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Hydrogen Combustion

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Abstract:

The significant and steadily increasing consumption of non-renewable energy driven by daily human activities has contributed to the fossil fuel crisis observed in recent decades. Growing concerns regarding emissions from internal combustion engines are also motivating the search for alternative energy sources to either replace or reduce reliance on conventional non-renewable fossil fuels. In this context, hydrogen emerges as a promising solution for internal combustion engines to tackle these challenges. Albeit not thoroughly, this review paper aims to address hydrogen combustion as a fuel for gas turbines and internal combustion engines, focusing more on both spark ignition and compression ignition engines, for electricity and heat generation, along with other applications. Use of hydrogen, ammonia and methane as fuel blends in such engines has also been discussed. Most studies reviewed indicate that hydrogen-enriched fuels significantly enhance engine performance, particularly in terms of thermal efficiency, fuel consumption and energy utilization. Furthermore, proper operating conditions can lead to substantial reductions in exhaust emissions either carbon or NOx emissions. Notably, the application of hydrogen fuel has resulted in remarkable combustion characteristics in both types of engines. This can be primarily attributed to unique combustion properties of hydrogen, which boasts a higher energy content, higher heating value, rapid flame speed and superior octane rating compared to gasoline, as discussed in this paper. In brief, the use of hydrogen- enriched as a fuel in internal combustion engines has led to enhancements in engine performance, reduced exhaust emissions and improved combustion behavior, achievable under suitable operating conditions and with minor modifications to the engine. Another primary benefit of hydrogen combustion is that it primarily produces water vapor as a byproduct, which greatly reduces greenhouse gas emissions and air pollution in comparison to fossil fuels.

Keywords: Combustion, heating value, internal combustion, ignition, knocking.

1. **Introduction:**

Notably, the substantial and continually rising use of these non-renewable fossil fuels, fueled by everyday-human activities, has played a key role in the fossil fuel crisis notably emerged in recent decades. As a remedy, hydrogen has the capacity to replace fossil fuels in many current applications, where it can lead to immediate reductions in pollution and contribute to cleaner environments [1]. Hydrogen serves as a fuel and energy carrier across various applications in sectors such as industry, electricity generation, heating and transportation [2]. Numerous established technologies leverage hydrogen, including industrial processes, electricity generation and heating through combustion, energy storage, grid balancing, and fuel cells for electricity generation and vehicle propulsion. These hydrogen-utilizing technologies enable its application across different sectors, promoting a transition to a sustainable energy system with reduced carbon emissions, thus advancing decarbonization efforts. Hydrogen has significant potential to support the decarbonization of the electric power sector by storing energy produced from renewable sources for long durations. This stored hydrogen can subsequently be converted back into electricity during peak demand periods when renewable energy output is low

Hydrogen has a wide range of current and potential uses as a fuel or energy carrier. In industrial applications, it serves as a propellant for rockets and acts as a feedstock or reducing agent in various processes. An industrial process encompasses a series of operations that transform raw materials, components or energy into final products or services [3]. These processes may involve physical, chemical or biological changes and are typically designed for large-scale production. In the United States, nearly all hydrogen is employed for industrial purposes, including petroleum refining, metal treatment, fertilizer and chemical manufacturing and food processing. Hydrogen plays a crucial role in U.S. petroleum refineries by helping to lower sulfur content in fuels. Furthermore, biofuel producers depend on hydrogen to produce hydro-treated vegetable oil for renewable diesel.

Hydrogen is increasingly utilized for energy storage and grid balancing. The process of hydrogen storage is essential for facilitating its widespread use across various locations. This involves capturing and storing energy for future use. Depending on several factors and the existing infrastructure, hydrogen can be stored either as a gas or a liquid. Generally, storing hydrogen in its gaseous form is the most common and feasible option for enhancing storage capacity for diverse energy applications. However, liquid hydrogen serves as an effective fuel for internal combustion engines and fuel cells [4]. A notable example of a hydrogen storage initiative is the Advanced Clean Energy Storage project in Utah, which aims to store substantial amounts of gaseous hydrogen generated from renewable sources for seasonal energy storage. Grid balancing, also referred to as load balancing or grid management, ensures that the electricity supply from power plants and other sources aligns with demand.

Additionally, the use of hydrogen as a fuel in fuel cells has gained significant attention. Hydrogen-fueled fuel cells produce electricity by combining hydrogen and oxygen molecules in a chemical reaction, eliminating the need for combustion [5]. This process occurs within an electrochemical cell, similar to a battery, resulting in the generation of electricity, water and a small amount of heat. Fuel cells come in various sizes and types, serving a wide range of applications, including electricity generation and vehicle propulsion. They are utilized in power plants that supply electricity to specific facilities, as well as in micro-grids and remote locations lacking access to conventional power grids. Fuel cell power plants primarily serve as backup or supplementary power sources for individual buildings or facilities, generating electricity and, in some cases, heat. As of the end of March 2024, there were approximately 210 operational fuel cell electric power generators across 151 facilities in the United States, with a combined nameplate electric generation capacity of around 384 megawatts. The capacities of these fuel cells vary significantly; the largest single fuel cell, located at the Bridgeport fuel cell facility in Connecticut, has a nameplate capacity of about 17 megawatts, while the smallest consists of 10 fuel cells, each with a capacity of 0.1 megawatts, at the California Institute of Technology. Most operational fuel cells in the U.S. utilize pipeline natural gas as their hydrogen source, although there are five fuel cell power plants that use biogas from wastewater treatment and one that utilizes landfill gas. Despite their potential; however, fuel cells represented less than 1% of total annual electricity generation in the U.S. in 2022.

Several automotive manufacturers have developed fuel cells to power their vehicles. According to the Energy Policy Act of 1992, hydrogen is recognized as an alternative fuel for vehicles. The growing interest in hydrogen as a transportation fuel stems from its ability to power fuel cells that produce zero air pollutants. Fuel cells are significantly more efficient than traditional gasoline-powered internal combustion engines, with some estimates indicating that they can be two to three times more efficient. However, despite the advancements made by various manufacturers in creating hydrogen fuel cell vehicles, their widespread adoption has been limited by the high costs of fuel cells and the scarcity of hydrogen fueling stations. Without convenient access to refueling options, consumers are; then, reluctant to invest in hydrogen-fueled vehicles, and companies are hesitant to build more stations without a solid customer base.

Besides, utilizing hydrogen for electricity and heat generation through combustion is emerging as a viable option and is gaining attention as a renewable and environmentally friendly energy carrier, whether in its pure form or mixed with ammonia and/or natural gas. The combustion of hydrogen involves a reaction with oxygen in the presence of heat or flame, resulting in water production and the release of energy in the form of heat and electricity [6]. This energy can be harnessed in internal combustion engines or gas turbines to generate heat and mechanical power. In fact, some operators of natural gas-fired power plants are exploring the use of hydrogen as a substitute for or supplement to natural gas. Additionally, hydrogen has the potential to serve as an indirect energy storage solution for electric power generation applications Albeit not thoroughly, this review paper aims to address hydrogen combustion as a fuel for gas turbines and internal combustion engines, focusing more on both spark ignition and compression ignition engines, for electricity and heat generation, along with other applications. Use of hydrogen, ammonia and methane as fuel blends in such engines is also discussed

2. Hydrogen Combustion:

Hydrogen is highly abundant, constituting 93% of all molecules. At standard temperature and pressure, it is colorless, odorless and tasteless, it does not mix nor dissolve in water. Due to its lighter-than-air nature, hydrogen ignites easily and spreads rapidly. It can be liquefied at 20 K, allowing for storage in specialized cryogenic systems [7-8]. However, the use of compressed gaseous or liquefied hydrogen in onboard storage systems for ground transportation and aircraft propulsion is complicated by its high flammability and low volumetric energy density. For instance, storing compressed gaseous hydrogen may require four times the volume of gasoline to provide the same energy output. Additionally, the storage and transportation of liquid hydrogen pose challenges related to cryogenic conditions, transportation and metering [9-12]. Hydrogen boasts the highest specific energy of all fuels, with 1 gram of hydrogen containing the same energy as 2.8 grams of gasoline. When cooled and liquefied, hydrogen occupies 700 times less volume than in its gaseous state. Its density is significantly lower than that of air, measuring 0.08967 kg/m³ compared to air's 1.2928 kg/m³, making hydrogen 14.4 times less dense than air [7]. In fact, hydrogen has 2.6 times more specific energy than gasoline. Under normal atmospheric conditions, hydrogen has a flammability range of 4 to 75 vol.%, which is broader than that of methane (4.3–15 vol.%) and gasoline (1.4–7.6 vol.%) [8].

Moreover, hydrogen demonstrates superior combustion characteristics compared to other hydrocarbon fuels and ammonia, exhibiting better ignitability, shorter ignition delays, enhanced flame stability and a high calorific value that allows for significant energy release [13-14]. When confined, hydrogen can detonate across a wide range of concentrations and has a faster flame speed (1.85 m/s) than gasoline vapor (0.42 m/s) and methane (0.38 m/s). The temperature of a hydrogen-air flame is higher than that of methane but lower than that of gasoline, with respective temperatures of 2207, 1917, and 2307 °C. Additionally, hydrogen requires very little energy to ignite (0.02 MJ), while gasoline and methane require more energy (0.24 and 0.28 MJ, respectively) [15]. Table 1 compares various combustion properties of hydrogen with those of other hydrocarbon fuels and ammonia.

Table (1): Comparison of some Combustion Properties of Hydrogen, other Hydrocarbon Fuels and Ammonia. Reproduced from [14].

Property	Hydrogen	Gasoline	Diesel	Methane	Propane	Ammonia
Lower heating value, MJ/Kg	119.9	43.9	42.83	50	46.4	18.8
Upper heating value, MJ/Kg	141.8	-	44.8	55.5	-	22.5
Flammability limits in air, vol.%	4-75	1.0-7.6	0.6-5.5	15	9.5	15-28
Detonability limit in air, %	18.3-59.0	-	-	6.3-14	1.1-1.3	-
Detonation speed in air, m/s	2055	-	-	-	-	-
Laminar flame speed in air, m/s	2.75	0.51	0.30	0.38	0.45	0.07
Minimum ignition energy, MJ	0.02	0.25	0.24	0.29	-	8
Ignition temperature, ℃	560	228-471	250	540	-	650
Maximum flame temperature in air, ℃	2045	-	-	1957	1980	-
Adiabatic flame temperature, ℃	2207	2307	2027	1941	1980	1800
Evaporation heat, KJ/Kg	456	350-400	275	510	428	23.37

Hydrogen combustion, the process of burning hydrogen in the presence of an oxidizer such as oxygen or air, is a vital technology for capturing the energy it releases [6]. This energy can be applied across various sectors, making hydrogen combustion an essential method for utilizing hydrogen. It can be employed in furnaces, boilers and other heating systems to generate heat for industries like steel production, glass manufacturing and chemicals processing [16]. Beyond its role as an energy carrier, hydrogen serves as an effective propellant for rocket and air-breathing engines, enhancing its value in diverse energy, power and propulsion applications [14]. Furthermore, hydrogen combustion can act as an alternative to natural gas or oil for heating buildings in space heating scenarios [17]. Recently, hydrogen combustion has been adopted to power vehicles with modified internal combustion engines, offering a more environmentally friendly alternative to fossil fuel-powered vehicles [18]. Investigation of hydrogen combustion is crucial for two primary reasons: its utilization and safety. From a utilization perspective, hydrogen is an attractive option for power generation due to its environmentally friendly nature and lower pollutant emissions during combustion compared to conventional fuels. In contrast to fossil fuels, hydrogen combustion emits no carbon dioxide, a significant contributor to greenhouse gas emissions. However, it is important to recognize that hydrogen production involves energy-intensive processes, making it more suitable as an energy carrier rather than a primary energy source, unlike fossil or nuclear fuels [14].

Hydrogen, via hydrogen combustion, can be utilized as a fuel in both internal combustion engines and gas turbine technologies. Hydrogen internal combustion engines function similarly to conventional gasoline or diesel engines, but they operate on hydrogen instead of traditional fuels [19]. These engines can be classified as either spark ignition or compression ignition. Spark ignition engines, similar to diesel engines, utilize a spark plug to ignite the hydrogen-air mixture [20]. They are relatively straightforward to convert from gasoline engines and have been employed in various demonstration vehicles. In contrast, compression ignition engines, similar to diesel engines as well, depend on the heat produced from compressing the hydrogen-air mixture to initiate combustion [21]. While less common than spark ignition engines, compression ignition engines offer enhanced efficiency and lower emissions [22]. However, challenges such as high cyclic variability, limited operating ranges and difficulties in ignition timing control complicate the commercialization of hydrogen-fueled compression ignition engines [23-25]. In fact, using hydrogen as a fuel in spark ignition engines presents several advantages over compression ignition engines. These benefits include increased lean operating limits, improved combustion stability, higher braking thermal efficiency and reduced emissions of carbon monoxide and unburned hydrocarbons [26-29]. Additionally, hydrogen's higher heating value, faster laminar flame speed and superior octane rating compared to other hydrocarbon fuels (such as gasoline) can lead to reduced knocking in spark ignition engines and enhanced combustion stability [30]. Consequently, numerous studies have explored the potential of hydrogen-powered spark ignition engines [31-35], which will be discussed further.

Hydrogen is a potent fuel for internal combustion engines, primarily due to its high ignition temperature and compatibility with high compression ratios. Its unique properties make it an ideal candidate for fuel-injection systems in gasoline engines [36]. When hydrogen is used as fuel, engines typically employ spark plugs with lower energy requirements [37]. Ongoing research and advancements in hydrogen combustion technology for internal combustion engines focus on optimizing hydrogen's use as a clean fuel across various applications while minimizing environmental impacts through improved engine designs. This aims to enhance the overall efficiency of hydrogen utilization in such technologies [38-39]. Innovations in hydrogen combustion technology via internal combustion engines include advanced ignition systems, direct injection methods, intelligent control systems and lean burning strategies. Additionally, flameless hydrogen combustion in a highly diluted oxygen environment allows for a uniform and low-temperature combustion process [40], resulting in a slower combustion rate, reduced NOx emissions and improved efficiency and safety. Furthermore, advanced rotating detonation engines, which utilize continuous detonation waves to combust hydrogen, offer higher efficiency and lower emissions compared to conventional combustion processes [41].

Moreover, hydrogen can also be burned in gas turbines, which ought to be modified to utilize hydrogen for generating electricity in utility-scale power plants or distributed generation systems or for generating mechanical power [16,42]. Hydrogen-enriched gas turbines offer improved efficiency and lower emissions, rendering them suitable for various applications [43]. These turbines are commonly used in power plants and can be paired with steam turbines in combined-cycle power plants to boost overall efficiency. Ongoing research and advancements in hydrogen combustion technology in gas turbines are focused on discovering new applications and improving the effectiveness of hydrogen use in this context. One notable example is fuel cell gas turbines, which integrate fuel cells and gas turbines by using the hot exhaust from a solid oxide fuel cell to drive a conventional gas turbine [44]. This combined system achieves high efficiency and low emissions, making it particularly well-suited for stationary power generation facilities [22].

The combustion of hydrogen involves a reaction between hydrogen and oxygen, facilitated by heat or a flame, which ultimately produces water and releases energy in the form of heat and electricity [6]. This energy can be harnessed in internal combustion engines or gas turbines to generate both heat and mechanical power. Notably, some operators of natural gas power plants are exploring the use of hydrogen as a substitute for or supplement to natural gas. Understanding the fundamental reactions that take place during hydrogen combustion is essential for recognizing its potential as a significant fuel source. A study by Li et al. focused on developing an updated, comprehensive kinetic model of hydrogen combustion, revealing that hydrogen combustion reactions involve a series of chain reactions between hydrogen and oxygen, as well as dissociation and recombination reactions of these gases, along with the formation and consumption of water and hydrogen peroxide [45]. Highlighting its considerable significance, numerous groundbreaking studies have been published over the past decade that elucidate the mechanisms of hydrogen combustion [46-74]. Understanding the oxidation chemistry of hydrogen is vital for both fundamental kinetic research and practical applications in combustion systems, including fire safety, energy conversion and propulsion. The importance of hydrogen as a fuel in these areas highlights the significance of understanding the hydrogen-oxygen reaction mechanism [14,45]. However, a detailed discussion of this topic is beyond the scope of this review paper.

Besides, recent combination of hydrogen fuel and ammonia for combustion engines has emerged as a promising approach to enhance engine performance and lower emissions [79], following the successful application of ammonia as a hydrogen energy carrier [80-87]. This blended fuel presents several advantages over conventional fossil fuels [79] by leveraging the beneficial properties of both hydrogen and ammonia. Hydrogen is recognized for its high energy density and clean combustion characteristics, which contribute to improved combustion efficiency and a reduced environmental footprint [88]. Conversely, ammonia, being carbon-free, has the potential to eliminate the production of carbon dioxide and other harmful greenhouse gases during combustion. While ammonia has a lower energy density than hydrogen and a slower ignition rate, these limitations can be mitigated by incorporating hydrogen into the mixture. This combination leads to a more efficient combustion process, characterized by reduced ignition delays and enhanced flame propagation speeds [89]. However, the use of this blend also presents challenges, including elevated NOx emissions, a high minimum ignition energy and limited flame propagation speed [87]. As flame speed decreases, engine combustion efficiency can decline, and higher NOx levels can lead to environmental concerns. To optimize the combustion characteristics of hydrogen-ammonia blends, it is essential to adjust parameters such as the hydrogen-to-ammonia ratio, equivalence ratio and engine operating conditions. Overall, the use of hydrogen-ammonia blends holds significant promise for improving engine efficiency and minimizing environmental impact in the future [90-91]. The role of ammonia as a hydrogen additive to enhance combustion and increase flame speed while reducing NOx emissions has been the subject of previous investigations, highlighting its importance in this field [92-107].

Numerous investigations have investigated the use of hydrogen-ammonia-methane fuel in internal combustion engines [95-99,108] and gas turbines [95,100-104]. The high heating value of hydrogen can lead to engine knocking in internal combustion engines due to its low ignition temperature, making it unsuitable for use alone or at high blending levels. Consequently, a blend of methane, hydrogen and ammonia appears to be a promising approach to enhance the combustion efficiency of methane-fueled engines [109-110]. Frigo et al. have explored the viability of using ammonia and hydrogen mixtures to power a four-stroke spark-ignition engine. They determined that the minimum energy ratio of hydrogen to ammonia should be 7% at full load and 11% at half load to maintain stable operation and prevent cyclic fluctuations. Under full load conditions, peak NOx emissions were estimated at just 1700 ppm, with higher hydrogen ratios contributing to improved engine stability [105]. Additionally, Bayramoglu and co-workers have used a numerical model to analyze the effects of burning binary and ternary blends of methane with hydrogen and ammonia on combustion chamber temperature and emissions. Initially, blends of methane with 5%, 10% and 15% hydrogen were modeled, followed by mixtures of methane with 5% hydrogen and varying levels of ammonia (5%, 10% and 15%). The introduction of 15% hydrogen to methane raised the chamber temperature by 100 K, while adding 15% ammonia lowered the temperature by 200 K and altered the temperature peak. An increase of 10% in hydrogen content resulted in a 28% rise in NOx emissions, whereas a 10% increase in ammonia led to a 3000 ppm increase in NOx. The addition of 5%, 10% and 15% ammonia to methane-hydrogen blends raised NOx emissions by 1970, 3010 and 3790 ppm, respectively, at a location 0.444 cylinder diameters from the injector. When comparing to pure methane, burning 85% methane, 15% hydrogen and 80% methane, 5% hydrogen and 15% ammonia resulted in reductions of carbon dioxide emissions by 30.7% and 14%, respectively [111].

Additionally, Lhuillier et al. have conducted experimental studies on the performance of hydrogen-ammonia blends as fuel in conventional spark ignition engines. Their results indicated that these blends could be utilized in such engines with minimal modifications [106]. This aligns well with the findings of Stepien, A., who provided a thorough review of hydrogen-fueled internal combustion engines. Furthermore, using hydrogen as a fuel in these engines can lead to enhanced brake thermal efficiencies, attributed to the higher flame speeds of hydrogen. Emissions of hydrocarbons and carbon monoxide are nearly negligible, with trace amounts resulting from the vaporization and combustion of lubricating oil on the cylinder walls. The performance of hydrogen engines outperforms that of gasoline engines. Hydrogen engines demonstrate superior performance compared to gasoline engines, particularly under partial load conditions [112]. Also, recent experimental research by Ji and colleagues has evaluated the emissions and performance of spark-ignition engines fueled by a pre-mixed combination of air, ammonia and hydrogen. The engine operated at a speed of 1300 RPM, with the manifold absolute pressure set to 61 kPa. This study compared pure hydrogen fuel to a mixture containing 2.2% ammonia by volume. The introduction of ammonia led to longer ignition delays, extended flame development periods and a reduced rate of in-cylinder pressure rise; however, the overall performance of the engine remained stable when considering the ignition timing strategy. The addition of ammonia also resulted in increased nitrogen oxide emissions, providing valuable insights for the advancement of hydrogen-fueled engines by suggesting that ammonia may act as a combustion inhibitor [88]. Moreover, Jingding et al. discovered that incorporating hydrogen into a gasoline spark ignition engine reduced hydrocarbon and carbon monoxide emissions compared to a pure gasoline engine [113]. In another study by Changwei, J. and Shuofeng, W., the impact of hydrogen addition on the idle performance of a spark-ignited gasoline engine at stoichiometric conditions was explored under varying operating conditions. The results indicated that blending hydrogen with gasoline enhanced indicated thermal efficiency and reduced most emissions, although there was a slight increase in hydrocarbon and carbon monoxide emissions at hydrogen volume fractions exceeding 4.88% [114]. Furthermore, Rahaman, M. M. and Mohammed, K. R. A. B. have investigated the performance of a single-cylinder spark-ignited engine fueled by hydrogen-gasoline blends, focusing on the effects of air-fuel ratio and engine speed. They found that while brake mean effective pressure and brake thermal efficiency initially increased, they subsequently declined as air-fuel ratios and speeds increased, likely due to hydrogen's lower density and flammability, which reduced volumetric efficiency compared to gasoline [115].

Moreover, Pochet et al. have investigated the application of hydrogen-ammonia fuels in a homogeneous charge compression ignition engine for combined heat and power generation. The high ignition resistance of ammonia promotes stable combustion in such engines. Experiments were conducted using a single-cylinder, constant-speed homogeneous charge compression ignition engine at intake pressures ranging from 1 to 1.5 bar and temperatures between 428 and 473 K. At an intake pressure of 1.5 bar and a temperature of 473 K, stable combustion was achieved with fuel blends containing up to 70% ammonia by volume at an equivalence ratio of 0.28. The efficiency only decreased by 0.6 points when transitioning from pure hydrogen to a blend containing 60% ammonia. However, NOx emissions rose significantly, from less than 6 ppm with pure hydrogen to between 750 and 2000 ppm for hydrogen-ammonia blends [107]. In a related study, Wang and colleagues have examined the combustion characteristics of hydrogen-ammonia blends in a medium-speed marine diesel engine of the type homogeneous charge compression ignition engine, aiming to reduce thermal NOx emissions. They analyzed the ignition properties of these blends by varying the equivalence ratio, hydrogen fraction and intake pressure and temperature. The findings revealed that adding hydrogen increased the laminar flame velocity of ammonia, which likely affected NOx emission levels. The study also suggested that strategies such as lowering combustion temperatures, utilizing exhaust gas recirculation and implementing post-treatment techniques could help reduce NOx emissions [89].

Also, the combustion properties and emissions of hydrogen-ammonia mixtures in a swirl burner were investigated by Valera-Medina et al., aiming to enhance fuel-flexible gas turbines. Their findings indicated that strong swirling flows facilitated stable combustion and low emissions for hydrogen-ammonia blends, although this was limited to a specific range of equivalence ratios [116]. In addition, Zhang et al. have investigated the impact of adding methane and hydrogen on air-ammonia flame emissions in a gas turbine combustor by measuring instantaneous OH profiles and outlet emissions. They found that ammonia-air flame emission trends aligned with 1D modeling when maintained around an equivalence ratio of 1.15. Low blending ratios of 0.1 for methane or hydrogen-enhanced flames did not increase NOx emissions; however, higher equivalence ratios of 0.3 resulted in elevated NOx and carbon monoxide emissions for ammonia-methane blends, while hydrogen showed better performance in emissions control, particularly below 0.3 due to its lower carbon content [117]. Elsewhere, Dinesh et al. have examined the performance of a spark ignition engine fueled by hydrogen-ammonia blends. They varied the compression ratio and hydrogen fraction while operating the engine at different speeds under wide-open throttle conditions. The results indicated that adding hydrogen raised peak temperatures, consequently increasing NOx emissions while decreasing ammonia emissions. To address the high NOx emissions, selective catalytic reduction was suggested as a viable solution [118]. Furthermore, Xin and co-workers have conducted experimental investigations on the effects of ammonia addition on combustion and emissions in hydrogen internal combustion engines. Tests were carried out on a modified engine under part-load and stoichiometric conditions with varying ammonia fractions. The results revealed that increasing ammonia extended the flame development and propagation periods while reducing peak heat release rates, thereby moderating the rapid combustion of hydrogen [119]. All in all, it can be concluded that hydrogen-ammonia blends; in particular, hold significant potential for enhancing engine efficiency and minimizing environmental impact in the future [90-91].

Summary:

Hydrogen combustion is an efficient approach for harnessing clean, green and sustainable hydrogen across various applications, thanks to its unique inherent properties and benefits, as previously highlighted. Furthermore, using hydrogen in internal combustion engines or gas turbines results in high efficiency and low emissions. A key advantage of hydrogen combustion is that one of its main byproducts is water vapor, which significantly lowers greenhouse gas emissions and air pollution compared to fossil fuels [75]. Additionally, hydrogen's high energy content per unit mass facilitates efficient combustion and reduces fuel consumption [17]. Also, integrating hydrogen combustion into existing power generation and heating systems requires only minor modifications, minimizing the need for new infrastructure investments [76]. As the demand for hydrogen increases and infrastructure develops, hydrogen combustion is anticipated to play a more significant role in clean energy applications [22]. However, hydrogen's low volumetric energy density poses challenges for storage and transportation when compared to conventional fuels [14,77]. Moreover, hydrogen's high flammability and broad flammability range raise safety concerns regarding its storage, handling and combustion applications [14,78]. Various factors can influence the flammability range of hydrogen or mixtures containing hydrogen and oxidant(s), including ignition energy, pressure, temperature, the presence of diluents and the design of the equipment. One strategy to mitigate flammability is to dilute these mixtures with another component until the concentration falls below the lower flammability limit [15]. While hydrogen is a promising alternative to gasoline for internal combustion engines due to its high flame temperature and compatibility with high compression ratios, its power output can be constrained by early ignition, unlike the knocking phenomenon encountered in gasoline engines [14]. Furthermore, advancements in hydrogen storage and transportation technologies are essential for the broader adoption of hydrogen combustion across various sectors [22], as current methods for storing compressed gaseous hydrogen require four times the volume of gasoline to deliver the same energy. Also, storing liquid hydrogen also presents challenges related to the transportation and metering of cryogenic fuels [9-12]. Additionally, there are obstacles to using hydrogen or hydrogen-rich blends, such as ammonia and/or natural gas (methane), within existing natural gas infrastructure and combustion equipment systems. While some progress has been made in modifying natural gas burners for high-hydrogen blends in combustion turbines, further research and development are needed before hydrogen can be widely implemented for utility-scale power generation. More studies are also required to assess the compatibility of hydrogen and hydrogen-ammonia-natural gas blends for power generation applications.

3. Conclusions:

Although not exhaustive, this review paper has aimed to explore hydrogen combustion as a fuel for gas turbines and internal combustion engines, with a particular emphasis on both spark ignition and compression ignition engines for electricity and heat generation, as well as other applications. The paper has also discussed the use of hydrogen, ammonia, and methane as fuel blends in these engines. Hydrogen combustion offers an effective method for utilizing clean, green and sustainable hydrogen across a range of applications, owing to its distinctive properties and advantages. Utilizing hydrogen in internal combustion engines or gas turbines leads to high efficiency and low emissions. A significant benefit of hydrogen combustion is that one of its primary byproducts is water vapor, which greatly reduces greenhouse gas emissions and air pollution compared to fossil fuels. Moreover, hydrogen's high energy content per unit mass enhances combustion efficiency and lowers fuel consumption. Additionally, incorporating hydrogen combustion into existing power generation and heating systems requires only minor adjustments, reducing the need for substantial new infrastructure investments. As the demand for hydrogen grows and infrastructure evolves, hydrogen combustion is expected to play an increasingly important role in clean energy solutions. However, hydrogen's low volumetric energy density presents significant challenges for its storage and transportation compared to traditional fuels. Additionally, its high flammability and wide flammability range raise safety issues related to storage, handling and combustion. Although hydrogen is a promising alternative to gasoline for internal combustion engines due to its high flame temperature and suitability for high compression ratios, its power output can be limited by early ignition, which differs from the knocking phenomenon inherent to current gasoline engines. To facilitate the broader adoption of hydrogen combustion across various sectors, advancements in hydrogen storage and transportation technologies are crucial. Furthermore, there are hurdles to using hydrogen or hydrogen-rich blends, such as ammonia and natural gas, within existing natural gas infrastructure and combustion systems. While some progress has been made in adapting natural gas burners for high-hydrogen blends in combustion turbines, further research and development are necessary before hydrogen can be widely utilized for utility-scale power generation. Additional studies are also needed to evaluate the compatibility of hydrogen and hydrogen-ammonia-natural gas blends for power generation applications.

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