher NO_x emissions. This highlights the need to carefully optimize the hydrogen ratio in the fuel mix to balance performance and emissions.

4. **Impact of fuel additives**: Adding hydrogen to fuels like ammonia, methane, and natural gas improves combustion efficiency and reduces emissions. Hydrogen-ammonia blends, in particular, offer significant benefits in reducing CO_2 emissions. However, careful management of ignition timing is essential to avoid excessive NO_x emissions.
5. **Optimizing combustion parameters**: To fully realize hydrogen's potential as a future fuel, further optimization of injection parameters and combustion processes is crucial. Developing advanced combustion control technologies will help reduce NO_x emissions while maintaining high efficiency.

Future directions

1. Optimizing hydrogen injection parameters to reduce NO_x emissions while maintaining high efficiency.
2. Further research on dual-fuel engines using hydrogen blends with biogas and natural gas to minimize emissions and improve stability.
3. Development of advanced combustion control technologies to better regulate combustion dynamics and emissions in hydrogen engines.

Nomenclature

CI	compression ignition
CNG	compressed natural gas
CO	carbon monoxide
COG	coke oven gas
DI	direct injection
EGR	exhaust gas recirculation
HC	hydrocarbons
H_2	hydrogen
LPG	liquefied petroleum gas
LSC	lean-stratified charge
NO_x	nitrogen oxides
PFI	port fuel injection
SCR	selective catalytic reduction
SI	spark ignition

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