HYDROGEN AS FUEL FOR INTERNAL COMBUSTION ENGINES

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Abstract- **This extensive study examines hydrogen's potential as a clean, sustainable fuel for internal combustion engines, solving the rising global energy demand while reducing the negative environmental effects of fossil fuels. The document investigates the use of renewable energy sources, such as wind, for hydrogen generation and discusses the many processes for producing hydrogen, including electrolysis, steam methane reforming, and others. It explores the benefits and drawbacks of the various techniques of injecting hydrogen into internal combustion engines, including carburetion, port injection, and direct injection.**

The emissions of internal combustion engines running on hydrogen are one of the document's main areas of concern. It shows the advantages of using hydrogen as a fuel, helping to cleaner and more ecologically friendly engine running by reducing emissions of carbon monoxide, carbon dioxide, unburned hydrocarbons, and soot. But it also solves the problems brought on by higher nitrogen oxide emissions.

The document discusses the crucial elements of backfire, pre-ignition, and knock in hydrogen-fueled engines and outlines design difficulties caused by the usage of hydrogen, including low energy density, a wide range of flammability, and a fast laminar flame.

It highlights the potential benefits of hydrogen as a sustainable and eco-friendly fuel for internal combustion engines in its promoting the development of a more sustainable energy future. For scientists and engineers working on internal combustion engines that run on hydrogen, the document is a comprehensive resource.

Keywords: **Hydrogen fuel, Internal Combustion Engine, Hydrogen fuel generation, hydrogen fuel injection, Advantages, Limitations, Criticalities.**

INTRODUCTION

The increase in the world's population and the extensive consumption of fossil fuels have led to a substantial rise in the global demand for energy production in the twenty-first century [1]. For instance, in 2008, the total global oil consumption reached 3928 million tons, and projections indicate that it is expected to reach 5300 million tons by 2021 [2,3]. Nevertheless, it's important to recognize that oil is a finite resource, and it is progressively becoming scarcer and more costly to extract and utilize. Transportation vehicles and machinery that rely on fossil fuels for their operation constitute a substantial portion of the overall energy consumption. As of 2018, there were approximately 1.42 billion automobiles and light trucks in use worldwide [4]. These vehicles significantly contribute to the global energy demand, primarily through their reliance on fossil fuels for propulsion.

The diminishing availability of fossil fuels has given rise to an energy crisis. However, internal combustion (IC) engines are expected to maintain their dominance in the transportation and power sectors owing to their flexibility and widespread use. It's important to note that IC engines are versatile and suitable for a wide range of applications. Nevertheless, one of the significant downsides of IC engines is the emission of pollutants that have adverse effects on atmospheric conditions, leading to problems such as global warming. The environmental impact of these emissions has raised concerns and highlights the necessity of transitioning towards more sustainable and environmentally friendly alternatives, like electric vehicles and clean energy sources [5]. Various solutions have been explored to enhance combustion and fuel quality, including the use of biofuels, water, nanoparticles, and other additives [6]. These approaches aim to reduce emissions and improve the overall efficiency of internal combustion (IC) engines. To ensure the long-term sustainability and environmental compatibility of IC engines, the development of "clean-burning" fuels derived from renewable sources is crucial and should be pursued as soon as possible [7]. These renewable and sustainable fuel sources can help reduce the environmental impact of IC engines and make them more environmentally friendly and energy-efficient in the future.

Hydrogen is considered one of the most promising options for addressing future energy requirements [8]. It is environmentally friendly when it is produced through sustainable and efficient processes using renewable sources [9]. One of the key advantages of utilizing hydrogen for transportation is that it promotes a shift towards renewable energy sources while decreasing our dependency on non-renewable fossil fuels [10]. This transition to hydrogen-based energy systems is seen as a critical step in achieving a more sustainable and environmentally responsible energy future.

Hydrogen offers a significant environmental advantage as a fuel because, when used in a fuel cell, it generates only water (H2O) as a byproduct [11]. Furthermore, hydrogen boasts a heating value that is notably higher than that of other common fuels: it is 4 times higher than coal, 2.8 times higher than gasoline, and 2.4 times higher than methane [12]. In terms of specific energy content, hydrogen, as the most abundant element, surpasses fossil fuels, making it an attractive and high-energy-density fuel source [13]. These characteristics make hydrogen a compelling and environmentally friendly option for various energy applications.

Hydrogen, owing to its distinctive properties, is better suited for use in spark ignition (SI) engines rather than compression ignition (CI) engines [14,15]. For instance, the adiabatic flame rate of hydrogen is significantly higher than that of gasoline, which enhances combustion stability [15,16]. Additionally, hydrogen possesses a significantly greater diffusion coefficient compared to gasoline, resulting in a more uniform mixture of air and fuel in the combustion process. Numerous studies have been conducted on the use of hydrogen in spark ignition engines [17,18]. These studies have encountered challenges such as low volumetric efficiency and decreased power density. Addressing these issues is essential to fully harness the potential of hydrogen as a clean and efficient fuel for SI engines.

Considering the significance of hydrogen fuels as renewable and environmentally friendly options for internal combustion engines, it is crucial to investigate their impact on both spark and compression ignition engines. The objective of this research is to explore the viability of using hydrogen as a fuel for both types of engines and to assess the limitations and critical factors associated with the use of hydrogen as a fuel source. This examination aims to provide insights into the potential advantages and challenges of hydrogen as a clean and sustainable fuel for internal combustion engines.

Methods to produce hydrogen

Hydrogen does not exist in its pure form in nature, especially in the Earth's atmosphere. However, it can be produced from various hydrogen-containing compounds, which include fossil fuels, hydrogen sulphide, biomass, and water. To obtain hydrogen, it is necessary to first separate it from the other elements present within these compounds [19]. This process of hydrogen production can be achieved through various methods, with one of the most common being the electrolysis of water, which breaks down water into its constituent elements, hydrogen, and oxygen.

Electrolysis is the method of dividing water into its components, hydrogen, and oxygen, using electricity. This process is often referred to as hydrogen generation. In an electrolyzer, an electrolyte substance serves as a separator between the anode and the cathode. Various types of electrolyte materials and the ionic species they conduct are used in different electrolyzers, leading to variations in the functioning and performance of these devices [20]. The choice of electrolyte and the specific design of the electrolyzer can impact the efficiency and effectiveness of the hydrogen generation process.

Recently, research has been done on hydrogen wind systems based on the electrolysis of water with wind energy to generate the electricity required by this method using a renewable wind source. In this context, renewable energy sources such as wind energy are harnessed as a sustainable energy option. Through this technology, electricity generated from renewable sources can be transformed into hydrogen, which serves as a carbon-neutral energy carrier without emitting greenhouse gases. This approach aligns intending the environmental impact of energy production and consumption.
[21,22].

There are some other methods also which can be used to produce hydrogen. Some of them are listed below.

1. Steam Methane Reforming
2. Coal Gasification
3. Biomass Gasification
4. Microbial Biomass Conversion
5. Thermochemical Water Splitting Cycles

Types of Hydrogen injection method in IC engines

The construction of hydrogen engines closely resembles that of conventional internal combustion engines. However, several modifications to the fuel delivery system and combustion system are necessary to address specific challenges such as low power output, elevated NOx emissions, and uneven combustion [23]. Under stoichiometric conditions, hydrogen typically constitutes about 30% of the combustion chamber [24]. Three distinct fuel delivery techniques described below have been examined to assess their potential for use in hydrogen fuel cells. These approaches are aimed at optimizing hydrogen utilization and improving the overall performance of hydrogen engines.

Carburetion Injection

In hydrogen engines, the use of a gas carburetor, an established and efficient technique, offers distinct advantages. This method is advantageous because it can be applied to convert a gasoline engine into a hydrogen engine. The gas carburetor, commonly used in gasoline engines, can be adapted to facilitate the hydrogen fuel gasification process. In this approach, the air-hydrogen mixture is regularly introduced into the engine's intake manifold. A valve controls the proportion of hydrogen-enriched air that combines with the air to power the engine. Some engines may require the addition of water in this process. However, it's important to note that this method may also result in engine issues such as pre-ignition, backfiring, and knocking since the air-fuel ratio remains constant [25,26]. Figure 1 illustrates a schematic representation of the fuel carburetion process in action [27].

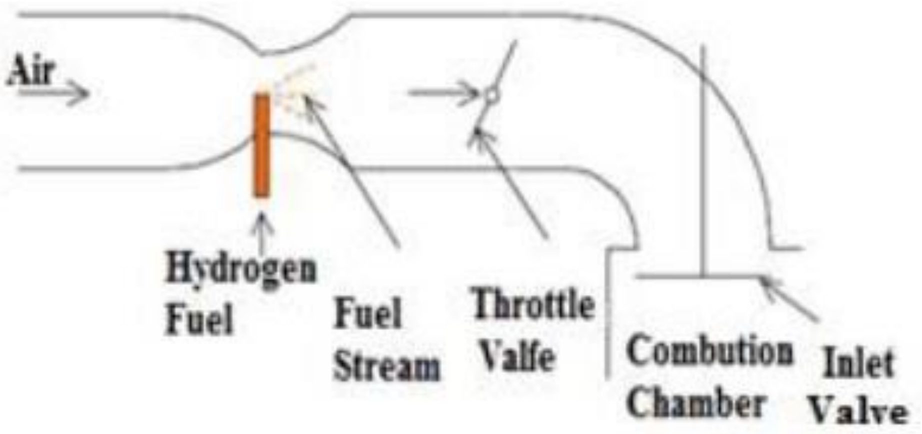

Figure 1: Carburation technique of hydrogen injection in IC Engine [28].

Port Injection Method

The intake port injection process, as shown in Figure 2, involves delivering hydrogen to the cylinder using mechanical or electrical injectors. These injectors can operate at variable rates and effectively mix hydrogen with the incoming air from the intake manifold. This method of hydrogen injection eliminates the adverse effects associated with the carburetion technique, including issues like premature aging, contraction, and shock formation [29,30]. Intake port injection provides a more controlled and efficient way of introducing hydrogen into the engine, leading to improved performance and reduced drawbacks compared to older carburetion methods.

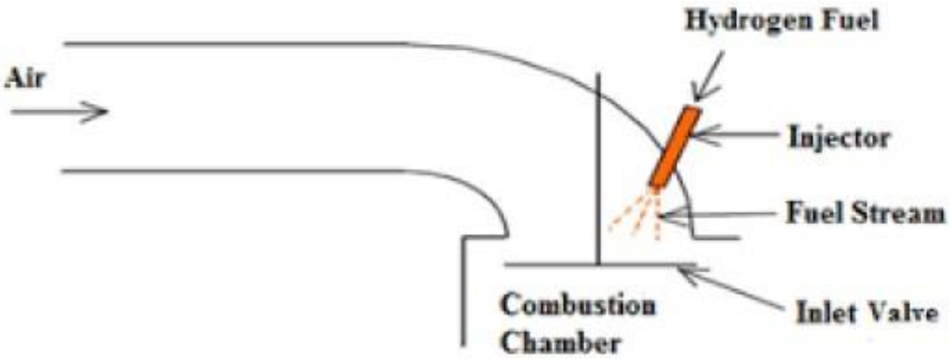

Figure 2: Direct port hydrogen injection [31]

Direct Injection Method

In the direct-injection system, hydrogen is introduced directly into the combustion chamber after the intake valve closes and compression occurs in the cylinder. This process is similar to multiple injections. Because of hydrogen's rapid diffusion, it quickly mixes with air and can serve as a source of ignition for the spark plug [32]. Direct-injection hydrogen engines outperform the other two technologies in terms of performance and efficiency. However, it's worth noting that in hydrogen direct-injection engines, challenges like excessive auto-ignition temperature, pressure increase, and combustion delay may occur [33]. Figure 3 provides a visual representation of the direct injection mode. This approach offers advantages in terms of combustion control and overall engine performance.

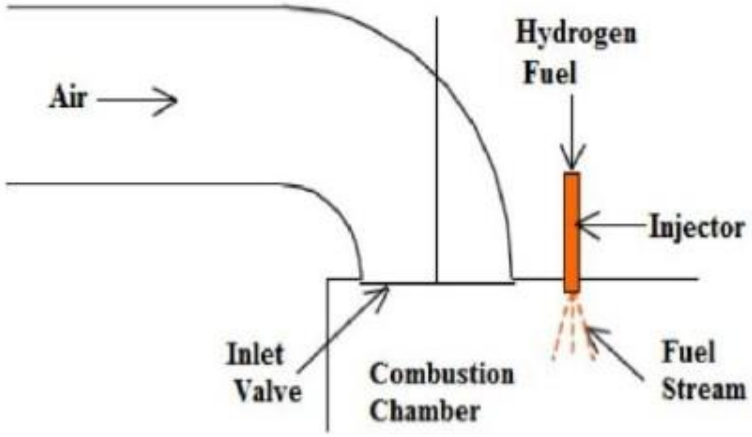

Figure 3: Direct Injection system [34]

Emissions of hydrogen-powered Internal Combustion Engine

Gasoline engines emit hazardous pollutants such as hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx). Hydrogen exhibits distinctive combustion properties that contribute to the complete combustion of these pollutants when used in conjunction with gasoline [35]. Diesel engines, on the other hand, emit even more harmful emissions, including nitrogen oxides (NOx), unburned hydrocarbons (UHC), carbon monoxide (CO), and soot. One of the advantages of using hydrogen as a motor fuel is its ability to reduce emissions. In fact, the combustion of hydrogen does not produce harmful chemicals, making it a cleaner and more environmentally friendly alternative to traditional gasoline and diesel fuels. The use of hydrogen as a motor fuel aligns with efforts to reduce air pollution and promote cleaner transportation technologies.

CO Pollutant

Incomplete combustion in an engine can result in the formation of carbon monoxide (CO) [36], a harmful pollutant. However, the introduction of hydrogen into internal combustion engines can significantly reduce carbon monoxide emissions in both compression ignition (CI) and spark ignition (SI) engines. Figure 4 illustrates the reduction of carbon monoxide emissions when hydrogen is used as a fuel in diesel, showcasing the environmental benefits of hydrogen as an engine fuel. This reduction in CO emissions is a positive step towards cleaner and more efficient engine operation.

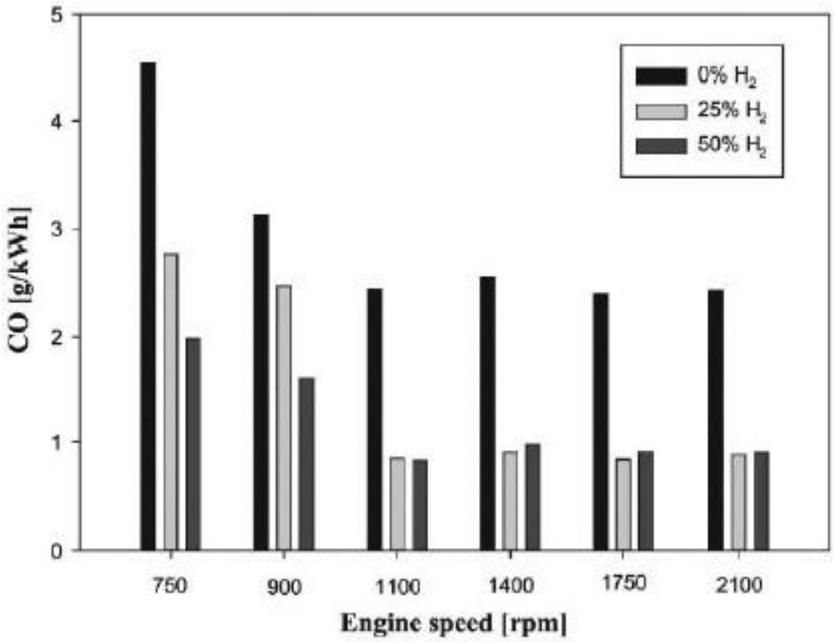

Figure 4: Reduction in CO emission by using different amounts of hydrogen [37].

CO_2 Pollutant

The production of carbon dioxide (CO2) can occur when there is insufficient oxygen and low temperatures in the combustion chamber, which is detrimental to the environment due to its contribution to global warming [38]. However, hydrogen, being a clean fuel, does not emit CO2 and consequently reduces CO2 emissions [39]. Researchers have documented instances of emission reductions resulting from the use of hydrogen, as depicted in Figure 5. These reductions underscore the environmental benefits of hydrogen as a fuel, particularly in terms of mitigating the impact of CO2 emissions on global climate change.

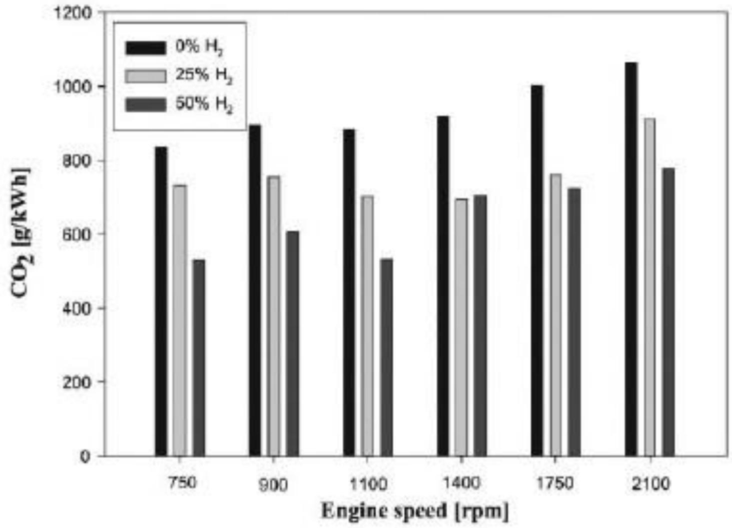

Figure 5: Reduction in CO_2 emission by using different amounts of hydrogen [37].

Unburned Hydrocarbons Pollutant

Hydrocarbons that do not undergo complete combustion within the combustion chamber will result in the emission of unburned hydrocarbons (UHC) in the exhaust gases [40]. Because hydrogen fuel does not contain hydrocarbons, its inclusion in combustion engine fuels leads to a reduction in the emission of unburned hydrocarbons. Reduced UHC emissions are apparent in Figures 6 and 7 for diesel and gasoline engines, indicating the positive impact of hydrogen on decreasing these harmful emissions. This reduction contributes to cleaner and more environmentally friendly engine operation.

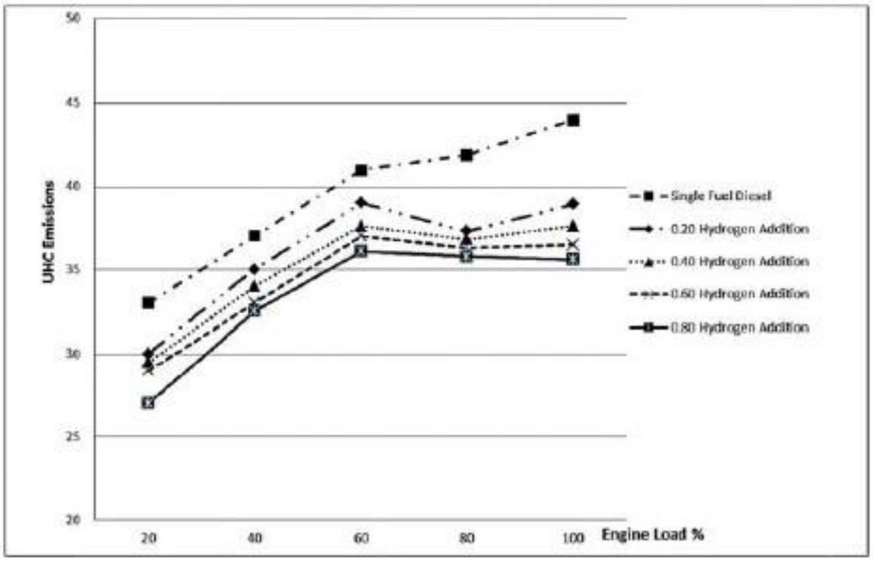

Figure 6: UHC emissions in diesel engines using hydrogen fuels [41]

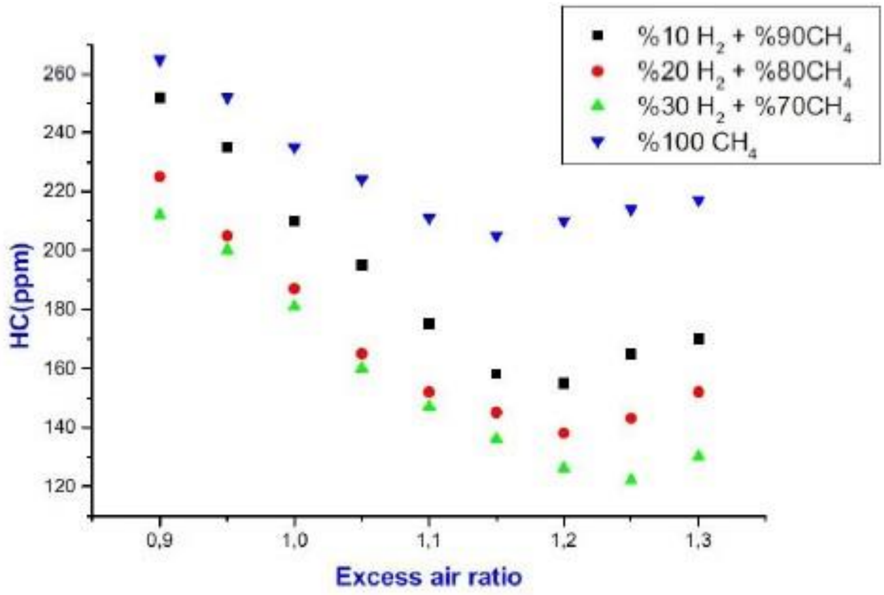

Figure 7: UHC emissions in petrol engines using hydrogen fuels [42]

NO_x Pollutant

Nitrogen oxides (NOx) are generated as a result of the high temperatures attained during the combustion process within the combustion chamber. In the presence of heat, some of the nitrogen in the air combines with oxygen, leading to the formation of NOx. Hydrogen, due to its characteristics like a fast flame speed, low ignition energy requirement, and high adiabatic temperature, is considered an appropriate fuel for combustion. However, these features can contribute to elevated temperatures in the working fluid within the cylinder, resulting in an increase in NOx emissions, as shown in Figure 8. Reducing NOx emissions while taking advantage of hydrogen's combustion benefits remains an important area of research and development.

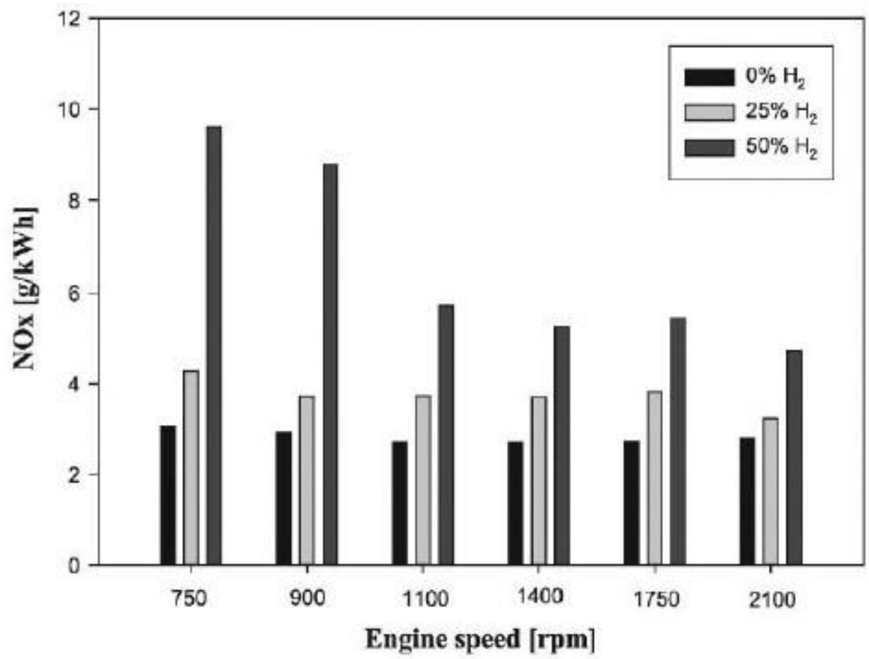

Figure 8: NO_x emissions using hydrocarbon as fuel in Diesel engines [37]

Shoot Emissions

Soot emissions are predominantly associated with diesel engines. These emissions arise from the heterogeneous nature of diesel combustion, where there is a broad range of fuel-to-air ratios within the cylinder. Soot formation primarily occurs in the fuel-rich zone, characterized by high temperatures and pressures. Soot is a characteristic byproduct of fuel-air mixtures that are either too lean to auto-ignite or sustain a propagating flame. Figure 9 illustrates instances of soot reduction achieved through the utilization of hydrogen in diesel engines.

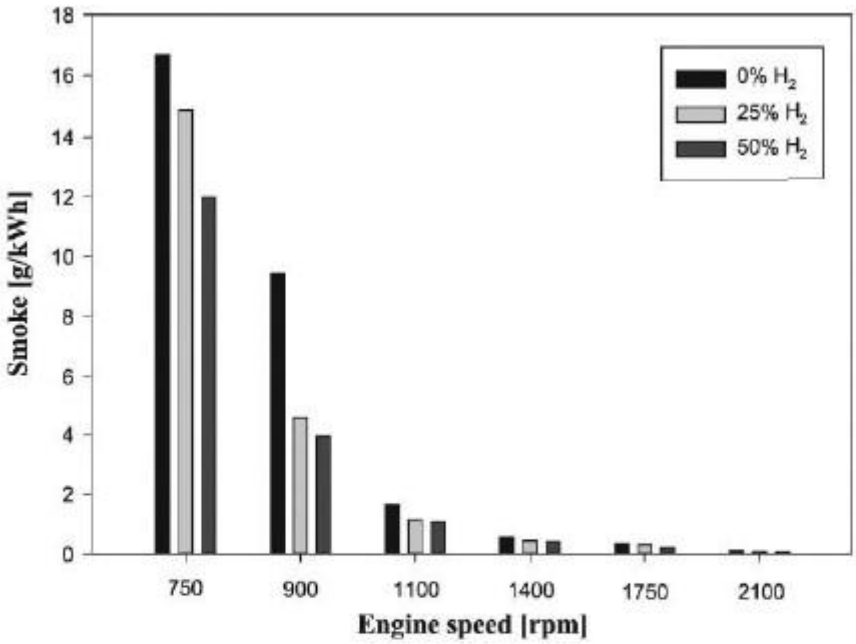

Figure 9: Shoot Emission using hydrogen fuel in diesel engines. [43]

Criticalities for hydrogen as a fuel

Due to the unique properties of hydrogen, hydrogen-fueled engines can exhibit abnormal combustion phenomena. These include spontaneous ignition during the intake stroke (backfire), premature uncontrolled ignition (pre-ignition), and self-ignition of the end-gas region or excessive flame rates (knock) [44,45]. While it is often assumed that the low ignition energy of hydrogen is the primary cause of backfire, research indicates that ignition by thermal masses (such as valves) is more related to the autoignition temperature of the mixture, which is very high.

Instead, some researchers argue that the reduced quenching distance, combined with the wide flammability limits of hydrogen, and the resulting combustion in the piston top land, is a parameter that is sometimes overlooked. Therefore, the exact reasons behind the occurrence of spontaneous and uncontrolled ignition in hydrogen-fueled engines remain a topic of ongoing debate and study [44]. Understanding and addressing these combustion challenges is crucial for the safe and efficient use of hydrogen as a fuel in internal combustion engines.

Design challenges for hydrogen-fueled engines.

Hydrogen as a fuel presents several unique challenges for its use in internal combustion engines:

- Low energy per unit volume: Hydrogen gas has a low density, which means it contains low energy per unit volume. To address this, high-pressure storage tanks, typically operating at 700 bar, are commonly used to store hydrogen [46].
- High flammability range: Hydrogen has a wide flammability range, with an equivalence ratio in air ranging from 0.1 to 7.1. It also possesses a very low minimum ignition energy, which makes it susceptible to uncontrolled ignition due to hot spots and hot gases acting as ignition sources. Although hydrogen direct injection (DI) can help solve the issue of pre-ignition in the intake manifold, there remains a risk of detonation in the cylinder due to the high speed of the flame and the resulting rapid pressure increase during combustion [47,49].
- Very high laminar flame speed: Hydrogen has a significantly higher laminar flame speed (LFS) compared to gasoline, ranging from 3 to 5 times faster. This high LFS is observed across a wide range of equivalence ratios, from 0.5 to 3.5. To control combustion, a maximum equivalence ratio value of 0.6 in air is often imposed, which helps reduce nitrogen oxide emissions and prevents pre-ignition [47].
- Very low quenching distance: Hydrogen flames have a short quenching distance, meaning they travel closer to the cylinder wall before extinguishing compared to other fuels. They ignite rapidly and are relatively short-lived [46].
- High diffusivity: Hydrogen's high diffusivity enhances the homogenization of the mixture, but it makes stratifying the mixture more challenging [50].

These unique properties and challenges associated with hydrogen as a fuel require careful consideration and innovative engineering solutions when implementing hydrogen-fueled engines to ensure safe and efficient operation.

The main drawbacks are the high NOx emissions which mainly depend on the spark timing and the homogeneity/stratification of the mixture [46] and low power output: several research efforts have been conducted by many authors to establish the relationship among NOx, air-to-fuel ratio and spark timing for engines fueled only by hydrogen [51,52] or fueled with the addition of hydrogen [53]. BMW has been working on a bi-fuel engine (gasoline plus hydrogen) [54] but reduced the compression ratio to 9.5 to allow the gasoline engine to run on hydrogen.

Conclusion

In conclusion, hydrogen represents a promising solution to address the growing global demand for energy in the 21st century while mitigating the environmental impact associated with fossil fuels.

Hydrogen, when produced using renewable sources, offers several key advantages. It is a clean fuel, generating only water as a byproduct when used in fuel cells, and boasts a high energy density compared to common fossil fuels. Its unique properties, such as a higher adiabatic flame rate and greater diffusion coefficient, make hydrogen well-suited for use in spark ignition engines, although challenges remain, including addressing low volumetric efficiency and power density. The use of hydrogen can significantly reduce emissions of harmful pollutants like carbon monoxide, carbon dioxide, unburned hydrocarbons, and soot, contributing to cleaner and more environmentally friendly engine operation. However, it can lead to increased nitrogen oxide emissions, necessitating further research and development to control these emissions effectively.

Despite the challenges, the ongoing exploration of hydrogen as a fuel for internal combustion engines and the development of innovative engineering solutions are crucial steps toward achieving a sustainable and environmentally responsible energy future. Hydrogen holds great promise as a vital component of the transition away from fossil fuels, promoting cleaner transportation technologies and reducing the environmental impact of energy production.

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