

EFFECT OF HYDROGEN FUEL IN COMPRESSION IGNITION ENGINE

Submitted in partial fulfilment of the requirements for the completion of

INTERDISCIPLINARY PROJECT

By

SABINESH V (Reg. No. 40860003)

JOSEPH BRAITTON S (Reg. No. 40150018)



**DEPARTMENT OF AUTOMOBILE ENGINEERING
SCHOOL OF MECHANICAL ENGINEERING**

SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY

(DEEMED TO BE UNIVERSITY)

Accredited with grade "A" by NAAC

JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI – 600119

APRIL 2023



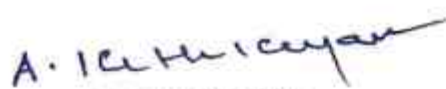
SATHYABAMA
INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)
Accredited with "A" grade by NAAC
Jeppiaar Nagar, Rajiv Gandhi Salai, Chennai - 600 119
www.sathyabama.ac.in



DEPARTMENT OF AUTOMOBILE ENGINEERING

BONAFIDE CERTIFICATE

This is to certify that this Project Report is the Bonafide work of, JOSEPH BRAITTON S (Reg. No. 40150018) and SABINESH V (Reg. No. 40860003) who carried out the Interdisciplinary Project entitled "**EFFECT OF HYDROGEN FUEL IN COMPRESSION IGNITION ENGINE**" under our supervision from February 2023 to April 2023.


Internal Guide
Dr. KARTHIKEYAN., M.E., Ph.D.


External Guide
Dr. NIVIN JOY., M.E., Ph.D.


Head of the Department
Dr. B. B. UPESH RAJA, ME., PhD.,

Submitted for Viva voce Examination held on 28/04/2023


Internal Examiner


External Examiner

DECLARATION

I SABINESH V (Reg. No. 40860003) hereby declare that the Project Report entitled "EFFECT OF HYDROGEN FUEL IN COMPRESSION IGNITION ENGINE" done by me under the guidance of Dr. NIVIN JOY, M.E., Ph.D., and Dr. KARTHIKEYAN., M.E., Ph.D., is submitted in partial fulfilment of the requirements for the completion of Interdisciplinary Project.

DATE: 28/04/2023

PLACE: CHENNAI



SIGNATURE OF THE CANDIDATE

ACKNOWLEDGEMENT

I am pleased to acknowledge my sincere thanks to Board of Management of **SATHYABAMA** for their kind encouragement in doing this project and for completing it successfully. I am grateful to them.

I convey my sincere thanks to **Dr. S. Prakash, M.E., Ph.D.**, Dean, School of Mechanical Engineering and **Dr. Bhupesh raja M.E., Ph.D.**, Head of the Department, Department of Automobile Engineering for providing me necessary support and details at the right time during the progressive reviews.

I would like to express my sincere and deep sense of gratitude to my Internal Guide **Dr. KARTHIKEYAN., M.E., Ph.D.**, and External Guide **Dr. NIVIN JOY., M.E., Ph.D.** for their valuable guidance, suggestions and constant encouragement paved way for the successful completion of my project work.

I also express my thanks to all Teaching and Non-teaching staff members of the Department of Automobile Engineering who were helpful in many ways for the completion of the project work.

ABSTRACT

Hydrogen fuel is increasingly being considered as a viable alternative to traditional fossil fuels due to its potential as a clean and sustainable source of energy. One area where hydrogen fuel has the potential to make a significant impact is in compression ignition engines. Compression ignition engines are widely used in the transportation sector, particularly in heavy-duty vehicles such as trucks and buses. They operate by compressing a mixture of air and fuel until it reaches a temperature high enough to ignite the fuel without the need for a spark. This process is known as compression ignition, and it results in higher thermal efficiency and lower fuel consumption compared to spark ignition engines. Hydrogen has a high energy density per unit mass, which means that it can provide more energy per unit of fuel compared to conventional fossil fuels. Additionally, hydrogen fuel can be produced from renewable sources, such as water and solar energy, making it a sustainable option. However, there are several challenges associated with using hydrogen fuel in compression ignition engines. One of the biggest challenges is the need for high-pressure storage and transportation systems, as hydrogen gas is less dense than conventional liquid fuels. This can make the storage and transportation of hydrogen fuel more complex and expensive.

TABLE OF CONTENTS

CHAPTER No.	TITLE	PAGE No.
	ABSTRACT	V
	LIST OF FIGURES	Ix
	LIST OF TABLES	xi
	LIST OF SYMBOLS AND ABBREVIATIONS	Xii
1	INTRODUCTION	1
2	INTERNAL COMBUSTION ENGINE	2
3	IMPLICATIONS ON FOSSIL FUELS	3
4	HYDROGEN FUELS	6
	4.1 BENEFIT OF HYDROGEN FUEL	8
	4.2 CHALLENGES OF HYDROGEN FUEL	8
	4.3 PRODUCTION	
	4.3.1 STEAM METHANE REFORMING	9
	4.3.2 ELECTROLYSIS	9
	4.3.3 COAL GASIFICATION	10
	4.3.4 BIO MASS GASIFICATION	11
	4.3.5 RENEWABLE ENERGY SOURCE	12
	4.4 PROPERTIES	13
		13
5	METHODS OF HYDROGEN FUEL ADDITION IN CI ENGINE	15
	5.1 HYDROGEN INJECTION	15
	5.1.1 PORT INJECTION	17
	5.1.2 DIRECT INJECTION	17
	5.2 HYDROGEN BLENDING	17
	5.2.1 EXTERNAL MIXING	18
	5.2.2 INTERNAL MIXING	18
	5.3 DUAL FUEL COMBUSTION	18
	5.3.1 PILOT INJECTION	19
	5.3.2 PREMIXED COMBUSTION	20
6	PROPERTIES COMPARISON OF HYDREGEN WITH ALTERNATE FUELS	20

CHAPTER No.	TITLE	PAGE No.
7	REVIEW ON IC ENGINE PERFORMANCE WITH HYDROGEN FUEL	28
8	REVIEW ON IC ENGINE EMISSION WITH HYDROGEN FUEL	29
	8.1 EMISSION PERFORMANCE	29
	8.2 CHALLENGERS	30
9	STRATEGIES TO IMPROVE IC ENGINE PERFORMANCE	30
	9.1 INCREASE THE COMPRESSION RATIO	31
	9.2 OPTIMIZE THE IGNITION TIMING	31
	9.3 USE ADVANCED ENGINE MATERIALS	31
	9.4 ENGINE MODIFICATION	31
	9.5 COOLING SYSTEM	31
	9.6 LUBRICATION SYSTEM	32
	9.7 COMBUSTION CHAMBER DESIGN	32
10	TECHNO-ECONOMIC ANALYSIS	32
	10.1 TECHNICAL FEASIBILITY	33
	10.2 ECONOMIC FEASIBILITY	33
	10.3 ENVIROMENTAL FEASIBILITY	33
11	FUTURE DIRECTIONS	33
12	CONCLUSION	33
13	REFERENCES	34

LIST OF FIGURES

FIGURE No	TITLE	PAGE No.
3	GLOBAL FUEL CONSUMPTION	5
4	HYDROGEN FUEL	7
4.3.1	STEAM METHANE REFORMING	10
4.3.2	ELECTROLYSIS	11
4.3.4	BIO MASS GASIFICATION	12
5.1	HYDROGEN INJECTION	16
5.3	DUAL FUEL COMBUSTION	19

LIST OF TABLES

TABLE No	TITLE	PAGE No.
4.4	PROPERTIES OF HYDROGEN FUEL	14
6	PROPERTIES COMPRASION OF HYDROGEN WITH ALTERNATE FUELS	21

LIST OF SYMBOLS AND ABBEREVIATIONS

NO _x	Nitrogen oxides
PM	Particular
HDDF	Hydrogen-diesel dual fuel
CI	Compression ignition engine
GHGs	Greenhouse gases
CO ₂	Carbon dioxide
N ₂ O	nitrous oxide
SO ₂	Sulphur dioxide
ECU	Electronic control unit
SMR	Steam methane reforming
CH ₄	methane

EFFECT OF HYDROGEN FUEL INJECTION IN COMPRESSION IGNITION ENGINE

1.INTRODUCTION:

One of the most prevalent elements in the universe, hydrogen is seen as a possible future alternative fuel. The fact that hydrogen burns cleanly and sustainably, releasing just water vapor and heat, is one of its main advantages. As a potential method to lower pollutants and increase fuel efficiency, researchers have recently concentrated on the use of hydrogen in compression ignition engines, also referred to as diesel engines. Compression ignition engines work by increasing the temperature and pressure of the air in the combustion chamber to a point where the fuel will ignite on its own. In diesel engines, the combustion chamber receives a direct injection of fuel, which ignites as it meets the hot compressed air. However, substantial levels of nitrogen oxides (NO_x) and particulate matter (PM), which are bad for the environment and people's health, are produced when diesel fuel is burned. Numerous characteristics of hydrogen make it a desirable fuel for compression ignition engines. The fuel has a high-octane rating, which indicates that it has a low knocking resistance and can be squeezed to a greater ratio before ignition. This makes it possible for greater combustion efficiency, which can enhance fuel efficiency and reduce emissions. In addition, hydrogen has a high flame speed, which means it burns more quickly than diesel fuel and produces fewer emissions as a result. Because hydrogen has a lower energy density than diesel fuel, employing it in compression ignition engines can be difficult. To provide the same amount of energy as diesel fuel, more hydrogen is needed, according to this. This can be lessened, though, by using high-pressure storage devices or by burning hydrogen and diesel fuel in a process known as hydrogen-diesel dual fuel (HDDF). The use of hydrogen as a fuel in compression ignition engines is now the subject of

research, which will be examined in this review paper. We'll talk about the difficulties using hydrogen, the various techniques used to enhance its combustion properties, and the possible advantages of using hydrogen in compression ignition engines.

2.INTERNAL COMBUSTION ENGINE:

An internal combustion engine is a heat engine that produces mechanical energy through the combustion of fuel and air. Small engines for power tools, lawn mowers, and other equipment as well as automobiles, motorbikes, and other vehicles frequently employ this sort of engine. Internal combustion engines can be divided into two categories: spark-ignition engines and compression-ignition engines. Compression-ignition engines rely on the heat produced by the compression of the fuel and air mixture to ignite the gasoline, as opposed to spark-ignition engines, which employ a spark plug to ignite a mixture of fuel and air.

Compared to other types of engines, internal combustion engines have a few benefits. They can be smaller and lighter than electric motors, and they are often more efficient than steam and external combustion engines. They can also create greater power relative to their size and weight due to their better power-to-weight ratio. Internal combustion engines have a few advantages as well as a few drawbacks. They emit gases including carbon dioxide, nitrogen oxides, and particulate matter that can damage the environment and accelerate climate change. Additionally, they are less effective than electric motors, especially at passive and low speeds. Researchers have created a number of technologies to improve internal combustion engine efficiency and lower emissions to address these problems. For instance, exhaust gas recirculation and selective catalytic reduction can lower emissions from both spark-ignition and compression-ignition engines while increasing the efficiency of spark-

ignition engines.

As an alternative to internal combustion engines, electric vehicles have gained popularity in recent years. On the other hand, it is anticipated that internal combustion engines will continue to be used for a very long time to come, especially in heavy-duty applications like trucks, ships, and aero planes where electric power is still not practical. While having several disadvantages, internal combustion engines continue to be a vital and popular technology for propulsion of machinery and vehicles. Future advancements in research and development are projected to result in even greater reductions in their emissions and efficiency, making them a more sustainable choice.

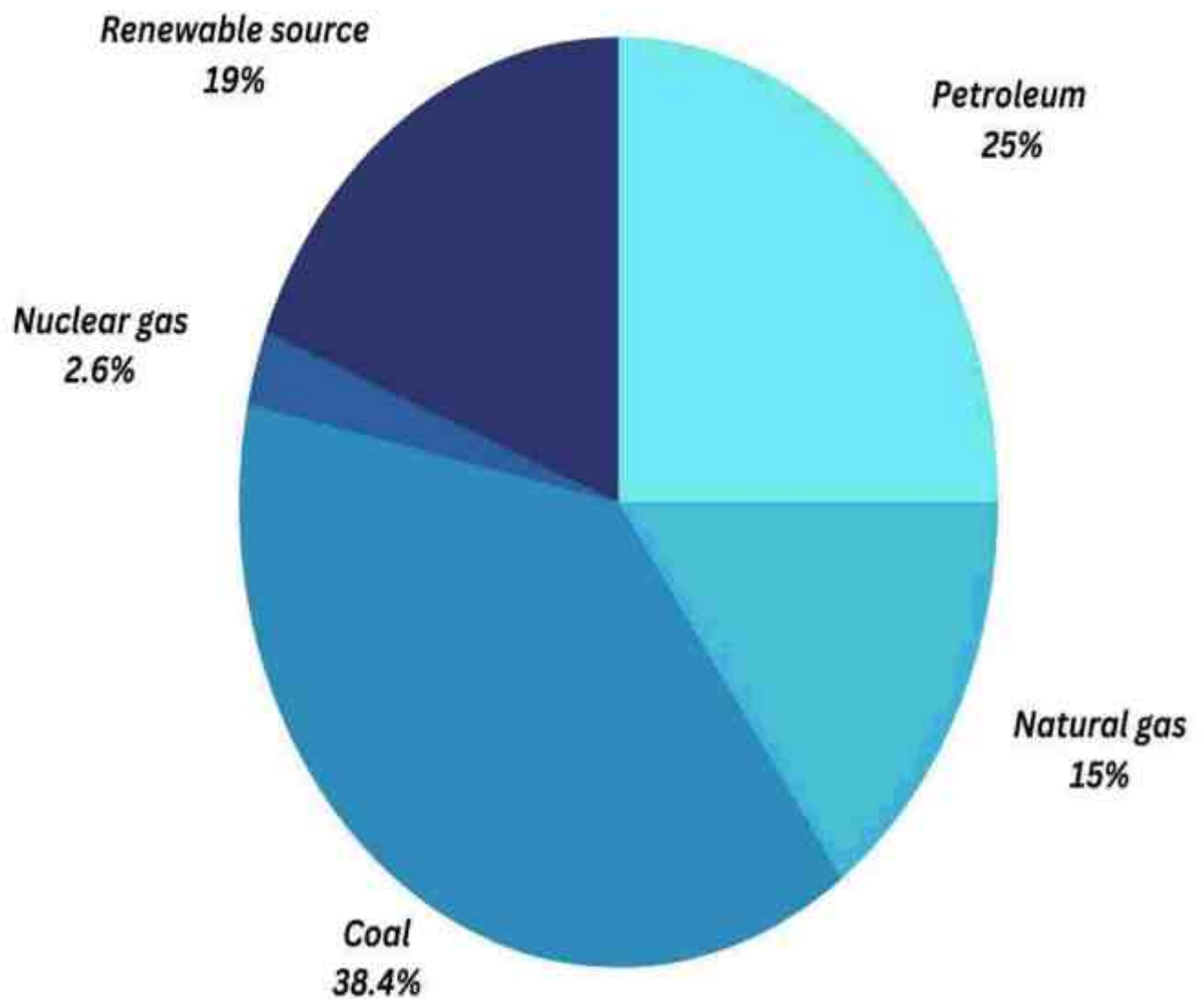
3.IMPLICATION ON FOSSIL FULES:

For many years, fossil fuels like coal and oil have been the main source of energy. In the compression ignition (CI) engine, also referred to as the diesel engine, fossil fuels are one of the primary uses. However, using fossil fuels in the CI engine has a few consequences, including economic, social, and environmental ones. The CI engine's use of fossil fuels has several negative effects on the environment. During combustion, fossil fuels give off greenhouse gases (GHGs), including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). GHGs are the main contributors to climate change, which has several negative effects on the environment, including sea level rise, glacier melt, and extreme weather events. Additionally, the use of fossil fuels results in the discharge of a few pollutants such as Sulphur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM), which have a variety of negative effects on the environment including acid rain, smog, and respiratory illnesses.

The use of fossil fuels in the CI engine has a number of economic repercussions as

well. The supply of fossil fuels is constrained since they are a finite resource. The cost of fossil fuels rises along with the demand for them. Furthermore, using fossil fuels includes several unintended costs that may not appear in their market prices, such as environmental and health expenses. The expense of health care and environmental remediation are only two examples of how these hidden costs can have a large economic impact.

In addition to fossil fuels, the CI engine may also utilize a number of other fuels. These consist of hydrogen, ethanol, and biodiesel. A renewable fuel, biodiesel can be created from leftover cooking oil, animal fats, and vegetable oils. In comparison to fossil fuels, biodiesel provides a number of benefits, including lower greenhouse gas emissions, greater lubricity, and biodegradability. Ethanol may be made from biomass, such as corn, sugarcane, and switchgrass, and is another renewable fuel. Compared to fossil fuels, ethanol provides several benefits, including lower greenhouse gas emissions, a higher-octane rating, and domestic availability. Through electrolysis, hydrogen may be created from water as a clean fuel. In comparison to fossil fuels, hydrogen provides a number of benefits, including zero emissions, a high energy density, and domestic availability.

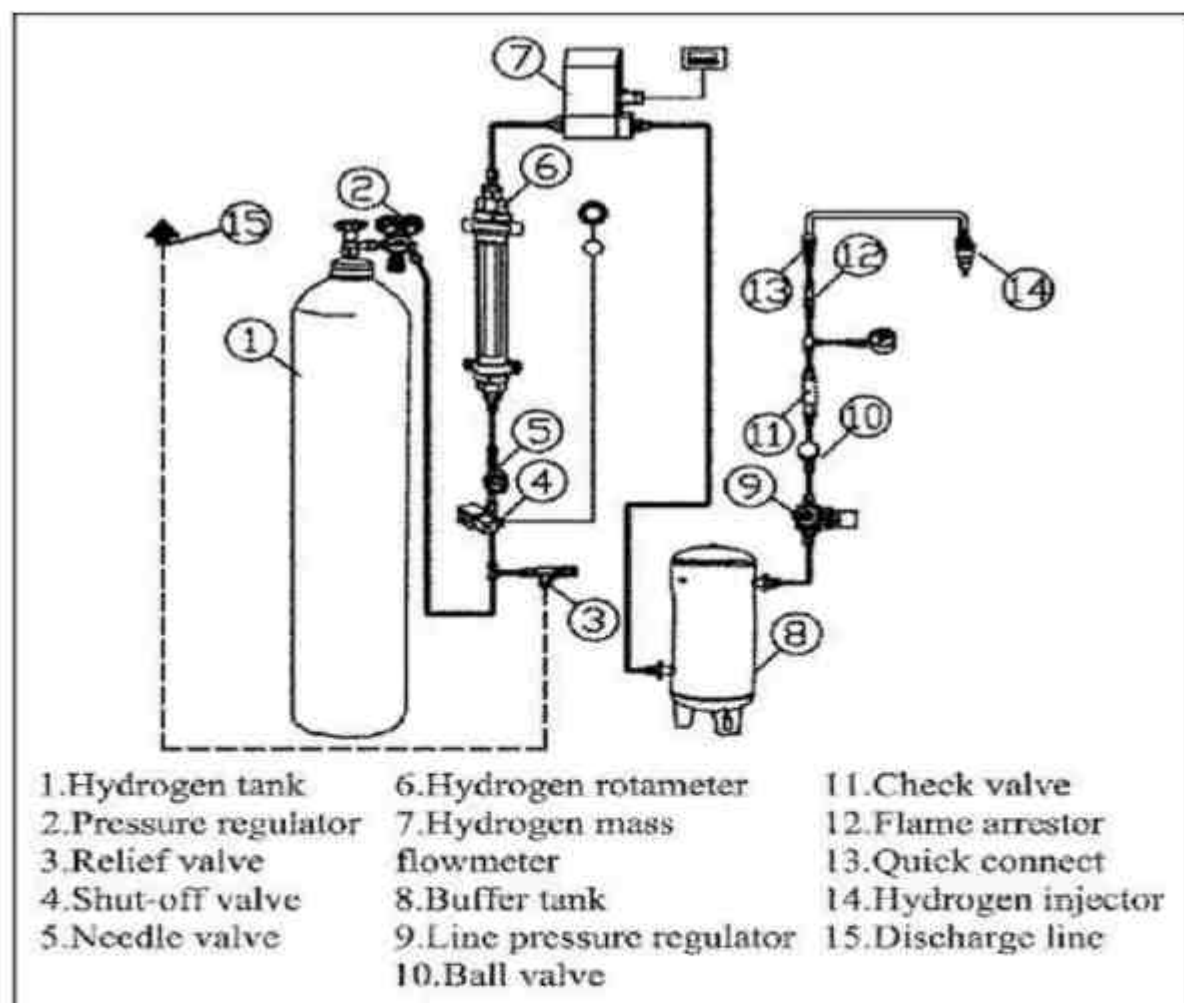


GLOBAL FUEL CONSUMPTION

4. HYDROGEN FUELS:

The investigation of alternative fuel sources, particularly hydrogen fuel, is being driven by the demand for sustainable energy and the growing concern over climate change. Due to its potential to lower greenhouse gas emissions and contribute to a

cleaner environment, hydrogen fuel, sometimes known as "green" or "clean" fuel, is an alternative energy source that has attracted a lot of attention. It is created from water using electrolysis. In comparison to fossil fuels, hydrogen provides a few benefits, including zero emissions, a high energy density, and domestic availability. Through the electrolysis process, which divides water into hydrogen and oxygen with the help of an electrical current, hydrogen fuel is created. After that, the hydrogen can be transferred and stored for use as fuel. Using natural gas or other hydrocarbons in a procedure known as steam reforming is another way to make hydrogen fuel. However, because carbon dioxide is a byproduct of this process, it is not as pure as electrolysis.



4.1 BENIFITS OF HYDROGEN FUEL:

Compared to conventional fossil fuels, hydrogen fuel has a few advantages. First off, it is an environmentally friendly fuel source that doesn't emit any dangerous gases like carbon dioxide, nitrogen oxides, or Sulphur dioxide. Because of this, hydrogen fuel presents a possible substitute for lowering air pollution and greenhouse gas emissions. Second, hydrogen fuel has a high energy density, or a lot of energy in a given amount of mass or volume. Because it has a greater range than conventional fossil fuels, it is the perfect fuel for transportation. Third, a number of sources, including renewable ones like solar and wind energy, can be used to create hydrogen fuel. As a result, hydrogen fuel has the potential to be totally created using renewable energy sources, making it a genuinely sustainable fuel.

4.2 CHALLENGES OF HYDROGEN FUEL:

While hydrogen fuel has numerous advantages, there are also a number of obstacles that need to be overcome before it can be used as a common fuel source. The expense of manufacturing and delivering hydrogen fuel is one of the major obstacles. Because of the high cost of electrolysis and the absence of infrastructure for transporting and storing hydrogen fuel, the generation of hydrogen fuel is now more expensive than the production of traditional fossil fuels. Safety issues related to the transportation and storage of hydrogen fuel. Due to its great flammability, hydrogen gas must be handled and stored according to specific rules to ensure safety. Furthermore, the need for high pressure to hold hydrogen fuel can present safety issues.

An enormous amount of energy is needed to produce hydrogen fuel, and this energy can be obtained from non-renewable sources like natural gas. The sustainability advantages of hydrogen fuel may be compromised as a result; hence precautions must be taken to guarantee that hydrogen fuel production does not increase

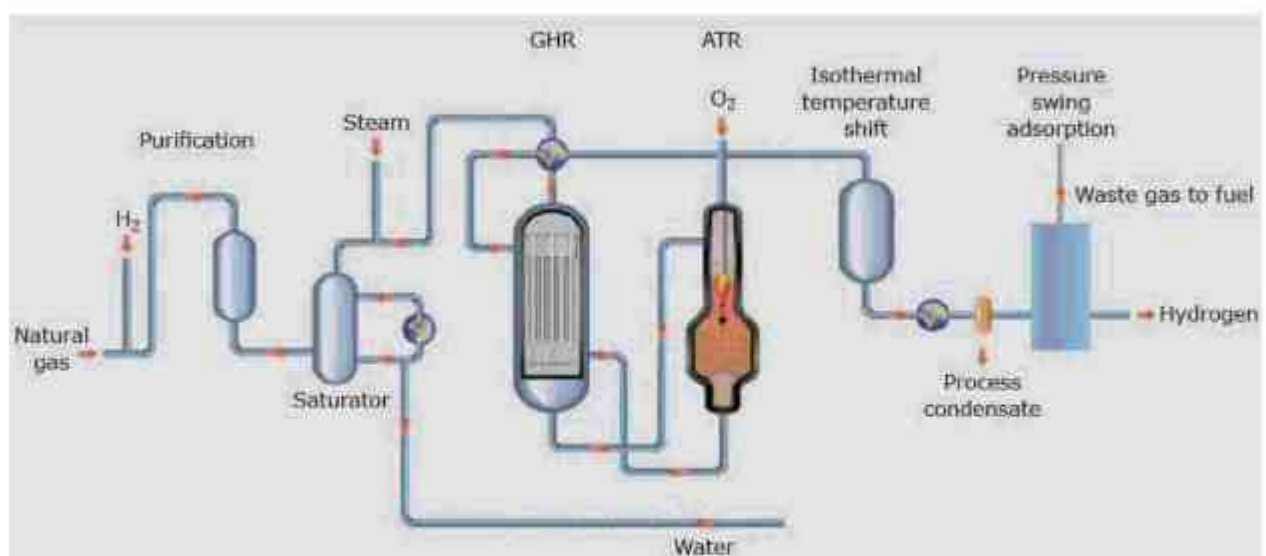
greenhouse gas emissions or other environmental problems.

4.3. PRODUCTION:

Hydrogen is a plentiful and adaptable element that may be employed in a variety of sectors, including manufacturing, transportation, and energy. As a potential means of decreasing greenhouse gas emissions and ensuring a sustainable energy future, hydrogen production has been gaining popularity. There are several methods for producing hydrogen, including steam methane reforming, electrolysis, and coal gasification.

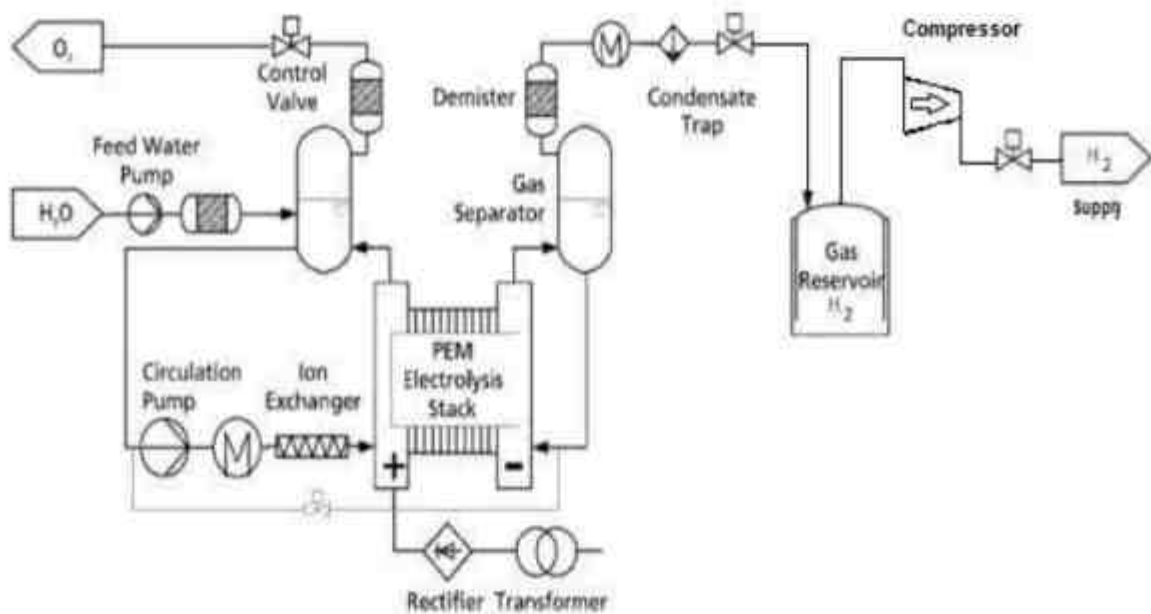
4.3.1. Steam Methane Reforming (SMR):

The most used technique for making hydrogen is steam methane reforming (SMR). Natural gas and hot steam are combined in this process to create hydrogen and carbon dioxide. The method is quite effective and generates a lot of hydrogen, but it also releases a lot of greenhouse gases. SMR cannot produce hydrogen in a sustainable manner over the long term.



4.3.2 Electrolysis:

Using electricity, water molecules are split into hydrogen and oxygen. The method can be driven by renewable energy sources like solar or wind, making hydrogen production using it a sustainable process. However, electrolysis is currently more expensive than SMR, and the technology needs to be improved to be commercially viable.



4.3.3 Coal gasification:

In this process, biomass—such as wood chips or agricultural waste—is cooked at high temperatures with a finite amount of oxygen. A gas mixture containing hydrogen and carbon monoxide is created as a result, and this gas mixture can be separated and used as fuel.

4.3.4 Biomass gasification:

To produce hydrogen and other gases, biomass—such as wood chips or

hydrogen. Renewable electrolysis is currently more expensive than SMR, therefore more work needs to be done on the technology before it can be considered economically viable.

4.4. PROPERTIES:

The process of producing hydrogen gas for use as a fuel is referred to as hydrogen fuel production. A versatile and clean-burning fuel, hydrogen may be used to power fuel cells, power vehicles, and power many industrial processes.

- **High energy content:** In comparison to other fuels like petrol or natural gas, hydrogen has a very high energy content per unit mass. In other words, it can produce a lot of energy from a small amount of fuel.
- **Clean combustion:** Water is the only byproduct of hydrogen's clean combustion. Because of this, it is an extremely desirable fuel for lowering greenhouse gas emissions and enhancing air quality.
- **Abundant:** The most prevalent element in the universe is hydrogen, which can be created from a multitude of sources, including renewable energy sources like wind and solar energy.
- **Lightweight:** Since weight plays a crucial role in energy efficiency in transportation applications, hydrogen is a particularly lightweight gas.
- **Safe:** Despite being incredibly combustible, hydrogen is very safe when used properly. Systems using hydrogen fuel are extremely dependable and risk-free

to use thanks to a few safety features.

- **Versatile:** Hydrogen is versatile and can be used in a wide range of operations, including the production of energy in fuel cells, transportation fuel, and industrial feedstock.
- **Efficiency:** When compared to conventional combustion engines, hydrogen fuel cells are more effective, which means they can convert a higher proportion of the fuel's energy into useful power

Properties of hydrogen fuel:

Property	Hydrogen	Gasoline	Methane
Chemical formula	H ₂	C ₈ H ₁₈	CH ₄
Flammability limits	0.1 - 7.1	0.7 - 4	0.4 - 1.6
Minimum ignition energy	0.02	0.25	0.28
Laminar flame speed at NTP	1.90	0.37 - 0.43	0.38
Flame velocity	2.65 -3.25	0.30 - 0.50	0.4 - 0.6
Quench distance at NTP	0.64	2.0	2.03
Density at 1atm and 300K	0.082	730	0.651
Stoichiometric composition in air	29.53	1.65	9.48
Stoichiometric fuel / air mass ratio	0.029	0.0664	0.058
High heating value	141.7	48.29	52.68

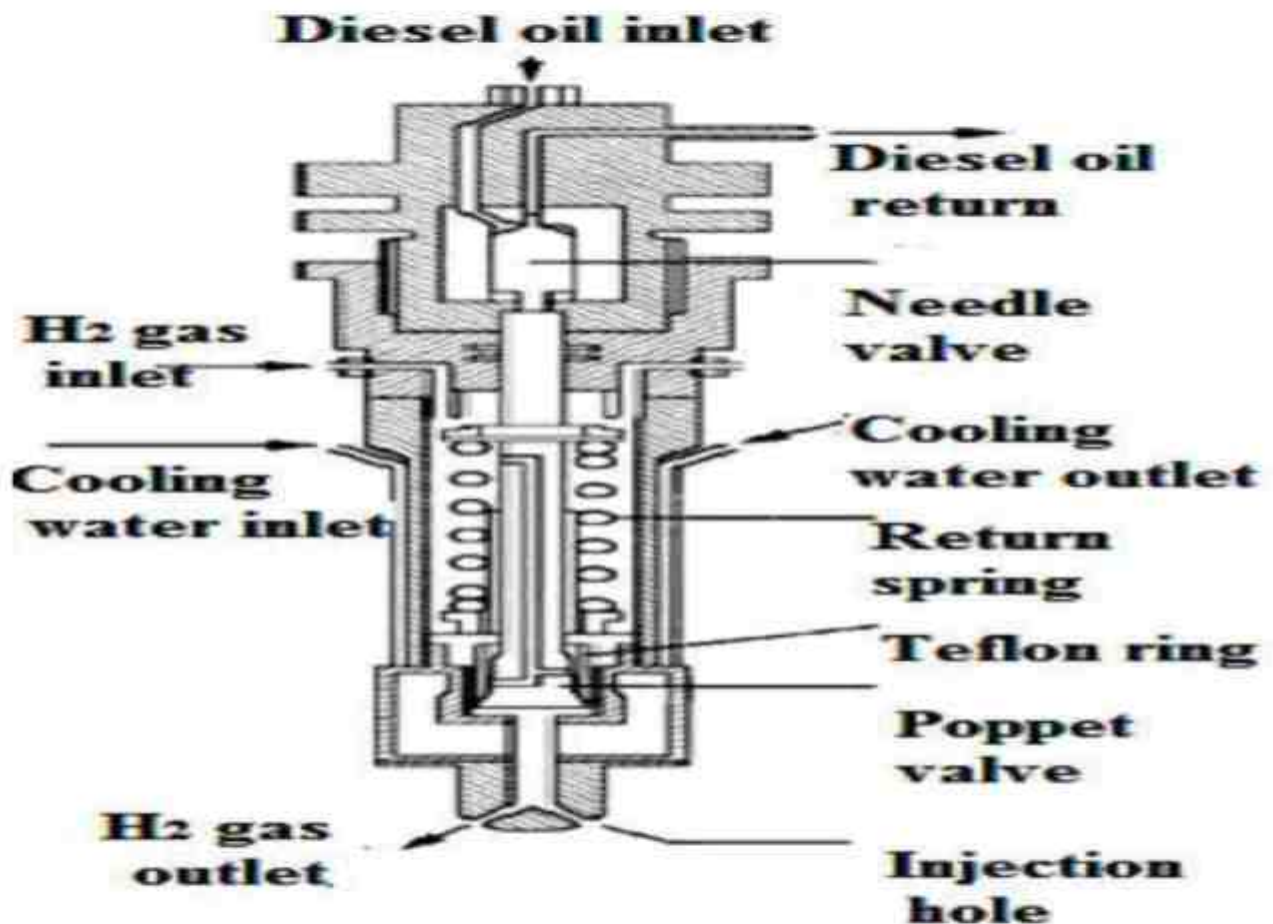
5.METHODS OF HYDROGEN FUEL ADDITION IN CI ENGINE:

Due to its potential advantages, such as lower pollutants, increased engine performance, and higher fuel efficiency, hydrogen fuel addition in a compression ignition (CI) engine has been taken into consideration as an alternative fuel source.

There are several methods of hydrogen fuel addition in CI engines, including hydrogen injection, hydrogen blending, and dual fuel combustion.

5.1 HYDROGEN INJECTION:

Hydrogen injection involves injecting hydrogen gas directly into the combustion chamber of a CI engine.



5.1.1 Port injection:

In this technique, air and hydrogen gas are both fed into the engine's intake port. Before entering the combustion chamber, the hydrogen gas and air combine, creating a homogenous mixture. Depending on the engine operating circumstances, an electronic control unit (ECU) can regulate the injection timing and volume. Port injection has the advantage that it may be applied to existing engines and does not require significant engine modifications. In contrast to direct injection, it delivers

hydrogen more inefficiently.

5.1.2 Direct injection:

In this procedure, a fuel injector is used to deliver high pressure hydrogen gas straight into the combustion chamber. The combustion chamber's air and hydrogen gas combine to create a more uniform mixture. An ECU can be used to precisely manage the injection timing and volume. Direct injection has the advantage of having a higher hydrogen delivery efficiency than port injection, which leads to improved engine performance and lower emissions. But it necessitates considerable engine modifications, such as the installation of high-pressure fuel injectors and a separate hydrogen storage system.

5.2 HYDROGEN BLENDING:

Hydrogen blending involves mixing hydrogen gas with the diesel fuel in the fuel tank before entering the engine.

5.2.1 External mixing:

In this method, a blending system is used to combine hydrogen petrol and diesel fuel outside the engine. The current fuel system is then used to feed the engine with the blended fuel. The benefit of external mixing is that it does not necessitate significant engine or fuel system changes. In contrast to internal mixing, it delivers hydrogen more inefficiently.

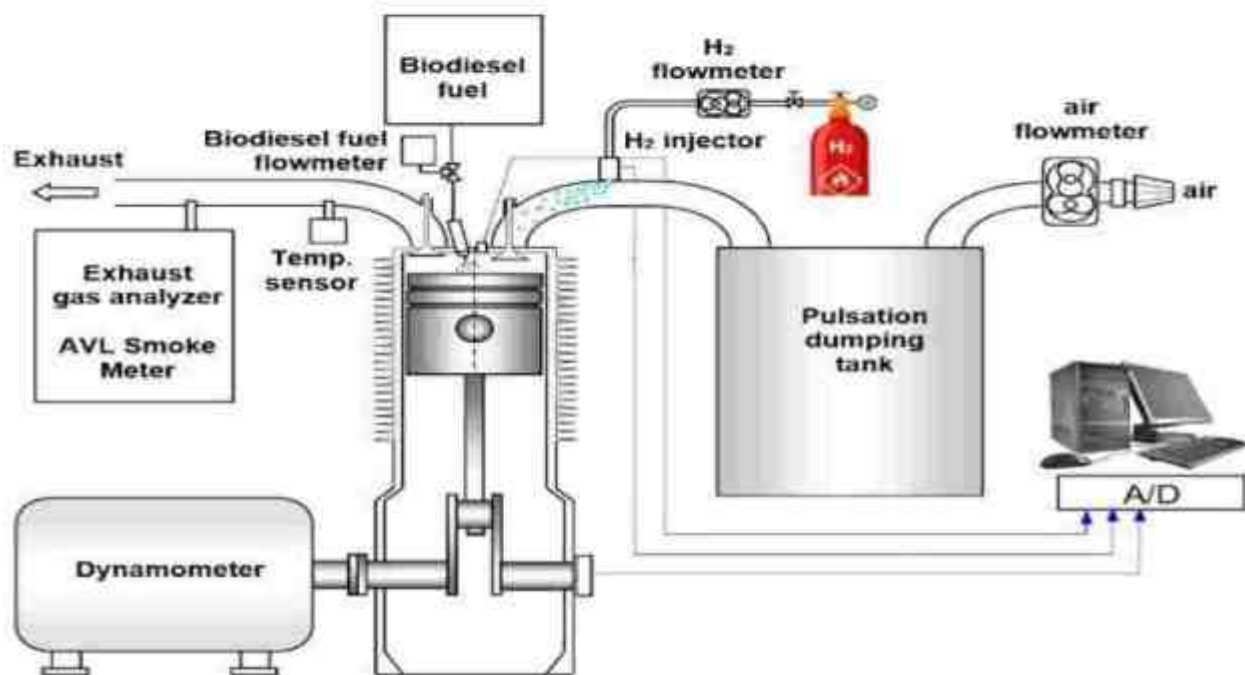
5.2.1 Internal mixing:

Inside the engine, hydrogen petrol and diesel fuel are blended using a specialized injector or mixer. The conventional diesel injection method is then used to ignite the blended fuel. Internal mixing has the advantage of having a higher hydrogen delivery efficiency than external mixing, which improves engine performance and

reduces emissions. However, it necessitates major engine changes, such as the installation of a unique injector or mixer and a separate hydrogen storage system.

5.3 DUAL FUEL COMBUSTION:

Dual fuel combustion involves using two different fuels in the same engine, namely diesel and hydrogen.



5.3.1 Pilot injection:

To ignite the hydrogen-air mixture, a small amount of diesel fuel is pumped into the combustion chamber as a pilot injection. After a brief interval, the hydrogen gas is then introduced into the combustion chamber to finish the combustion process. Pilot injection has the benefit of not requiring significant engine modifications and allowing the engine to continue operating solely on diesel fuel. However, compared to premixed combustion, it is less efficient at delivering hydrogen.

5.3.2 Premixed combustion:

Before entering the combustion chamber, hydrogen gas and air are combined using a specialized injector or mixer. A little amount of diesel fuel is then delivered straight into the combustion chamber, where it ignites the blended mixture. Premixed combustion has the advantage of having a higher hydrogen delivery efficiency than pilot injection, which leads to improved engine performance.

6.PROPERTIES COMPARISON OF HYDROGEN WITH ALTERNATE FUELS:

- **Energy content:** Compared to conventional fuels like petrol and diesel, hydrogen fuel has a lower energy content. The energy content of one kilogram of hydrogen is comparable to that of one gallon of petrol. However, compared to the batteries used in electric cars, hydrogen has a far higher energy content.
- **Availability:** The most prevalent element in the universe, hydrogen may be created from a variety of materials, including biomass, water, and natural gas. However, these sources demand a large amount of energy to produce hydrogen.
- **Emissions:** When utilized in fuel cell vehicles, hydrogen fuel emits no emissions, making it a clean energy source. However, the creation of hydrogen from fossil fuels may result in the emission of greenhouse gases.
- **Efficiency:** Compared to internal combustion engines, hydrogen fuel cells are more effective. Hydrogen can be energy-intensive to produce, store, and transport, which lowers overall efficiency.
- **storage:** Because hydrogen has a low density, it is difficult to store significant amounts of it. It can be kept under high pressure, in cryogenic tanks, or in chemical mixtures like hydrides or ammonia.
- **Cost:** Although hydrogen fuel production costs have been falling in recent years, they are still higher than those of traditional fuels like petrol and diesel. However, as production technology advances, the price of hydrogen fuel is anticipated to decline.
- **Infrastructure:** A network of hydrogen fuel production, storage, and refueling facilities needs to be established, although this infrastructure is still in its infancy.

PROPERTIES COMPARISON OF HYDROGEN WITH ALTERNATE FUELS

TABULATION:

Property	Gasoline /E10	Low sulfur diesel	Electricity	Biodiesel	ethanol/E100	Compressed natural gas (CNG)	Liquefied natural gas (LNG)	Propane (LPG)	Hydrogen	methanol
Chemical structure	C ₄ to C ₁₂ & ethanol ≤ to 10%	C ₈ to C ₂₅	N/A	Methyl esters of C ₁₂ to C ₂₂ fatty acids	CH ₃ CH ₂ OH	CH ₄ (majority), C ₂ H ₆ and inert gases	CH ₄ same as CNG with inert gasses <0.5%	C ₃ H ₈ (majority) and C ₄ H ₁₀ (minority)	H ₂	CH ₃ OH
Fuel material	Crude oil	Crude oil	Natural gas, coal, nuclear, wind, hydro, solar & small percentages of geothermal	Fats and oils from sources such as soy beans, waste cooking oil, animal fats & rapeseeds	Corn, grains or agricultural waste (cellulose)	Underground reserves and renewable biogas	Underground reserves and renewable biogas	A by-product of petroleum refining or natural gas processing	Natural gas, methanol, and electrolysis of water	Natural gas, coal, or woody biomass

			and bio mas s	eed						
Gas olin e or dies el gall on equi vale nt	1gal = 1.00GGE 1 gal = 0.88DGE	1gal = 1.12 GG E 1 gal = 1.00 DGE	1 kW h=0. 030 GG E 1k Wh =0.0 27 DGE	0.02 7 DG EB1 001 gal = 1.05 GG E 1 gal = 0.93 DGE B20 1 gal = 1.11 GG E 1 gal = 0.99 DGE	1 gal = 0.67 GGE 1 gal = 0.59 DGE	1 lb. = 0.1 8 GG E 1 lb. = 0.1 6 DGE	1 lb. = 0.19 GGE 1 lb. = 0.17 DGE	1 gal = 0.7 4 GG E 1 gal = 0.6 6 DGE	1 lb. = 0.45 GGE 1 lb. = 0.40 DGE 1 kg = 1 GGE 1 kg = 0.9 DGE	1 gal = 0.50 GGE 1 gal = 0.45 DGE
Ene rgy com pari son	97% - 100 % of energy in 1GGE is contain ed in 1 gallon of petrol.9 0% &	Due to dies el fuel high er ener gy den sity, 1gal lon	Wh en utili zed for tran spor tatio n, a typi cal batt	1 gall on of B10 0 has 93 % of the ene rgy	73% - 83% of the ener gy in 1 GGE can be foun d in	5.6 6 lb., or 12 3.5 7 ft3, of CN G ha s	5.37 lb. of LNG has the same energy as 1 GGE, and 6.06 lb. of LNG	1 gall on of pro pan e has 73 % of the ene	2.2 lbs. (1 kg) of H ₂ have the same energy as 1 GGE.	1 gallon of methan ol contain s 50% of the energy as 1 GGE.

	10% ethanol make up standard fuel	of Diesel has 113% more energy than 1 GGE	ery the size of a gallon of petrol (0.134 ft3) can store 15.3% of the energy in 1 GGE.	in 1 DGE, and 1 gallon of B20 has 99% of the energy in 1 DGE due to a lower energy density in biodiesel.	1 gallon of E85. 67% of the energy in 1 GGE is present in 1 gallon of E100. For the blending of oxygenate (a component of petrol), ethanol is combined with blend stock.	the same energy as 1 GGE, and 6.37 lb., or 13.30 ft3, of CNG has the same energy as 1 DGE	has the same energy as 1 DGE	ergy in 1 GGE due to the lower energy density of propane.		
Energy content (lower heating value)	112, 114-116, 090 Btu/gal (c)	128, 488 Btu/gal (c)	3,414 Btu/kWh	B100 119, 550 Btu/gal B20 126, 700 Btu/gal	76,330 Btu/gal for E100 (c)	20,160 Btu/lb.	21,240 Btu/lb.	84,250 Btu/gal	51,585 Btu/lb. 33.3 kWh/kg	57,250 Btu/gal

				(c)						
Energy content (higher heating value)	120,388 – 124,340 Btu/gal(c)	138,490 Btu/gal(c)	3,414 Btu/kWh	127,960 Btu/gal for B100 (c)	84,530 Btu/gal for E100 (c)	22,453 Btu/lb.	23,726 Btu/lb.	91,420 Btu/gal	61,013 Btu/lb.	65,200 Btu/gal
Physical state	Liquid	Liquid	Electricity	Liquid	Liquid	Compressed gas (lighter than air)	Cryogenic liquid (lighter than air as a gas)	Pressurized liquid (heavier than air as a gas)	Compressed gas (lighter than air) or liquid	Liquid
Cetane number	N/A	40 – 55 (t)	N/A	48 – 65 (t)	0 – 54 (e)	N/A	N/A	N/A	N/A	N/A
Octane number	84 – 93 (f)	N/A	N/A	N/A	110 (l)	120+	120+	105	130+	112
Flash point	-45°F (j)	165 °F(j)	N/A	212 ° to 338 °F(d)	55°F (j)	-30 °F	-306°F	-100 ° to -150 °F	N/A	54°F
Autoignition tem	495°F(j)	600 °F(j)	N/A	300 °F(d)	793°F(j)	1,004°F	1,004°F	850 ° to 950 °F	1,050° to 1,080°F	897°F

per atur e										
Mai nten anc e issu es				Lub ricit y is impr ove d over that of con vent iona l low sulf ur dies el fuel.	Spec ial lubric ants may be requi red. Pract ices are very simil ar, if not identi cal, to thos e for conve ntio nally fuele d oper ation s	Hig h- pre ssu re tan ks req uir e peri odi c ins pe ctio n an d cer tifi cati on.	LNG is stored in cryoge nic tanks with a specifi c hold time before the pressu re build is relieve d. The vehicle should be operat ed on a sched ule to mainta in a lower pressu re in the tank	N/A	When hydrog en is used in fuel cell applicat ions, mainte nance should be very minimal . High- pressur e tanks require periodi c inspecti on and certifica tion.	Special lubrica nts must be used as directe d by the supplie r as well as M85- compat ible replace ment parts. Can cause serious damag e to organs in the body if a person swallo ws it, breath es it in, or gets it on their skin.
Ene rgy sec urity imp act	Created with oil. 30% of all U.S energy needs and 70% of petroleu m use are	prod uce d usin g oil. Abo ut 30% of the	Elec tricit y is a vers atile fuel bec aus e it is	Bio dies el is dom esti call y pro duc ed, ren	Etha nol is prod uced dom estic ally. E85 redu ces lifecy	CN G is do me stic ally pro du ce d	LNG is domes tically produc ed from natural gas and renew able	App roxi mat ely half of U.S . LP G is deri	Hydrog en is produc ed domest ically and can be produc ed from renewa	Methan ol is domest ically produc ed, someti mes from renewa ble

	attribute d to transportation	nation's total energy requirements and 70% of petroleum use are attributed to transportation.	produced locally from a variety of sources, including through coal- fired power plants and renewable sources.	available, and reduces petroleum use 95% through its lifecycle	clean petroleum use by 70%, and E10 reduces petroleum use by 6.3%	from natural gas and renewable biogas. The United States has vast natural gas reserves	biogas . The United States has vast natural gas reserves	derived from oil, but no oil is imported specifically for LPG production	renewable sources	resources.
--	-------------------------------------	---	--	--	---	---	--	---	----------------------	------------

7.REVIEW ON IC ENGINE PERFORMANCE WITH HYDROGEN FUEL:

For more than a century, internal combustion engines (IC engines) have been the main form of propulsion in the automotive industry. However, because of their role in the production of greenhouse gas emissions, they have been linked to environmental issues. A clean, sustainable substitute for fossil fuels that has the potential to greatly lessen IC engines' negative environmental effects is hydrogen fuel. Comparing hydrogen fuel to traditional fossil fuels, there are a number of benefits. It is an excellent fuel for lowering emissions because it burns cleanly and only releases water as a byproduct. Additionally, it is a renewable fuel that may be created from a range of materials, such as biomass, natural gas, and water. Hydrogen is also an effective fuel for power generation due to its high energy content. The low energy density of hydrogen makes it one of the main obstacles to using it as a fuel in IC engines. Due to its low volumetric energy density, hydrogen gas requires more room

than fossil fuels to produce the same amount of energy. This issue can be resolved by employing liquid hydrogen or compressing hydrogen gas to make it denser. However, both techniques demand more equipment and energy, which could raise the price of using hydrogen as a fuel.

Hydrogen burns very quickly due to its fast flame speed. The combustion stability may suffer as a result, especially at low loads and speeds. A spark-ignition engine may find it challenging to ignite hydrogen due to its high auto-ignition temperature. Internal combustion engines that run on hydrogen (H_2 ICEs) are one of the most exciting uses for hydrogen fuel in IC engines. Though designed to run on hydrogen fuel, H_2 ICEs are similar to traditional petrol engines. Depending on the type of combustion being used, they can either be spark-ignition engines or compression-ignition engines. H_2 ICEs can reach great efficiency and minimal emissions, according to studies. According to one study, a hydrogen-fueled spark-ignition engine has a thermal efficiency of up to 40% compared to a gasoline engine's thermal efficiency of about 25%. The hydrogen engine had lower emissions of carbon monoxide, nitrogen oxides, and particulate matter than the petrol engine, according to the same study. In a similar vein, a study of a compression-ignition engine powered by hydrogen discovered that it had lower emissions of nitrogen oxides and particulate matter than a diesel engine.

Hydrogen fuel cell vehicles (FCVs) are a promising new use for hydrogen fuel in IC engines. In FCVs, hydrogen is transformed into energy by a fuel cell, which is then utilized to drive an electric motor. The fact that FCVs create no emissions at the tailpipe is their main benefit over H_2 ICEs. However, they call for a limited infrastructure for hydrogen refueling.

8.REVIEW ON IC ENGINE EMISSION WITH HYDROGEN FUEL:

For many years, the main form of propulsion has been internal combustion engines (ICEs), however they are also one of the main causes of air pollution. Numerous health issues, including as cancer, heart disease, and respiratory ailments, can be brought on by the emissions from ICEs. Researchers have been looking into using hydrogen as a fuel source for ICEs to cut emissions in recent years. When burned, hydrogen only emits water vapor and heat, making it a clean-burning fuel. This indicates that ICEs fueled by hydrogen don't release any damaging pollutants like carbon monoxide, nitrogen oxides, or particulates. In comparison to conventional petrol or diesel engines, hydrogen combustion can dramatically lower emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM), according to a study of the literature on hydrogen-fueled ICEs. The great combustion efficiency of hydrogen, which produces complete combustion and little pollutant production, is to blame for this reduction in emissions.

Studies have demonstrated that when compared to conventional petrol or diesel engines, ICEs fueled by hydrogen can dramatically lower pollutants. A hydrogen-powered engine produced 99% less carbon monoxide, 80% less nitrogen oxides, and 60% less particulate matter than a gasoline-powered engine, according to research from the University of California, Riverside.

Before hydrogen can be employed as a common fuel for transportation, however, there are still several obstacles to be solved. The expense and infrastructure needed to create and deliver hydrogen fuel are a significant obstacle. Only a small number of hydrogen filling stations are now accessible, and the price of manufacturing hydrogen is still very high when compared to other fuels. Additionally, because hydrogen has a poor energy density compared to conventional fuels, it necessitates larger fuel tanks

or more frequent refueling. For automakers, who must create vehicles that can properly store and use hydrogen, this can be a difficult design task.

8.1 EMISSION PERFORMANCE:

An ICE powered by hydrogen will operate best under certain operating circumstances and engine design. In general, enhanced combustion properties and lower emissions can be obtained when using hydrogen as a fuel in ICEs. Hydrogen burns quickly and completely, resulting in increased thermal efficiency and less emissions. This is due to its high flame speed and short ignition latency.

Numerous studies have demonstrated the remarkable thermal efficiency and power output that hydrogen-fueled ICEs are capable of. For instance, a study by Cho et al. (2017) that examined the performance of a hydrogen-fueled spark ignition (SI) engine discovered that it had a greater thermal efficiency than petrol engines, up to 45%. Additionally, the engine's minimal NO_x and PM emissions were discovered by the study, proving that hydrogen may be a clean-burning fuel.

8.2 EMISSION:

Pollutant emissions including NO_x, PM, and GHG can be significantly reduced when hydrogen is used as the fuel in ICEs. Because hydrogen combustion only emits water as a byproduct, there are no emissions of the strong greenhouse gas CO₂.

Studies that have looked at the emissions of ICEs running on hydrogen have found that these engines emit just small amounts of pollutants. For instance, a study by Shen et al. (2018) that looked at the emissions of a SI engine powered by hydrogen discovered that the engine produced extremely low levels of NO_x and PM emissions. The study also discovered that the engine had lower CO₂ emissions than engines powered by petrol.

8.3 CHALLENGES:

Despite the potential advantages of using hydrogen as an alternative fuel for ICEs, there are still several obstacles that must be overcome before this technology can be widely adopted. The low energy density of hydrogen, which necessitates a higher storage volume compared to more conventional fuels like petrol or diesel, is one of the key problems. Costs may rise as a result, and driving range may be affected. Another issue is hydrogen's severe flammability, which necessitates specialized safety protocols and infrastructure to ensure secure handling and storage. Additionally, there isn't much infrastructure in place for hydrogen production, storage, or delivery, which could reduce availability and raise costs.

9.STRATEGIES TO IMPROVE IC ENGINE PERFORMANCE:

For more than a century, internal combustion engines (IC engines) have been a popular option for propulsion systems in automobiles. There has been a move towards alternative fuels, particularly hydrogen, as environmental worries about the use of fossil fuels have grown. A fuel that burns cleanly, hydrogen emits only water vapor and no hazardous byproducts.

9.1 INCREASE THE COMPRESSION RATIO:

Increasing the compression ratio is one of the best strategies to make an IC engine run better when using hydrogen fuel. Due to its high-octane rating, hydrogen can endure high compression ratios without exploding. Higher compression ratios enable more thorough fuel burning, which results in more power and improved fuel economy. To avoid engine damage from the greater pressures, however, increasing the compression ratio necessitates careful consideration of engine design and

materials.

9.2 OPTIMIZE THE IGNITION TIMING:

When the spark plug ignites and ignites the fuel-air mixture in the engine, it depends on the ignition timing. Engine performance can be greatly enhanced by tuning the ignition time for hydrogen fuel. Because hydrogen has a quick flame, it burns more quickly than conventional fuels like petrol. As a result, improving ignition timing to happen earlier in the engine cycle might result in more complete combustion and higher power.

9.3 USE ADVANCED ENGINE MATERIALS

Because hydrogen fuel has a high energy content, it can provide more power than other fuels. But it also implies that additional heat may be produced, which could harm engine parts. To reduce heat and improve engine durability, modern engine materials like carbon fiber and ceramic can be used.

9.4 ENGINE MODIFICATION:

An IC engine must undergo several modifications to run on hydrogen fuel. The fuel system will be converted to a hydrogen injection system as the initial alteration. The hydrogen injection system is comparable to a conventional fuel injection system, except rather than fueling the engine with petrol, it fuels it with hydrogen. The engine's compression ratio is being raised as the second alteration. Since hydrogen has a greater octane rating than petrol, a higher compression ratio can be used by the engine. Better performance results from an engine's efficiency being increased through higher compression ratios.

9.5 COOLING SYSTEM:

Compared to petrol engines, hydrogen fuel engines emit more heat. Therefore, to stop the engine from overheating, a more effective cooling system is needed. To keep the engine operating at ideal temperatures, the cooling system must be able to handle the additional heat generated by the engine.

9.6 LUBRICATION SYSTEM:

Because hydrogen is a dry fuel, it doesn't lubricate the engine in any way. To ensure that the engine is adequately lubricated, the lubrication system must be adjusted. One option is to lubricate the engine by blending a little amount of oil with the hydrogen fuel. Altering the engine to utilize a new lubricant that is more suited to hydrogen fuel is another option.

10. TECHNO-ECONOMIC ANALYSIS:

Hydrogen fuel is receiving more attention as a potential replacement for conventional fossil fuels in the transportation industry as the focus on decreasing carb on emissions grows. Internal combustion engines, such as compression ignition engines, which are frequently seen in heavy-duty vehicles like trucks and buses, can run on hydrogen fuel. The purpose of this techno-economic analysis is to assess if using hydrogen fuel in a compression ignition engine is practical.

10.1 Technical feasibility:

A procedure known as hydrogen compression ignition (HCCI) allows hydrogen fuel

to be used in compression ignition engines. In this method, hydrogen is heated and compressed to high pressures, which causes it to ignite spontaneously. The great efficiency and low emissions of HCCI have been demonstrated, making it a potential technology for cutting carbon emissions in the transportation industry. However, there are other technical difficulties with HCCI, such as the requirement for high-pressure fuel storage systems and the need for accurate combustion process control to avoid engine knock.

10.2 Economic feasibility:

The cost of hydrogen fuel, the price of the engine and its related components, and the cost of the infrastructure needed to manufacture and distribute hydrogen fuel are only a few of the variables that affect whether using hydrogen fuel in a compression ignition engine is economically feasible. Currently, the price of hydrogen fuel is higher than that of conventional fossil fuels, in part because the infrastructure for its production and transport is more expensive. However, as production technologies advance and economies of scale are realized, it is anticipated that the price of hydrogen fuel would fall in the upcoming years. In comparison to conventional diesel engines, employing hydrogen fuel in a compression ignition engine may result in cheaper maintenance costs. Hydrogen combustion generates less pollutants that might harm engine parts, necessitating less frequent maintenance and repairs. The necessity for specialized equipment, however, may result in a greater starting cost for the engine and related parts than for conventional diesel engine.

10.3 Environmental feasibility:

Compared to using conventional fossil fuels, using hydrogen fuel in a compression ignition engine has the potential to drastically lower carbon emissions. Nitrogen oxides and particulate matter are not produced when hydrogen is burned; instead, only water vapor is produced as a byproduct. The environmental advantages of hydrogen fuel, however, depend on the method used to manufacture the hydrogen. Currently, the majority of hydrogen is made from natural gas via a method called steam methane reforming, which also results in the production of carbon dioxide. Alternative manufacturing techniques, such as electrolysis driven by renewable energy sources, must be developed and scaled up to fully realize the environmental benefits of hydrogen fuel.

11.FUTURE DIRECTIONS:

The implementation of hydrogen fuel in CI engines is headed in a favorable direction. Recent research has shown that it is possible to overcome these hurdles and obtain high efficiency and low emission levels in CI engines despite the difficulties associated with using hydrogen fuel. Continued study in this field is necessary to enhance hydrogen combustion in CI engines and create new technologies that can enhance the handling and storage of hydrogen fuel.

12.CONCLUSION:

Because it emits substantially less pollution than typical fossil fuels, hydrogen fuel has the potential to be a viable replacement for internal combustion (CI) engines. Hydrogen fuel is also renewable and can be created in a variety of ways, including electrolysis of water using renewable energy sources like solar or wind power. However, there are a number of drawbacks to using hydrogen fuel in CI engines. For example, hydrogen has a lower energy density than petrol or diesel, which implies that more fuel would be required to produce the same amount of power. Furthermore, hydrogen is highly combustible and must be handled and stored with caution. To summaries, while hydrogen fuel shows promise as a potential replacement for CI

engines, further research and development is required to solve the technical and logistical obstacles involved with its utilization.

13. REFERENCES:

- [1] Garni M. A simple and reliable approach for the direct injection of hydrogen in internal combustion engines at low and medium pressures. *Int J Hydrogen Energy* 1995;20:723e6.
- [2] Das LM. Near-term introduction of hydrogen engines for automotive and agricultural application. *Int J Hydrogen Energy* 2002;27:479e87.
- [3] Tsolakis A, Megaritis A. Partially premixed charge compression ignition engine with on-board H₂ production by exhaust gas fuel reforming of diesel and biodiesel. *Int J Hydrogen Energy* 2006;30:2448e57.
- [4] Syed Y, Masood M. Effect of ignition timing and compression ratio on the performance of a hydrogen eethanol fuelled engine. *Int J Hydrogen Energy* 2009;34:6945e50.
- [5] Szwaja S, Rogalinski KG. Hydrogen combustion in a compression ignition diesel engine. *Int J Hydrogen Energy* 2009;34:4413e21.
- [6] Ali HM, Ali A. Measurements and semi-empirical correlation for condensate retention on horizontal integral-fin tubes: effect of vapour velocity. *Appl Therm Eng* 2014;71(1):24e33.
- [7] Porpatham E, Ramesh A, Nagalingam B. Effect of hydrogen addition on the performance of a biogas fuelled spark ignition engine. *Int J Hydrogen Energy* 2007;32:2057e65.
- [8] Kahraman N, Ceper B, Akansu SO, Aydın K. Investigation of combustion characteristics and emissions in a spark-ignition engine fuelled with natural gas e hydrogen blends. *Int J Hydrogen Energy* 2009;34:1026e34.
- [9] Wang J, Chen H, Liu B, Huang Z. Study of cycle-by-cycle variations of a spark ignition engine fueled with natural gas e hydrogen blends. *Int J Hydrogen Energy* 2008;33:4876e83.
- [10] Bauer CG, Forest TW. Effect of Hydrogen addition on the performance of methane-fueled vehicles. Part I: effect on S.I. engine performance. *Int J Hydrogen Energy* 2001;26:55e70.
- [11] Saravanan N, Nagarajan G, Dhanasekaran C, Kalaiselvan KM. Experimental investigation of hydrogen port fuel injection in DI diesel engine. *Int J Hydrogen Energy* 2007;32:4071e80.
- [12] Varde KS, Varde LK. Reduction of soot in diesel combustion with hydrogen and different H/C gaseous fuels. In: *Proceedings of the 5th world hydrogen energy conference*; 1984. Toronto, Canada.
- [13] Lee JT, Kim YY, Lee CW, Caton JA. An investigation of a cause of backfire and its control due to crevice volumes in a Hydrogen fueled engine. *ASME* 2001;123.
- [14] Lee Jong T, Kim YY, Caton Jerald A. The development of a dual injection Hydrogen fueled engine with high power and high efficiency. In: *2002 fall technical conference of ASME/ICED*; 8e11 September, 2002. p. 2e12.
- [15] Brent Bailey, James Eberhardt, Steve Goguen, Erwin Jimell.

- Diethyl ether (DEE) as a renewable diesel fuel. J Fuel Lubr 1996;106 [Section 3, SAE 972978, SAE transactions].
- [16] Furuhashi S, Yamane K, Yamaguchi I. Combustion improvement in Hydrogen fueled engine. Int J Hydrogen Energy 1977;2:329e40.
- [17] Tomita E, Kawahara N, Piao Z, Fujita S, Hamamoto Y. Hydrogen combustion and exhaust emissions ignited with diesel oil in a dual-fuel engine. SAE technical paper no. 2001-01-3503. 2001.
- [18] Senthil Kumar M, Ramesh A, Nagalingam B. Hydrogen Induction for improving the performance of a vegetable oil fueled CI Engine. In: Proceedings of the international conference on waste to energy; 2002. Jaipur, India.
- [19] Senthil Kumar M, Ramesh A, Nagalingam B. Use of Hydrogen to enhance the performance of a vegetable oil fuelled compression ignition engine. Int J Hydrogen Energy 2003;28:1143e54.
- [20] Saravanan N, Nagarajan G. An experimental investigation of Hydrogen-enriched air induction in a diesel engine system. Int J Hydrogen Energy 2008;33:1769e75.
- [21] Saravanan N, Nagarajan G, Sanjay G, Dhanasekaran C, Kalaiselvan KM. Combustion analysis on a DI diesel engine with Hydrogen in dual fuel mode. Fuel 2008;87:3591e9.
- [22] Dec JE. A conceptual model of DI diesel combustion based on laser-sheet imaging. SAE Paper. 1997. 970873.
- [23] Dec JE, Kelly-Zion PL. The effect of injection timing and diluent addition late combustion soot burnout in a DI diesel engine based on simultaneous 2-D imaging of OH and soot. SAE Paper. 2000. 200001-0238.
- [24] Michael FJ, Brunt Harjit Rai. The calculation of heat release energy from engine cylinder pressure data. J Fuel Lubr 1998;107 [Section 4, SAE 981052, SAE transactions].
- [25] Naber JD, Siebers DL. Hydrogen combustion under diesel engine conditions. Int J Hydrogen Energy 1998;23(5): 363e71.
- [26] Saravanan N, Nagarajan G, Kalaiselvan KM, Dhanasekaran C. An experimental investigation on Hydrogen as a dual fuel for diesel engine system with exhaust gas recirculation technique. Renew Energy 2008;33:422e7.
- [27] Bari S, Esmail MM. Effect of H₂/O₂ addition in increasing the thermal efficiency of a diesel engine. Fuel 2010;89:378e83.
- [28] Demirbas
 , A. Fuel properties of Hydrogen, liquefied petroleum gas (lpg), and compressed natural gas (cng) for transportation. Energy Sources 2002;22:601e10.
- [29] Mitchell W, Bowers BJ, Garnier C, Boudjemaa F. Dynamic behavior of gasoline fuel cell electric vehicles. J Power Sources 2006;154:489e96.
- [30] Gjirja S, Olsson E, Olsson L, Ekman S. Experimental investigation on the Hydrogen peroxide fumigation into the inlet duct of a diesel engine. SAE technical paper no. 2001-01-1919. 2000.