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Implementation of Hydrogen as a Green Fuel in Internal Combustion Engines: A Brief Review

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***Abstract* - Hydrogen has long been recognized as a revolutionary component in the transition to a post-carbon era. However, there is significant debate regarding the exact nature of this future, with some expressing concerns about insufficient demand, while others overlook the limitations of hydrogen. The recent crisis in fossil fuel supply has been driven by the massive and steadily increasing consumption of non-renewable energy due to human daily activities. The development of alternative energy sources to complement or reduce the reliance on conventional non-renewable energy is further motivated by growing concerns over emissions from internal combustion engines. In this context, hydrogen has emerged as a promising solution for use in internal combustion engines to address these challenges. The primary contribution of this review is to provide a comprehensive overview of hydrogen utilization as a fuel in internal combustion engines, specifically examining its application in both spark-ignition (SI) and compression-ignition (CI) engines. The majority of studies indicate that hydrogen-enriched fuels significantly enhance engine performance, particularly in terms of thermal efficiency, fuel consumption, and energy utilization.**

Keywords: Hydrogen, Green Fuel, Internal, Combustion Engine, Renewable.

I. Introduction

Hydrogen is an efficient energy carrier and emission-free candidate to supersede the continuous use of fossil fuels in future because of its high mass-energy density, fast kinetic rate of electrochemical reaction and only water-containing emission gas[1]. Hydrogen gas (H_2) can be produced from biomass gasification, steam reformation of fossil fuel, coal gasification, partial oxidation of hydrocarbons and biomass fermentation [2].

Global energy-related CO_2 emissions in 2019 totalled 33.3 metric gigatons (Gt) annually, and they are expected to continue to grow at a rate that will cause the Earth's temperature to rise by several degrees without human intervention. Since fossil fuels account for the majority of CO_2 emissions, particularly in the sectors of power, buildings and heating, transportation, and industry, it is challenging to reduce emissions in the energy-related sectors. As a result, many nations have been pushing for the adoption of renewable energy technologies, which could result in the sourcing of clean energy for many end-use processes. However, many sectors continue to be difficult to decarbonize by electricity alone due to the variety of uses for fossil fuels [3].

The demand for non-renewable fossil fuels is still rising daily although fossil fuel supplies are limited and finite. This is because so many aspects of daily life, such as the production of electricity, transportation, and other industries, depend heavily on fossil fuels. According to reports, in 2017, Global consumption of oil, natural gas, and coal all increased at the same time, reaching 4622, 3165, and 3732 million tonnes of oil equivalent, respectively [4]. The International Energy Agency recently announced that by 2030, the world's energy needs will have doubled. The amount of power used and the size of the human population are correlated.

The US Energy Information Administration (EIA) reports that as the world's population grows, so does the energy demand. By 2030, the population of the world is anticipated to triple. Over the next 30 years, the energy demand will rise by 47%, primarily as a result of population growth and economic development in developing Asian nations. This will call for more oil and natural gas production if neither technology nor law are significantly advanced. By 2050, liquid fuel will provide 28% of the world's energy needs compared to renewable energy sources 27%. In comparison to the 2020 values taken into account in this scenario, a 36% increase in liquid fuel requirements and a 165% increase in renewable energy sources are anticipated. Although advanced and developing economies are experiencing a decline in carbon and energy intensity, the EIA anticipates an increase in energy-related carbon dioxide emissions between now and 2050 [5].

One of the most promising alternative fuels is hydrogen. Internal combustion engines powered by hydrogen have received a lot of attention from researchers due to their characteristics as clean burning fuels and availability from renewable sources. Hydrogen's high diffusivity aids in reducing the spray's heterogeneity sothe combustible mixture becomes more uniform as a result. Additionally, hydrogen has a higher laminar flame speed than hydrocarbon fuels, which enhances combustion[6]. Neither carbon nor sulphur can be found in hydrogen. This means that when the hydrogen is burned in a combustion chamber, significant pollutants like hydrocarbons (HC), carbon monoxide (CO), sulphur dioxide (SO2), lead, smoke, particulate matter, ozone, and other carcinogenic compounds don't occur.

II. Hydrogen Production Approaches

Hydrogen is a colourless, odourless and zero (harmful) emission fuel when burned with oxygen. The combination and reaction of two hydrogens and one oxygen atom lead to energy release and water formation only. This reaction can take place either in the form of a chemical reaction with the help of a fuel cell's anode or by combusting the fuel at high pressure and temperature conditions.

One of the main advantages of hydrogen fuel is its large energy content. Hydrogen's energy density is one of the highest among the commonly used fuels for internal combustion engines. For instance, compared to diesel and gasoline fuels, 1 kg of hydrogen can produce almost three times as much energy. However, the significantly low density of hydrogen gas raises significant concerns about the amount of storage space needed to power a car for a sufficient driving distance. Additionally, the low energy density of the fuel reduces the energy density of the hydrogen-air mixture inside an engine's cylinder chambers, which may result in a low power output.

The wide flammability range of hydrogen fuel makes it suitable for engine operation over a wide range of air-fuel mixtures, even at extremely low equivalence ratios of $\varphi = 0.1$. The lean mixture operation can also increase the fuel economy of the hydrogen-fuelled engine due to complete combustion inside the cylinder chambers with fewer fuel residuals. Moreover, its high diffusivity and flame speed result in a faster uniform mixture of fuel and air and an improved combustion of a wide range inside the cylinder. On the other hand, the high auto-ignition temperature of the fuel necessitates the implementation of a combustion trigger such as a spark or a supplementary low auto-ignition temperature fuel. Also, hydrogen's low ignition energy demand often leads to the production of knocking or detonation of the engine [7].

Due to its renewability and environmentally friendly characteristics, hydrogen is regarded as the most suitable alternative energy to replace traditional fossil fuels. Both in elemental and molecular form, hydrogen does not exist in nature; it must be extracted further from other compounds. Low density and viscosity are its main characteristics, which also predominate when hydrogen is present in gaseous form. Most hydrogen productions are based on hydrogen-rich compounds, such as fossil fuels, due to the lower cost. In contrast, there are currently concerns and demands to lessen our reliance on fossil fuels. Previous studies found that photocatalysis, thermochemical cycles, and water electrolysis could all be used to produce hydrogen [8].

2.1 Coal gasification

Coal is one of the market’s most widely known fossil fuel, and its production cost is comparably low. However, there is no denying that the direct burning of coal for energy production increased environmental pollution and accelerated climate change. Utilizing coal gasification will help to reduce this issue. The solid coal is transformed into a gaseous mixture that primarily contains hydrogen, carbon monoxide (CO), methane, and other hydrocarbons through chemical and thermal processes. Given that it makes up one-fifth of the hydrogen production line in today's industries all over the world, coal gasification is one of the frequently used processes for producing hydrogen from fossil fuels. This method has a significant drawback because greenhouse gases, particularly CO_2 emissions in greater amounts, tend to be released into the atmosphere during the production processes [9].

The use of technologies like carbon capture, storage, and sequestration, however, can stop this phenomenon. In addition, although the process is more difficult and expensive, it is possible to produce less hazardous gases through processes that increase energy efficiency [10].

2.2 Biomass gasification

The process of burning biomass, such as plant crops and wood waste, at a high temperature while using oxygen and steam is known as biomass gasification [11]. Temperature, dry matter content, and catalysts are a few significant factors that affect biomass gasification. The most promising method to increase hydrogen conversion rates and decrease char and tar formation is said to be supercritical water gasification. In particular, supercritical water is used as the medium in supercritical water gasification to transform biomass into hydrogen gas. It has temperature and pressure characteristics that are higher than 374 °C and 22.1 MPa, respectively. As a result, producing hydrogen through biomass gasification is almost completely safe for the environment and emits fewer greenhouse gases[6].

2.3 Water electrolysis

Water electrolysis is a process of decomposing the chemical elements in salt water by passing the electric current through the two electrodes immersed in the electrolyte [13]. Therefore, hydrogen and oxygen gas can be produced at the cathode and anode respectively by using water as the electrolyte. For instance, alkaline electrolysis is considered one of the most common techniques used in the water electrolysis industry [14]. This process is green and safe since it does not emit hazardous gases to the environment [15]. Besides, hydrogen produced through electrolysis is clean and has high purity. The electrolysis process is irreversible and hydrogen can be directly collected at the cathode without mixing with other gaseous products.

2.4 Steam reforming by using natural gas

It was reported that around four-fifths of the hydrogen gas is produced from natural gas and by-products of an industrial process [16]. Methane and ethane are the two main components that make up natural gas, and hydrogen can be extracted by going through steam reforming processes [17]. Notably, the experimental temperature has to be high enough (e.g. 800 ◦C) for the endothermic process to occur for the production of hydrogen gas. Usually, a second stage process is carried out in the presence of excess steam by using a water–gas shift reactor for the further reaction of carbon monoxide with the steam to form more hydrogen gas, along with carbon dioxide gas as the by-product [18].

Turchetti et al [19], recently discovered a new technology. They asserted that because the multi-stage processes had been consolidated into a single stage, the membrane reforming process could be carried out at a lower temperature than the conventional approach. When compared to the previous method, the new technique is more advantageous due to its lower production costs and carbon monoxide content. However, for better hydrogen production, several variables must be optimized. For instance, catalysis, hydrogen separation and heat exchange.

2.5 Photochemical water-splitting

Greater hydrogen production should be established due to the high demand for hydrogen as a fuel replacement, especially through environmentally friendly methods. As seen in Figure1, photochemical water-splitting uses specialized semiconductors made of photochemical materials to split water into hydrogen and oxygen. Due to its reliance on free solar energy and zero emissions, this strategy is widely hailed as a sustainable energy option with complete environmental advantages. In addition to pure water, the photo-electrochemical production of hydrogen from seawater has been proposed as a way to lessen the burden of the world's water shortage issue [20].

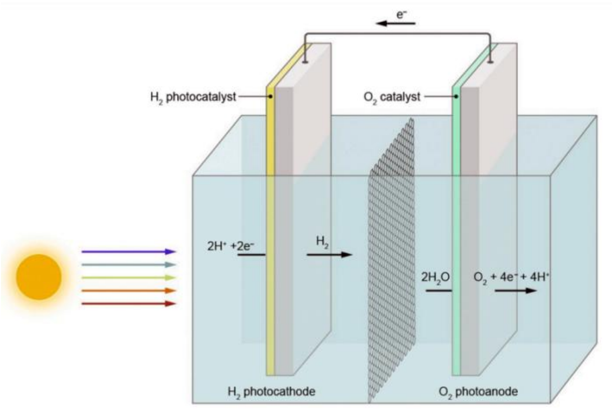

Figure 1: Schematic of a tandem photo-electrochemical cell. The photocathode where H_2O is reduced to H_2, and the photo anode, where water is oxidized to produce O_2 [22]

III. Implementation in Spark Ignition (SI) Engine

3.1 Special designs and modifications from traditional SI engine

A lot of work is being carried out on the utilization of various alternative fuels in internal combustion (IC) engines due to several limitations with fossil fuels and stringent emission norms. These two issues are the main reasons, which encouraged the utilization of various gaseous fuels such as biogas, compressed natural gas (CNG), hydrogen blended CNG, and hydrogen in both, compression ignition (CI) and spark ignition (SI), type of IC engines [22].

Due to differences in physiochemical properties between hydrogen and common fuels used in SI engines such as gasoline, alcohols, compressed natural gas (CNG) and liquid petrol gas (LPG). engine modifications are usually needed to successfully operate H_2ICE. Besides, when redesigning H_2ICE from conventional gasoline or dieselengines, a hydrogen fueling system is needed as hydrogen presents in a gaseous state even if it is usually compressed for engine uses as compared to liquid gasoline. Besides, hydrogen utilization as an ICE fuel also demonstrates its susceptibility to abnormal combustion phenomena including pre-ignitions, backfire, knock and spontaneous ignitions as reported in previous research ever since the idea was first introduced.

Hydrogen is an excellent alternate fuel for spark ignition engines with its highly desirable properties. When the hydrogen fuel is mixed with air to produce the combustible mixture for a spark ignition engine at an equivalence ratio below the lean flammability limits of gasoline results intoultra-lean combustion produces low flame temperature and leads directly to lower heat transfer to the walls, higher engine efficiency and lower exhaust of NOx emissions [23].

3.2 Effects of hydrogen-fuelled SI engine

3.2.1 Engine performance

Performance and emission analyses on a four-cylinder MPFI SI engine running on gasoline blends containing up to 10% hydrogen were performed by Chitragar et al. [24]. Improvements in BTE, engine brake power, and BSFC were noted by the authors. Overall, BTE and brake power production showed rising trends as hydrogen content in blends rose to 8%. As less air was present in the intake gas with higher hydrogen content, a higher level of 10% hydrogen blend showed reductions in BTE and brake powerasaresultof improper combustion. At 3000 rpm, the maximum BTE showed an improvement of 5.78%, and the highest brake power showed an improvement of 11.8% over base gasoline. The volumetric efficiency of the fuel also decreased across all engine speeds when more hydrogen content was present in the blends. This was attributed to the lower density of hydrogen than air that displaced cylinder volume more rapidly and caused lower mixture density.

An investigation into the combustion and emission characteristics of a dual-fuel SI engine fitted with hydrogen direct injection and port fuel injection systems for RON 97 gasoline. The experiments used 99.995% pure hydrogen fuel and were run at constant 1500 rpm, 14% throttle opening, and 6 MPa injection pressure. To blend and test up to 11.09% hydrogen by volume, the air-fuel equivalence ratio was changed to 1.0, 1.1, 1.2, and 1.5 as shown in Figure 2. With a higher hydrogen fraction used, the experimental results showed rising trends in mean effective pressure and engine thermal efficiency. The higher the hydrogen content in fuel, the faster the combustion occurs. The maximum thermal efficiency was observed at an equivalence ratio of 1.2 for 11.09 % hydrogen fraction, which was 7.4 % higher than the thermal efficiency achieved with a stoichiometric mixture. Another benefit noticed for the direct injection of hydrogen was higher volumetric efficiency recorded due to a rise in total in-cylinder fuel energy content by the addition of greater heating value hydrogen [25].

3.2.2 Exhaust emissions

NOx emission from SI engines generally increased when hydrogen was involved and combusted in SI engines due to higher adiabatic flame temperature caused by rapid flame propagation and high combustion rate. Emission characteristics from hydrogen operations also marked lower CO, HC and CO_2 emissions compared to SI engines fueled by hydrocarbon fuels such as gasoline and CNG. In fact, due to the absence of carbon elements in hydrogen, the combustion of hydrogen is expected to result in only NOx emission. However, high temperatures involved during combustion in engine cylinders may cause the oxidation or burning of lubricant oil in engine cylinders and thus cause unexpected emissions [26].

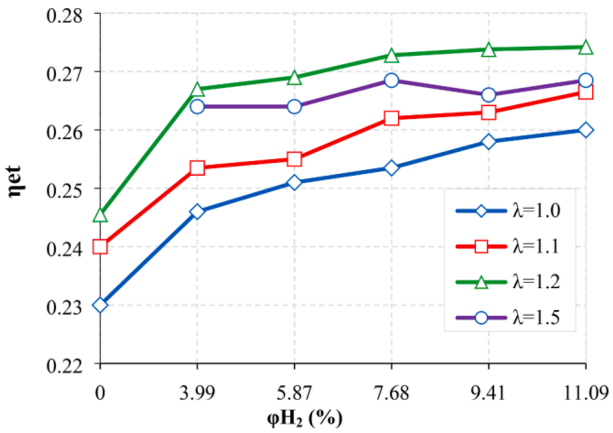

Figure 2: Effective thermal efficiency versus hydrogen addition fraction at different equivalence ratios [24]

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When higher hydrogen content was used in the blends, however, HC and CO_2 emissions from the engine decreased while CO and NOx emissions increased. HC and CO_2 emissions decreased on average by 21.5% and 14.76%, respectively, while CO and NOx emissions increased by 62.03% and 32.56%, respectively. Less HC was produced by hydrogen-enriched gasoline fuels due to short quenching distance and reduced crevice effect, while low CO_2 was produced due to the lack of carbon in the fuel blends. However, incomplete charge homogeneity along with hydrogen's propensity for rapid combustion may have contributed to an increase in CO emission. Besides, the results obtained by Tangoz et al. [27] also showed satisfactory engine emissions, such that HC and CO emissions produced were within the Euro 5 emission standards. The lowest HC emission was generally achieved by blending 5% hydrogen with CNG fuel, while the effect of hydrogen addition was not prominent in CO emissions. Nonetheless, near zero CO emissions were noticed when the engine was run with higher excess air ratios. In addition, hydrogen addition was found to increase the NOx emission from the test engine, especially in leaner mixtures. However, the NOx emission could also be reduced by retarding the ignition timing [27].

3.2.4 Combustion characteristics

Hydrogen combustion was reported to result in high combustion stability as indicated by the lower coefficient of variance (COV) of IMEP and maximum cylinder pressure in SI engines. As reported by Navale et al. [28], a higher combustion rate of hydrogen as a fuel in SI engines also resulted in relatively higher peaks of heat release rate (HRR) and pressure in comparison to baseline gasoline combustion. Pana et al. [29] also noticed an increment in peak pressure when a higher amount of hydrogen was added to the gasoline fuel in the SI engine.

The combustion process in the cylinder took place at a significantly higher temperature and pressure due to hydrogen’s superior flammability and higher flame propagation speed. However, when more than 20 % of the fuel was taken up by hydrogen, the peaks of heat release rate and cylinder pressure were decreased because of reduced volumetric efficiency [28].

Even when only a small amount of hydrogen was added, it had a significant impact on improvements in combustion characteristics. All HCNG fuels recorded lower exhaust gas temperatures than pure CNG operations. Higher cylinder pressure and HRR peak values were also seen after the addition of hydrogen. According to Aydin and Kenanoglu's research [30], pure hydrogen starts to burn considerably earlier than all other fuels. Due to its faster flame and greater flammability, hydrogen also produced the highest peak pressure and peak heat release rate, as well as the shortest ignition delay.

When hydrogen was added to gasoline, the combustion of hydrogen-gasoline blends exhibited advancements in ignition, combustion and pressure rise timings, which may be explained by the lower ignition energy of hydrogen in the blends. Besides, when a higher hydrogen fraction was used in the fuels, the value of maximum in-cylinder pressure was increased.Moreover, in terms of combustion characteristics, Tangoz et al. [27] observed increasing advancements in-cylinder pressure and heat release curves when more hydrogen was blended with CNG, due to hydrogen’s high flame propagation speed. For instance, when the engine was operated at 2500 rpm at stoichiometric conditions and 10^{o}BTDC ignition timing, the positions of occurrence of peak heat release were 20.04^{o}ATDC, 17.04 ^{0}ATDC, 14.03^{0}ATDC and 11.6^{0}ATDC for CNG, HCNG5, HCNG10 and HCNG20 respectively.

Analysis of hydrogen-fuelled turbocharged SI engine and based on the analysis they reported that the waste heat recovery could increase the thermal efficiency of the engine theoretically above 59%. The CNG with varying percentages of H$_2$ was used as fuel in a twin-cylinder SI engine with varying speeds (from 1500 to 3100 rpm) under full load conditions [31].

All hydrogen-enriched fuels released heat at a higher rate and higher intensities. Lower spark advance was required for the hydrogen-enriched fuels at MBT timing due to accelerated combustions, whereas significant advances and increments in heat release could be seen for hydrogen-blended methane fuels at equal spark timing. However, there was a trade-off between improving heat transfer and increasing engine efficiency because of how close the flame fronts were to the cylinder wall. The summary of hydrogen's effects on combustion properties when used as SI engine fuel.

IV. Implementation in Compression Ignition (CI) Engine

4.1 Special designs and modifications from traditional CI engine

The idea of implementing hydrogen, a clean, renewable and efficient fuel, for the operation of high-efficiency compression ignition engines, was and still is very promising. Back in 1978, tried to operate a CI engine with hydrogen fuel only. They soon realised that the operation range was very limited due to the high resistance of hydrogen fuel to autoignition. The limited operation range issue could not be resolved even at a compression ratio of 29:1. The feasibility of converting a diesel engine to hydrogen fuel operation with the assistance of a glow plug and a multiple-strike spark plug was later investigated by the authors. The results revealed that glow plug ignition is an attractive way to provide reliable ignition and smooth engine operation. The hydrogen ignition delay was very short and the indicated mean effective pressures were significantly higher than the corresponding results obtained with diesel oil. Similar values for indicated mean effective pressure (IMEP) and efficiency were also achieved by the multiple-strike spark system operation. However, significant cycle-to-cycle variations in the ignition delay, associated with the large amplitude pressure waves in the combustion chamber, were observed. The NOx concentrations measured in the exhaust gas were significantly higher than the corresponding results obtained in a previous study by the author with premixed hydrogen and air at low equivalence ratios.

The auto-ignition behaviour of hydrogen fuel was studied under a variety of thermodynamic conditions, including top dead centre (TDC) diesel engine conditions with significant dilution. It was discovered that there was a significant Arrhenius temperature dependence on the hydrogen ignition delay. Additionally, it was discovered that the fuel temperature and, to a lesser extent, the O_2 concentration had an impact on the ignition delay. Finally, it was discovered that there was very little dependence on the H_2O and CO_2 concentrations.

A single-cylinder, four-stroke, indirect-injection engine with water cooling and natural aspiration that uses hydrogen fuel. They attempted to run the engine exclusively on hydrogen fuel. It didn't take long, though, to realize that the operation's range was constrained. When the swirl chamber of the engine was vitiated by a small fuel leak or by a pilot fuel and a smooth combustion was possible, the engine's operating limits were significantly increased. This was primarily caused by the combustion chamber still having hot cores from the previous firing stroke, which helps to ignite hydrogen. However, too much pilot fuel was introduced, which caused auto-ignition and rough combustion [7].

4.2 Effects of hydrogen-fuelled CI engine

4.2.1 Engine performance

The engine performance can be significantly enhanced by the addition of hydrogen fuel to conventional diesel fuel. Most of the researchers claimed that the power output and the thermal efficiency of the engine fueled with hydrogen fuel marked incredible improvements. This was attributed to the hydrogen fuel's higher heating value, which led to a more thorough combustion process and a higher power output. However, in addition to the percentage of hydrogen in the dual fuel, other suitable operating conditions such as the engine load, air-fuel ratio, and injection timing had a significant impact on engine performance. They concluded that adding hydrogen only slightly enhanced the BTE. Under 80% load conditions, the dual fuel's highest BTE was recorded at 20% for both 50% and 60% hydrogen content. However, as the hydrogen substitution ratio and load increased, the BSFC and BSEC began to degrade, due to the higher amount of energy content in the hydrogen fuel than the conventional diesel fuel.

Regarding the BTE, it was reported that the thermal efficiency deteriorated notably with the hydrogen substitution at all load conditions, except at the full engine load. This is ascribed to the reduced heat loss through the cylinder wall at high load conditions, therefore resulting in higher BTE. Also, a study on the hydrogen substitution fuel in a 4-cylinder.The engine was run at various engine speeds under full load conditions to test the engine performance. Based on the results obtained, engine power can be boosted significantly with a greater percentage of hydrogen substitution, along with the rise of engine torque due to the improved air/hydrogen mixing process. In addition, the BSFC dropped slightly while BTE elevated with the application of 2.5 % hydrogen substitution. A research on 6-cylinder, turbocharged, heavy-duty diesel engine was conducted by Li et al. [32] with the operating conditions of a constant engine speed of 1200 rpm and changing loads ranging from 10 to 70 % for the hydrogen addition. The hydrogen was added by volume up to 6 %. They deduced that the BTE raised with the greater percentage of hydrogen addition under high engine load conditions, but it showed the opposite trend when the load was 50 % below [32].

An analysis of the engine performance was carried out by Pana et al. [29] for the dual fuel operation mode in a diesel engine running at 1450 rpm under 55 % load conditions. Based on the results obtained, the hydrogen addition favoured the decrement in BSEC by nearly 10 % concerning the baseline diesel. Next, based on the experimental investigation of the exhaust emissions of a 4-cylinder, turbocharged, light-duty diesel engine operating at 1800 rpm and 3600 rpm, they found that the BSEC raised with the hydrogen substitution percentage, due to the deteriorated volumetric efficiency. Simulation engine performance of a 4-cylinder, common-rail engine fueled with hydrogen-diesel fuel by using a numerical approach. The tests were done for different hydrogen addition percentages (0–3 %). The ITE raised with the increment of hydrogen addition ratio at the low engine speed of 1600 rpm, but the results were comparable at the moderate and high engine speeds of 2400 rpm and 3200 rpm. The thermal efficiency was optimized with the addition of hydrogen fuel but without the EGR technique used. Moreover, research on the substitution of conventional diesel fuel using hydrogen was executed by Barrios et al. [33]. The test engine used was a 4-cylinder, turbocharged, direct-injection engine running at various speeds under changing torque conditions. The SFC dropped with the substitution of hydrogen fuel with conventional diesel fuel under all operating conditions.

4.2.2 Exhaust emissions

Exhaust gas recirculation has been proven as an excellent approach for reducing NOx emissions and a practical method for suppressing the knocking of hydrogen-diesel dual-fuel engines. However, the use of exhaust gas recirculation (EGR) may harm engine efficiency and this increases with its percentage. This is due to the dilution effect of EGR. The increased pressure and heat release rate brought on by the hydrogen enrichment are offset by the addition of exhaust gas recirculation inside the cylinder chambers. As the EGR ratio rises, the formation of NOx emissions decreases. However, because there is less oxygen in the cylinder chambers when the EGR rate is increased, there are more emissions of smoke, CO, and HC. Additionally, the CO_2 rates at the exhaust are increased by the presence of CO_2 concentrations in the EGR flow [34].

Although the EGR introduction may lead to increased soot, HC, CO and CO_2 emissions compared to the dual-fuel engine without EGR, the emissions generated are often significantly lower than the neat diesel operation. Dual fuel operation with hydrogen induction coupled with exhaust gas recirculation could result in lower emissions and improved performance levels compared to the case of neat diesel operation. A simultaneous reduction of NOx and smoke emissions compared with using neat diesel fuel by applying a 20% hydrogen-energy-share ratio and 40% EGR in a single-cylinder DI engine. Suzuki and Tsujimura [35] achieved a simultaneous reduction of NOx and smoke emissions in the operation of a dual-fuel engine with high hydrogen rates over 70% and EGR. Compare the performance and emission generation of a neat diesel engine with a hydrogen-diesel dual-fuel engine with and without EGR.

The brake thermal efficiency of the hydrogen-diesel engine without EGR was 12.9% higher than the neat diesel operation. However, the high hydrogen rates led to uncontrolled combustion and engine deficiency. EGR was found to have an adverse effect on the engine's efficiency. The smoke levels decreased by 42% for hydrogen enrichment without EGR compared to neat diesel operation due to the absence of carbon in the hydrogen structure. EGR existence increased smoke levels but still were lower than the neat diesel operation. CO_2, CO and HC emissions were reduced by 40.5%, 45.8% and 57.7% respectively for hydrogen enrichment without EGR. A 20% EGR rate was found to be compulsory for a 40% reduction in NOx emissions [35].

The brake-specific fuel consumption (BSFC) of the hydrogen-diesel dual-fuel engine has shown an improvement compared to that of neat diesel operation according to SinghYadav et al. [34]. This is happening due to an improved mixing of hydrogen with air resulting in a complete combustion of fuel. However, this was not the case when EGR was applied where BSFC increased and decreased with the increase in EGR percentage. On the other hand, the brake-specific energy consumption (BSEC) in the case of hydrogen enrichment without EGR was higher compared to that of neat diesel operation. In the case of hydrogen use with EGR, the combustion efficiency is decreased and BSEC is increased. This is due to the negative effect of EGR on combustion.

The effects of separate hydrogen and nitrogen addition, from 2 up to 8% of the total intake charge, on the emissions and combustion characteristics of a compression ignition engine. The hydrogen addition assisted in decreasing smoke and CO at the expense of NOx emissions except in the low speed/load areawhere NOx emissions were maintained at the same levels. The reduction of NOx could be achieved by diluting the intake charge with nitrogen, but it came with a penalty on smoke, CO and fuel consumption. The brake thermal efficiency was improved at high speeds and slightly deteriorated at the low-speed area.

Although the synergy of hydrogen and EGR is a promising partway to meeting the low emissions and BSFC trade-off contingencies of the diesel engine, further development on the appropriate injection and boost strategies is required to overcome the main limitation of high NOx formation at high load operating points of the engine [36].

4.2.3 Combustion characteristics

The implementation of hydrogen fuel for CI engines was proved to be a more realistic approach when it was combined with an additional lower autoignition temperature fuel. Extensive research has been performed on the addition of diesel fuel as a combustion trigger in hydrogen-fuelled compression ignition engines. When the engine is getting close to its TDC, diesel fuel is most frequently directly injected into the cylinder, where it ignites the pre-mixed air/hydrogen mixture. In contrast, hydrogen fuel can be injected into a carburettor, an intake manifold, or an engine's intake ports. When compared to carburetion and manifold injection techniques, the performance of hydrogen/diesel dual-fuel engines with various injection systems has shown that the hydrogen port injection technique offers better efficiency and lower emissions.

Yuan et al. [37] carried out a test on the combustion behaviour of a diesel free-piston engine by adding hydrogen to the fuel. Based on the results obtained, the peak in-cylinder pressure and peak heat release rate elevated when the hydrogen addition percentage was beyond 10 %, as shown in Figure3. In addition, the greatest peak cylinder pressure and peak HRR were observed for the fuel with 53 % hydrogen content. Yilmaz et al. [6] focused on the study of the combustion behaviour of a turbocharged diesel engine that runs at different engine torques of 50, 75 and 100 Nm. They noticed that the peak cylinder pressure and rate of pressure rise marked maximum increments by 11.21 % and 48.59 % with the hydrogen substitution, at the expense of a reduced rate of heat release. In addition, the ignition delays and combustion durations for hydrogen blended fuels were longer than the neat diesel fuel.

Also, the increment of hydrogen percentage in the dual fuel marked a rise in the peak HRR due to the greater adiabatic flame temperature of hydrogen[38]. Meanwhile, the maximum cylinder pressure and the maximum HRR increased with the increase in the hydrogen addition ratio, particularly for the 42% hydrogen level, according to the experimental analysis of the combustion behaviour.

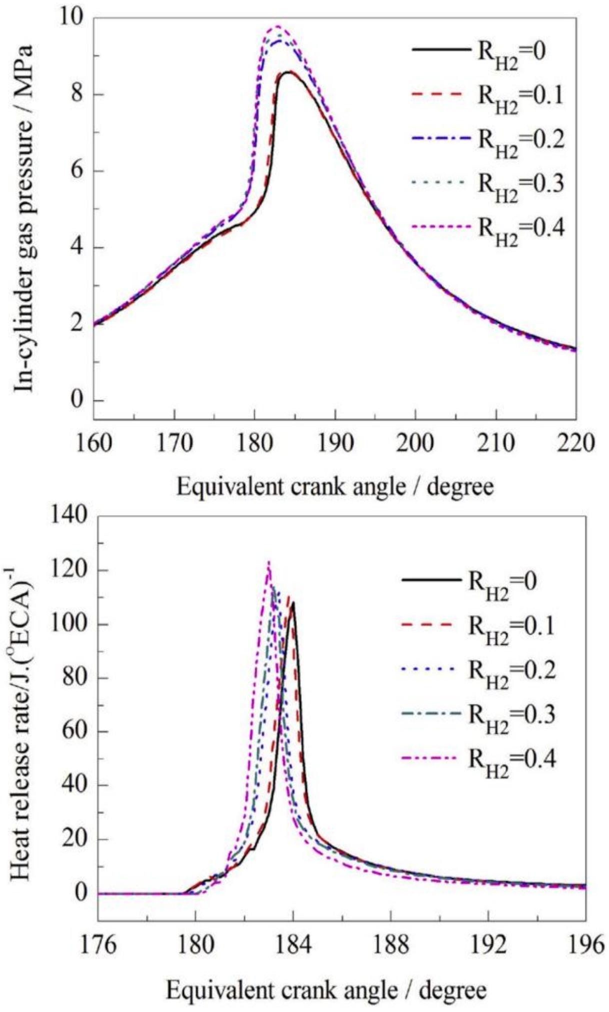

Figure 3: Comparison of cylinder pressure and heat release rate between baseline diesel and pure hydrogen fuel [37]

The maximum cylinder pressure and maximum HRR were better at high engine loads, whereas the combustion characteristics varied with engine load conditions. Due to the hydrogen's high flame speed and shorter combustion time, the addition of hydrogen caused both the maximum cylinder pressure and HRR to increase. Additionally, under the operating circumstance of a high engine load, increases in the peak in-cylinder pressure and the peak HR. This is primarily because hydrogen burns more quickly than other fuels, which shortens the combustion process. The highest cylinder pressure and HRR were recorded when the system was run at 70% load and 17% hydrogen enrichment.

V. Future Perspective of Hydrogen Engine

5.1 Techno-economic point of view

One of the main advantages is that both renewable and non-renewable resources can be used to produce hydrogen. Hydrogen can be created from a variety of sources using a variety of techniques, as was mentioned in the section before, including gasification, electrolysis, and steam reforming from coal, biomass, water, and natural gas. This demonstrates the adaptability of hydrogen in terms of its sources and production techniques, providing flexibility in terms of technology requirements and costs, though ongoing research is required to determine the optimal combinations of production, storage, and distribution models. In addition, recovering waste hydrogen from reduction furnace operations, including waste bio-mass, waste hydrocarbon, and waste, offers a sustainable and economically advantageous method of producing hydrogen [39].

For instance, hydrogen is a by-product in specific common chemical processes in industries such as the production of caustic soda or sodium hydroxide (NaOH), which is widely used in sectors including textile, alumina, electroplating, detergent, and paper productions [40]. As it was estimated that the growth of NaOH consumption would exceed 89 million metric tons by 2022, an appreciable amount of hydrogen and its energy content would be available to recover. In short, other than improvements to current hydrogen production approaches, attention should also be paid to unconventional sources and prevent waste hydrogen.

5.2 Infrastructure

Large-scale H_2ICE application is anticipated to fully realize and utilize the hydrogen-fueled ICE concept. It necessitates the support of an extensive infrastructure system that covers fuel distribution, transportation, and refuelling. For hydrogen storage to contain an equivalent amount of fuel energy as compared to gasoline, a volume four times larger than that of gasoline is required. As a result, this poses difficulties for the construction and layout of hydrogen fueling stations as well as for the storage of hydrogen before distribution. To tackle the problem, smaller-scale hydrogen facilities such as household-level hydrogen stations have also been proposed by several hydrogen suppliers [41].For instance, Honda introduced its Smart Hydrogen Station (SHS), which is a compact hydrogen generation and storage unit that could generate an estimated 1.5 kg H_2 per day.

5.3 Social point of view

Even though a large amount of research and studies on hydrogen have been done and proved its possibility as a fuel replacement for currently commonly used gasoline and diesel, the concept of hydrogen-fueled ICEs is still rather abstract in the public's eyes. Therefore, more needs to be done to educate end users of transportation and end vehicles about this issue. Hydrogen promises lower emissions of harmful pollutants, so it is anticipated that ICEs will release less CO and HC as a result of the combustion of hydrogen in H_2ICE. A hydrogen leak would not harm the environment because hydrogen is classified as a non-toxic gas. Additionally, accidental inhalation of the smoke from a hydrogen flame is completely safe for people.

The number of vehicles on the road by 2040 could reach 2 billion. The population will increase and concentrate in cities. The effectiveness of the used energy as well as the share of renewable energy in the global energy mix must be increased to meet the ambitious climate targets. The problem with intermittent renewable energy is that there are times when no energy can be produced. However, national initiatives like the German Energiewende and the Paris 1.5 °C target will increase the share of renewable energy in the electricity energy mix. The majority of the electricity produced in the European Union in 2040 will be produced using renewable energy sources [42].

5.4 Political point of view

The future role of hydrogen and fuel cell applications in the transport sector is very dependent on the policy framework and future targets. However, implemented policies, investments, as well as future targets differ significantly from country to country. A relatively low number of policies are applied directly to hydrogen and fuel cell technologies. The policy support for hydrogen and fuel cell vehicles as well as corresponding infrastructure is driven mainly by different national priorities such as air quality, climate change, and energy security [43]. There is also a broad portfolio of policies that indirectly support use of hydrogen and full cell vehicles, e.g. standards for CO_2 emissions from new cars, ban of ICE vehicles.

The major problem for the faster and broader deployment of hydrogen and full cell vehicles is a lack of regulations as well as coordinated action between different stakeholders. In addition, technology standards are needed, which would drive economies of scale and reduce risks of the investment. There is still lack of investments in hydrogen and fuel cells in most of countries and regions. Although, the European Commission acknowledges that the market uptake of alternative vehicles and infrastructure roll-out are fundamentally connected, its proposal for post-2021 CO_2 targets for passenger cars and vans does not link the availability of charging Fand refuelling infrastructure to the future CO_2 targets. However, to be able to reflect the reality of the market, Europe's long-term climate objectives should be linked to future infrastructure availability and consumer acceptance [44].

VI. Conclusion

This work offers a critical assessment and summary of earlier studies on the use of hydrogen in internal combustion engines, especially SI and CI engines. Three factors, namely engine performance, exhaust emissions, and combustion characteristics, were the main focus of the results analyses in those investigations. As a result, the main findings from those studies were compiled as follows in this paper. According to the majority of research, adding hydrogen to both SI and CI engines significantly increased thermal efficiency. This work offers a critical assessment and summary of earlier studies on the use of hydrogen in internal combustion engines, especially SI and CI engines. Three factors, namely engine performance, exhaust emissions, and combustion characteristics, were the main focus of the results analyses in those investigations. As a result, the main findings from those studies were compiled as follows in this paper. According to the majority of research, adding hydrogen to both SI and CI engines significantly increased thermal efficiency. Most authors came to the conclusion that operating hydrogen-diesel dual fuel in both SI and CI engines resulted in cleaner exhaust emissions than doing so with regular diesel fuel. For instance, the lack of carbon atoms in hydrogen fuel resulted in a reduction in the carbon-related emissions for both types of engines, such as CO, CO_2, and HC.

Additionally, the improved combustion process encouraged the reduction of smoke, soot, and PM emissions in CI engines. However, as noted by the majority of researchers, the high combustion rate and quick flame propagation caused the NOx formations in SI engines to tend to grow. Though some authors used EGR systems to lessen NOx formations, trends in NOx emissions from CI engines were inconsistent. Additionally, most researchers asserted that because hydrogen burns more quickly than traditional diesel fuel, the cylinder pressure and heat release rate for both internal combustion engines showed higher values for hydrogen enriched fuels than for conventional diesel fuel operation. Additionally, it was shown that SI engines running on hydrogen demonstrated good combustion stability with lower IMEP and COV maximum cylinder pressures. The majority of the mixed hydrogen operation modes in CI engines showed delayed ignition and prolonged combustion duration. In short, it was discovered that using hydrogen fuel for single or dual fuel operation in internal combustion engines was practicable. With the right operating circumstances and small engine modifications, such as an iridium spark plug for SI engines, hydrogen usage in internal combustion engines helped to increase engine performance, exhaust emissions, and combustion behavior.

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