

Review of Hydrogen as a Fuel in IC Engines

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Abstract: *The Internal Combustion Engines are used widely in present generation. The internal combustion engine is an engine in which the combustion of a fuel occurs with an oxidizer in a combustion chamber that is an integral part of the working fluid flow circuit. Hydrogen plays an important role for energy diversity. It stores energy from different local sources which includes clean nuclear, coal, and various available renewables for use in many applications. Vehicles operating on hydrogen can dramatically reduce our nation's dependence on oil and significantly reduce tailpipe emissions. Hydrogen offers a potential means to store and deliver energy from locally available resources—while reducing our nation's economy on fossil fuels. This paper presents the use of Hydrogen as an alternative fuel in IC engines and relevant facts and scope for future work. This paper also focuses on different researches and existing method of hydrogen generation system for producing hydrogen and injecting the hydrogen as a fuel supplement into the air intake of carburettor. Detailed review of the work in combustion and emission characteristics was done. The scope of this paper is to perform a detailed review of the use of Hydrogen in IC engines. The data about production, storage, and the effects of hydrogen on performance of engines was collected from research papers of various authors and then systematically presented here.*

Keywords: hydrogen, emission, combustion, emission, etc

1. Introduction

Transportation is one of the main pillars of this modern world and the world is witnessing fast changing trends in this field. IC engines have been a part and parcel of the transportation facilities available for many years.

Traditional fossil fuels such as petroleum, natural gas and coal, which feed most of the world's energy demand today, are being vanishes rapidly. Also, their combustion products are causing global problems, such as the greenhouse effect, ozone layer depletion, acid rains and pollution, which are posing great danger for our environment, and eventually, for the total life on our planet. Many scientists depicted that hydrogen will be one of the clean alternative fuel for traditional fossil fuels. Hydrogen is a very efficient and clean fuel. Its combustion produces no greenhouse gases, no ozone layer depleting chemicals, and little or no acid rain ingredients and pollution. Hydrogen, produced from renewable energy (solar, wind, etc.) sources would result in a permanent energy system which would never have to be changed. Due to the increasing consumption of these fuels, the prices of these fuels are on a rising note. Also, the stringent emission norms adopted by most of the countries have made developers to think on reducing the emissions from these engines. Different methods like EGR, turbocharging and supercharging, engine head modifications have been made and they have been taken to a most optimal level till date. But, only providing such measures is not useful in the upcoming emission norms which would be more stringent than ever before. Hence researchers have come forward with various fuels that can be used in place of gasoline and diesel or the diesel or gasoline can be used as a pilot fuel and the other fuels as main fuel. Here, Hydrogen comes into picture. India is a very large country by means of area with large number of population. Thus there is large demand for transportation vehicle which demands fossil fuels. Fossil fuel is the traditional source of fuel which meets most of the demand. Petroleum and its derivatives are in the phase of depletion. The combustion of the fossil fuels releases CO₂, CO, NO_x, SO_x, C_nH_m which all are responsible for global problems, such as greenhouse effect,

acid rain, ozone layer depletion and pollution. Thus there is a necessity of reliable alternative fuel which should overcome drawbacks of fossil fuels. Many researches prove that hydrogen as an alternative fuel which provides clean burning and ecofriendly performance.

1.1 Hydrogen as a fuel

Hydrogen is an odourless gas which is very light in weight. It is in the gaseous state at room temperature. At ordinary temperature and pressure it has the density of 0.08375 kg/m³. The main properties of Hydrogen as compared with other fuels used in IC engines given by Dimitriou et al. are listed in the Table 1 [1]. It is seen from the table that the auto-ignition temperature of hydrogen is more as compared to both Gasoline and Diesel. Hence it is easier for hydrogen to be used as a standalone fuel in SI engine as compared to CI engine. There is a need for pilot fuel to be used in case of CI engine. It is also seen that the energy content of Hydrogen is tremendous which makes it a suitable option for use as an alternative fuel. It is this energy content that has attracted a lot of researchers to develop safe and efficient methods of using hydrogen as a primary fuel in IC engines. Hydrogen also has a wide flammability range which makes it useful in wide range of air fuel ratios. The concern with hydrogen is the low ignition energy required which leads to the condition of knocking. The other concern is the effective and efficient storage of hydrogen.

Table 1: Comparison of properties of different fuels

Properties	H ₂	Natural Gas	Gasoline	Diesel
Density at NTP (kg/m ³)	0.09	0.7-0.9	737	820-950
Energy Content (MJ/kg)	120-142	53.6	46.4	48
Auto-ignition temperature (K)	858	813	520-583	473
Flammability Limits (% gas-to-air-volume ratio)	4-75	5-15	1.4-7.6	0.6-7.5
Minimum ignition energy (mJ)	0.02	0.29	-	-
Quenching gap at NTP (mm)	0.64	2.1	-	-
Diffusion coefficient into air at NTP (cm ² /s)	0.61	0.24	-	-

1.2 Properties of Hydrogen

There are various characteristics of hydrogen which are very useful for effective and clean emission from engine as well as engine performance.

- A. Wide Range of Flammability.** As compared to other fuels, hydrogen has a wide flammability range (4-74% versus 1.4-7.6% volume in air for gasoline). This leads to obvious concerns regarding the handling of hydrogen. But, hydrogen has wide range of fuel-air mixtures, including a lean mixture of F/A. Lean mixture allows engine with clean and complete combustion of fuel. There will be lower combustion temperature, which further lowers the emissions such as nitrous oxides (NO^x).
- B. Low Ignition Energy.** Amount of energy needed to ignite hydrogen fuel is too less than gasoline. (0.02 MJ for hydrogen and 0.2 MJ for gasoline). It creates proper ignition of hydrogen. There may be chances of pre ignition phenomenon or flash back due to low ignition energy.
- C. Small Quenching Distance.** Hydrogen has a very small quenching distance of 0.6mm for hydrogen (which is very greater than 0.2 mm for gasoline), which is the distance from the internal cylinder wall where flame diminishes. Thus it is a difficult task to quench a hydrogen flame than the flame of other fuels.
- D. High Flame Speed.** Hydrogen has a burning flame speed, which allows hydrogen engines nearer to ideal engine cycles. It has most efficient fuel power ratio when the stoichiometric fuel mixture is used. However, when the engine runs on lean mixture to improve fuel economy, flame speed slows significantly.
- E. High Diffusivity.** Hydrogen gets disperses quickly into air, which allows a more uniform fuel air mixture, It also decreases major safety issues from hydrogen leaks.
- F. Low Density.** Low density of hydrogen is a one of the major problem regarding with hydrogen storage. Without too much compression or conversion of hydrogen to a liquid, a large volume of fuel required to store enough hydrogen to provide an engine energy demand. Low density means fuel-air mixture which will be produced will have low energy density, Due to which it reduces the power output of the engine. There are issues of inadequate power when hydrogen engine runs of lean mixture.[2]

1.3 Method of Producing Hydrogen

Hydrogen can be easily produced in school classrooms by electrolysis of water, using Hofmann Voltmeter. These simple experiments suggest that water is made up of two parts of hydrogen and one part of oxygen. The main resource that has been applied for production of hydrogen is fossil fuel. There are numerous processes for the production of hydrogen from fossil fuels. Currently steam reforming process from the hydrocarbons is widely used. Other methods of hydrogen production from fossil fuels include partial oxidation, plasma reforming, petroleum coke and coal. Generation of hydrogen can be done from water using electrolysis, radiolysis, photo catalytic water splitting, and electrolysis. As a reactive nature, hydrogen seldom appears naturally as a pure gas. To consider the hydrogen as energy

carrier, the technology must be developed to produce pure hydrogen economical [3]

Hosseini et al. has described the various methods of production of hydrogen [4]. They had prepared a flowchart comprising the hydrogen development, production and storage. The main methods of production of Hydrogen are listed below.

Table 2: Methods of producing hydrogen [3]

Methods	Process
Steam Reforming of Methane gas	In presence of nickel as catalyst & at 700 – 1100 °C $CH_4(g) + H_2O(g) \rightarrow CO(g) + 3H_2(g)$ Next reaction at lower temperature: $CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$ Current major source of hydrogen
Electrolysis of water	Electric current will pass through water Reaction: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$ Not used widely due to cost of electricity
Hydrogen from Coal (Gasification)	At high temperature and pressure: $Coal + H_2O(g) + O_2(g) \rightarrow syngas$ $Syngas = H_2 + CO + CO_2 + CH_4$ Current method of mass production of hydrogen
Solar – Hydrogen System	Electric current passed through water: $2H_2O(l) \rightarrow 2H_2(g) + O_2(g)$ Not used widely due to cost of renewable source of energy

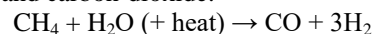
A. Water electrolysis

The splitting of water into hydrogen and oxygen using electricity is known as electrolysis. It consists of two electrodes immersed in an aqueous conducting solution called electrolyte. A DC current is passed through the electrodes, which splits the water in the electrolyte into water and hydrogen. Theoretically, this is the simplest form of hydrogen generation. This technology suffers from a disadvantage as an energy conversion system because its raw energy requirement must be supplied as a high quality energy form: electricity [5]. Also in the current water electrolysis technique, the electrodes are plated with platinum hence the process is not cost effective [4].

B. Natural Gas reforming

This technique is the most common and widely used technique for the production of hydrogen. 95 % of the total hydrogen produced in the United States comes from this technique. Natural Gas contains methane that can be used to produce hydrogen with thermal processes such as steam-methane reformation and partial oxidation.(Source: energy.gov)

Steam-methane reforming technique creates an environment in which methane (CH₄) reacts with steam(3-25 bar) in the presence of a catalyst to produce hydrogen (H₂), carbon monoxide (CO) and carbon-dioxide.



In partial oxidation method, methane and other hydrocarbons react with less amount of oxygen than needed for a stoichiometric reaction. This results in hydrogen and carbon monoxide as main products with fewer amounts of carbon dioxide and other compounds.



C. Gasification

It is process where coal is burned at about 1200°-1500°C to convert into gaseous components. The product of this reaction is processed to form hydrogen and carbon monoxide.

1.4 Hydrogen Storage Methods

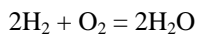
Hydrogen is conveniently stored in high pressure cylinders under a pressure of 35-70 MPa. This method of storage is very bulky because large quantities of steels are required to contain small quantities of hydrogen. In case of an accident, hydrogen is released instantaneously that causes explosion. Car manufacturers such as Honda and Nissan use this type of storage [6].

A more practical approach of storing hydrogen is the cryogenic technique in which hydrogen is stored at 21.2 K in cryogenic tanks. There are different drawbacks in this technique. Flammability danger comes into picture because liquefied gases of atmosphere would come in the vicinity of hydrogen storage tanks. Other problem lies in the energy required to convert hydrogen into liquid form. 25-30% of heating value of hydrogen is required to liquefy hydrogen.

A number of alloys and metals form solid compounds called metal hydrides, by direct reaction with hydrogen gas. When the hydride is heated, hydrogen is released and the original metal is recovered for further usage. Metal hydride is one of the solution for storage problem regarding hydrogen. The most promising hydrides are those of lanthanum nickel (LaNi₅)H₆, iron titanium (FeTi)H₂, and magnesium nickel (Mg₂NiH₄). The most common drawback of metal hydrides is the high cost and the ineffectiveness of metal or the alloy after some cycles. [5]

1.5 Stoichiometric Air/Fuel Ratio

The minimum amount of air required for complete and clean combustion (Gillingham, January 2007) of a fuel is known as Stoichiometric or Theoretical fuel. This is defined as the ratio of mass of m_a/m_f, which is required for stoichiometric combustion. Quantity of air required to complete combustion without any residual of oxygen. The stoichiometric combustion of hydrogen and oxygen is given as:



Moles of H₂ required for complete combustion = 2 mole

Moles of O₂ required for complete combustion = 1 mole

Because air is used as the oxidizer instead of oxygen, the nitrogen in the air should be included:

Moles of N₂ in air = Moles of O₂ x (79% N₂ in air / 21% O₂ in air)

$$= 1 \text{ mole of O}_2 \times (79\% \text{ N}_2 \text{ in air} / 21\% \text{ O}_2 \text{ in air})$$

$$= 3.762 \text{ moles N}_2$$

Number of moles of air = Moles of O₂ + Moles of N₂

$$= 1 + 3.762$$

$$= 4.762 \text{ moles of air}$$

Weight of O₂ = 1 mole of O₂ x 32 g/mole

$$= 32 \text{ g}$$

Weight of N₂ = 3.762 moles of N₂ x 28 g/mole

$$= 105.33 \text{ g}$$

Weight of air = weight of O₂ + weight of N₂

$$= 32\text{g} + 105.33 \text{ g}$$

$$= 137.33 \text{ g}$$

Weight of H₂ = 2 Moles of H₂ x 2 g/mole

$$= 4 \text{ g}$$

Stoichiometric air/fuel (A/F) ratio for hydrogen and air is:

A/F based on mass: = mass of air/mass of fuel

$$= 137.33 \text{ g} / 4 \text{ g}$$

$$= 34.33:1$$

From the above calculation it is seen that the stoichiometric A/F ratio for the complete combustion of hydrogen and air mixture is about 34:1 by mass. This means that 30kg of air are required for complete combustion of every kg of hydrogen. This is much higher than 14.7:1 A/F ratio which is required for gasoline. [3]

2. Literature Review

A. Hydrogen as a fuel in SI engines

S.Naveen, C. P. Kiran, M. Prabhu Das, P. Naga Dilip, Dr. V.V. Prathibha Bharathi et al. in his work they demonstrated and concluded higher efficiency of electrolysis was found with lesser distance between the electrodes. Specific features of the use of hydrogen as an engine fuel were analysed. Results of the tests stated that there will be low power generation at low speeds whereas high speed characteristics could compete with gasoline performance. [7]

Craig Davis, Bill Edelstein, Bill Evenson, Aviva Brecher et al. studied hydrogen fuel cell as well as different hydrogen storage system they also provide the safety features related to the hydrogen storage. [8]

Phool Chand, Mukesh Kumar et al. in their work, they had given some design modification required for using hydrogen as a fuel in existing four stroke gasoline engine that has been discussed. The change in values of torque, power, BTE, BMEP, exhaust gas temperature, and emissions of NO_x, CO, CO₂, HC, and O₂ versus engine speed are compared for a carburetted SI engine operating on gasoline and hydrogen. [9]

Shivaprasad K.V, Dr. Kumar G.N, Dr. Guruprasad K.R et al. studied the emission and performance characteristics of hydrogen fuelled SI engine. [10]

Mr. Deorukharsairaj R., Prof. Bhosale M.R., Mr. Salunkhe M.R., Prof.Gulavane T.S. et al. performed an experimental analysis for hydrogen as a supplementary fuel in 4 stroke ice. [11]

Vvn Bhaskar Dr. R. Hari Prakash Dr. B. Durga Prasad et al. they also studied the causes of abnormal combustion effects of hydrogen SI engine. An overview is given of the development by car manufacturers and also of the Research at the Laboratory of Transport Technology, Ghent University. [12]

Kirtan Aryal et al.they presented their work in this paper which reviews theproduction of hydrogen, Performance and emission of hydrogen fuelled IC engines which gives idea about various researches has been made in hydrogen as a fuel in ICE. [3]

Kenneth Gillingha et al. in his studies he stated about various fuel adoption technologies, various economy of hydrogen ice, etc. [2]

B.Rajendra Prasath, E.Leelakrishnan, N. Lokesh, H. Suriyan, E. Guru Prakash, K. Omur Mustaq Ahmed et al. their study focusing the various aspects and usage of hydrogen fuel in SI engine and CI engine. [13]

Ahmed Taha, Tarek Abdel-Salam, Madhu Vellakal et al. performed a comparative study on hydrogen, biodiesel and ethanol for ice. [14]

S. K. Sharma, P. Goyal And R. K. Tyagi et al. work specifically challenges with the use of hydrogen driven engines in automobile sectors. They had given possible suggestions to make this technology commercially viable. [15]

Aaditya, Abhishek, Ajay, Vipin, Deepak et al. performed an experiment in which gas generation by electrolysis is used for driving bike with gasoline and there performance parameters are measured. These results are such that which increases th mileage of bike by 30 to 60% and reduce the polluting contents from the exhaust gases.

Moreno1, M. Muñoz, O. Magén, C. Monné, J. Arroyo et al. work is mainly focusing on modifications of engine for hydrogen and methane engine. [16]

Medhat Elkelawy, Hagar Alm-Eldin Bastawissi, et al. performed a Numerical investigation to study the effect of using the Hybrid control strategy of pfi + di, and lean combustion To obtain maximum engine power outputs with an acceptable Efficiency which is equivalent to gasoline engines. [17]

Niculae Negurescu, Constantin Pana, Marcel Ginu Popa, And Alexandru Cernat et al. work is specifically on making comparison with gasoline and hydrogen fuel engines. [18]

P.R.Chitragara, Shivaprasad K.Vb, Vighnesh Nayaka, P.Bedara, Kumar G.Na et al.performed an comparative analysis of gasoline, hydrogen and LPG fuelled ice. [19]

As discussed earlier, the higher flammability of hydrogen, excessive energy content, high diffusivity and low ignition energy requirement makes hydrogen a great contender for fuel use in IC engines. But due to unstable operation, engines are operated at an equivalence ratio of 0.4-1. The wide flammability of hydrogen makes it capable for the fuel to be used for ultra-lean operation[20]. Fig. 1 below shows the range of equivalence ratio for engine operations.

Many researchers have carried out work on the use of hydrogenfuel for the SI engine operation. Hydrogen having a high self-ignition temperature requiresa spark plug for its combustion and hence gasoline fuelledengines are a better choice for hydrogen only operation.

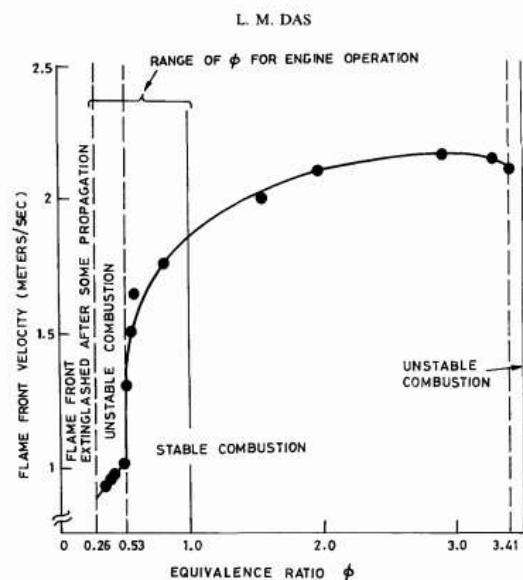


Figure 1: Equivalence ratio ϕ vs flame front velocity of hydrogen [20]

a) Combustion Characteristics

Jabbar AI et al. have studied various operating parameters of hydrogen fuelled spark ignition operation using computational methods [21]. The engine was a single cylinder gasoline engine working on 9:1 compression ratio and with a displacement volume of 530 cc. The engine ran at 2500 rpm. They found out that the power and efficiency of the engine were highly dependent on the in cylinder temperature and pressure. As ϕ increases the in cylinder pressure and temperature increases which results in greater combustion and greater efficiency. But at richer mixtures the required amount of air was not easily available and hence it led to the reduction in efficiency as well as BTE. They concluded that 0.7-1.1 was the best equivalence ratio for greater BTE and efficiency. Krishnan Unni J et al. in their research work developed 15 hydrogen- gasoline convertible three wheeler vehicles which could be used for transportation purposes in New Delhi area[20]. The engine studied by them was 396 cc gasoline engine with carburettor modified for duel fuel operation. Compression ratio of 9.5:1 was selected for optimisation and spark plug gap was kept at 0.4 mm. ECU was also kept for receiving various inputs of sensor for better performance of engines. The tests were carried out at wide throttle open position with varying speed, ϕ varied between 0.45-0.6. The experimental setup is as shown in the figure.[20]

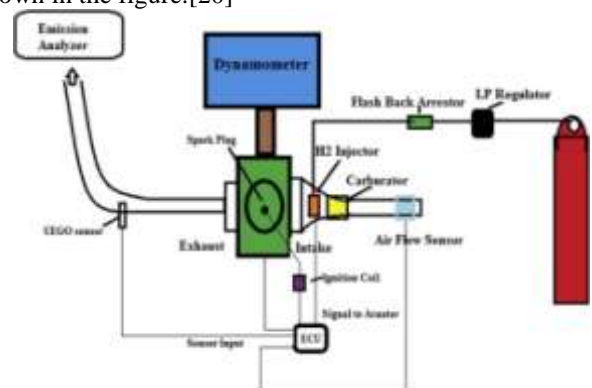


Figure 2: Layout of various components in the engine [20]

Fig.2 shows the layout of various components used by them in the engine. The researchers found out that the hydrogen operation resulted in a flat torque curve with a maximum torque of 13.2 Nm at 3200 rpm whereas gasoline engine produced a maximum torque of 19.5 Nm at 2800 rpm. This was because of the leaner operation to curb NO_x emissions in case of Hydrogen. Fig. 3 shows the variation of torque VS speed. The BTE obtained was higher in case of hydrogen engines due to leaner fuel mixture and high energy content of hydrogen. The variation of BSFC with engine speed was found to be a flat curve and very less as compared to that of gasoline and was in the range of 120 gm/KWh. The BSFC was a bit higher for low speed operation due to higher time available for cooling effect to take place and at high speed the increase in BSFC was due to increasing frictional losses.

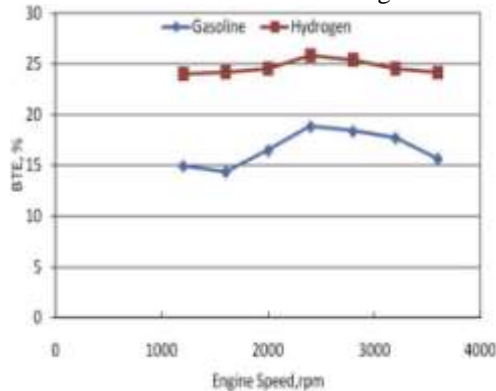


Figure 3: Torque characteristics vs Engine speed [20]

b) Emission Characteristics

The higher in cylinder pressure and temperature is very good for the combustion characteristics of hydrogen. But this altogether poses a new threat of NO_x emission in hydrogen fuelled engines. Researchers have found out that increase in the engine speed increases the NO_x emissions due to increase of temperature and pressure.

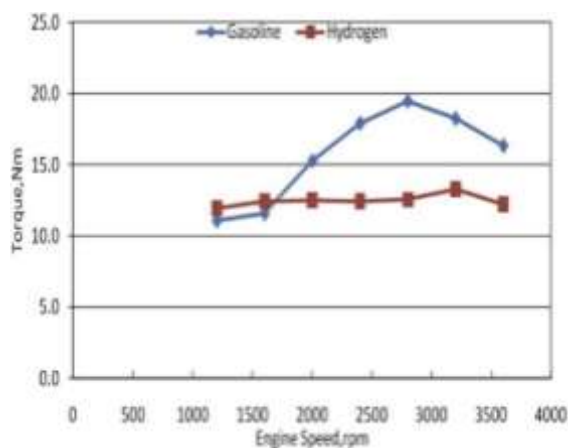


Figure 4: BTE characteristics vs Engine speed [20]

The CO content in the exhaust gases was bare minimum due to no carbon content in the Hydrogen. The little amount of CO was due to the combustion of lubricating oil. The CO₂ content was also very less as compared to gasoline engines. Krishnan Unni J et al. found that the amount of HC in gasoline was far more than the hydrogen engines. Jabbr et al. found that advancing of ignition timing increased the NO_x emissions in the hydrogen engine. Advancing the ignition

timing gave a greater time for combustion resulting in higher in cylinder temperature and pressure.

P. Singh et al. carried out comparative particulate emissions from diesel, hydrogen, gasoline, CNG and 20HCNG[22]. They found out the hydrogen combustion showed the least amount of particle number concentration amongst all the fuels. Theoretically, there was no soot formation in case of hydrogen. But incomplete combustion of lubricating oil leads to soot formation and increase in particulate emissions. They also found that at maximum engine load the hydrogen fuelled engine emitted relatively bigger particles which were higher in number than the gasoline powered engines. High flame speed and high diffusivity were the factors as concluded by them. Singh AP et al. carried out detailed comparison of particulate emission of SI and LI (laser ignited) hydrogen engines. They found out that the at higher torque requirement the nucleation mode particle content was higher as compared to other loads. They also found out that at all loads the nucleation mode particle concentration was greater than accumulation mode particle concentration. The study concluded with the fact that the LASER ignited engines were the ones that had more particulate emissions than SI engines at all loads.

Exhaust Gas Recirculation or EGR is a method in which exhaust gas from the engine after cooling is sent into the combustion chamber through the inlet valve at the time of suction. Thus EGR dilutes the charge that is inducted into the engine. This method is very useful to reduce NO_x emissions since induction of exhaust gases reduces the peak

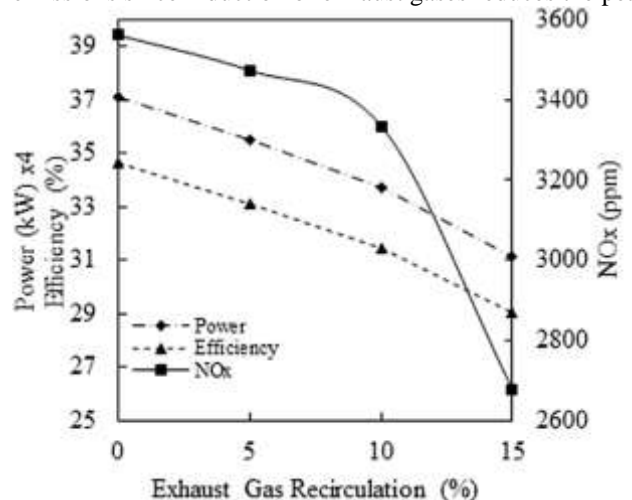


Figure 5: Effect of EGR on power, efficiency and NO_x emissions [21]

temperature that is produced and thus the formation of NO_x is reduced. Jabbr et al. in their research work found out that increase in the percentage of EGR reduces the level of NO_x considerably but it also decreases the BTE and the power output of the engine. They concluded that increasing EGR reduced the volume of air and fuel inside the cylinder as well as decrease in the hydrogen flame speed, so engine power and efficiency decreased as well. Fig. 5 shows the variation of power, efficiency and NO_x emissions with the concentration of EGR. [21]

c) Hydrogen dual fuel operation

Many researchers have tried testing hydrogen with other fuels in the SI engines. They tested hydrogen mainly with fuels like CH₄, Gasoline and CNG. Hydrogen having a high self-ignition temperature acts as a better fuel in gasoline engine operations as compared to diesel operations.

d) Combustion Characteristics

Açıkgoz et al. in their research work tested CH₄-H₂ dual fuel varying the percentage of CH₄ and H₂. The fuels used were 20% H₂- CH₄ 80%, 10% H₂- CH₄ 90% and 30% H₂- CH₄ 70%. They used LGW523MPI type of engine with 505cc of displacement volume having a compression ratio of 10.7:1. They found out that hydrogen fuelled engines had lower power output as compared to CH₄ fuelled engines for the same engines size, owing to the low specific energy content in terms of volume of hydrogen. They also found out that the BTE increased with increase in the hydrogen content in the fuel used. This is shown in the Fig. 6. Also increase in hydrogen content increases the mixture burning speed and this increases the BTE.

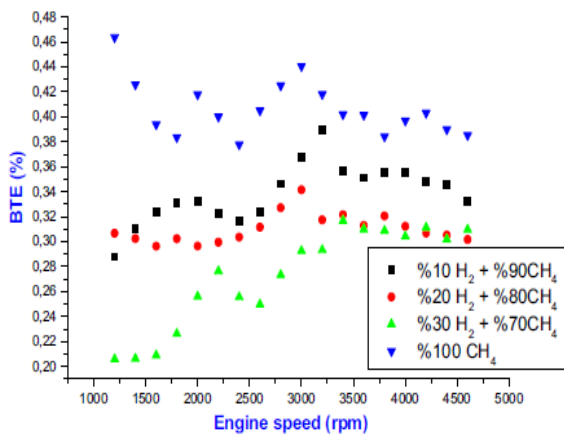


Figure 6: Variation of BTE with engine speed [24]

Baulahlib MS et al. in their research measured load in terms of electrical output. The research work was performed using MAN E2866E engine coupled to an alternator. The engine was a six cylinder spark ignition engine working of 12.5:1 CR. They tested various fuels like natural gas, CH₄ and CH₄/H₂ (85-15) blend for their research work. They found out that the efficiency of the engine increased as the load increased for all types of fuels but the hydrogen-methane blend had the highest efficiency as compared to other fuels at all loads. [23] Fig. 10 clear shows this variation.

e) Emission characteristics

A. P. Singh et al. found out in their study that the hydrogen-CNG blend and CNG had the least number of particulate emissions that were generated due to homogenous mixture and complete combustion. They also concluded that the particulate emission for hydrogen-CNG blend was less as compared to CNG [22]. Açıkgoz et al. found that as the HC emission reduced as the percentage of hydrogen was increased in the CH₄ fuel [24]. The reason was given that hydrogen addition increases the rate of formation of OH radical which reduces HC emission. Also as the air fuel ratio increased the HC emissions reduced. For CO emissions the researchers found out that CO emission increases with hydrogen addition when air ratio was stoichiometric but

decreases with increase in hydrogen under lean conditions. The increased in cylinder temperature converts CO into CO₂ when hydrogen % is increased. For NO_x emissions they found out that increased hydrogen content decreased the NO_x emissions.

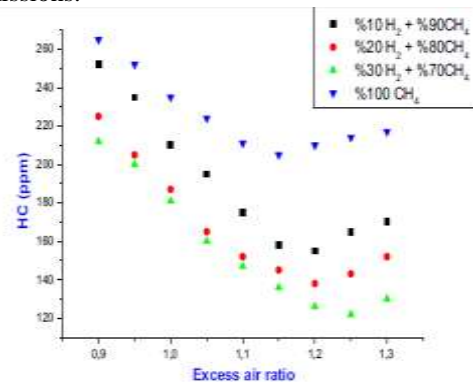


Figure 7: Variation of HC with air ratio [24]

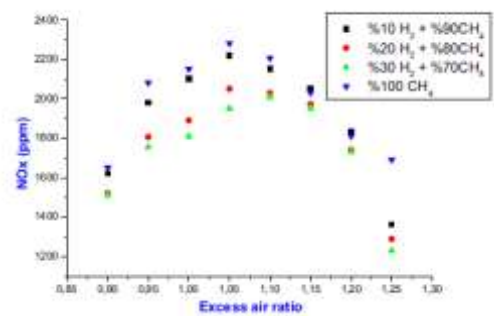


Figure 8: Variation of NO_x with air ratio [24]

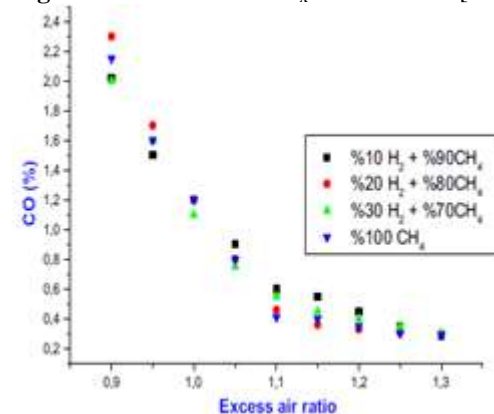


Figure 9: Variation of CO with air ratio [24]

f) Hydrogen as a fuel in CI Engines

Using only hydrogen as a fuel in compression ignition engine has a great limitation owing to its high auto ignition temperature. The operating range was quite limited if hydrogen was used as a fuel in CI engine. Hence researchers always focus on hydrogen dual fuel operation.

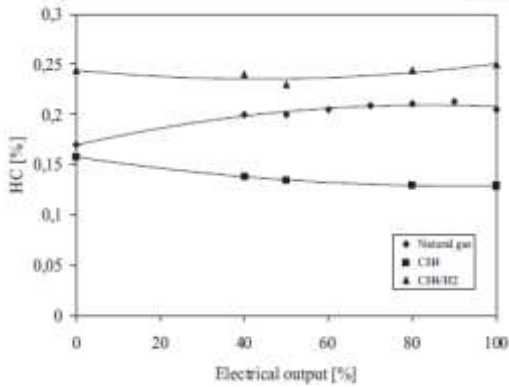


Figure 10: Variation of HC with electrical output [23]

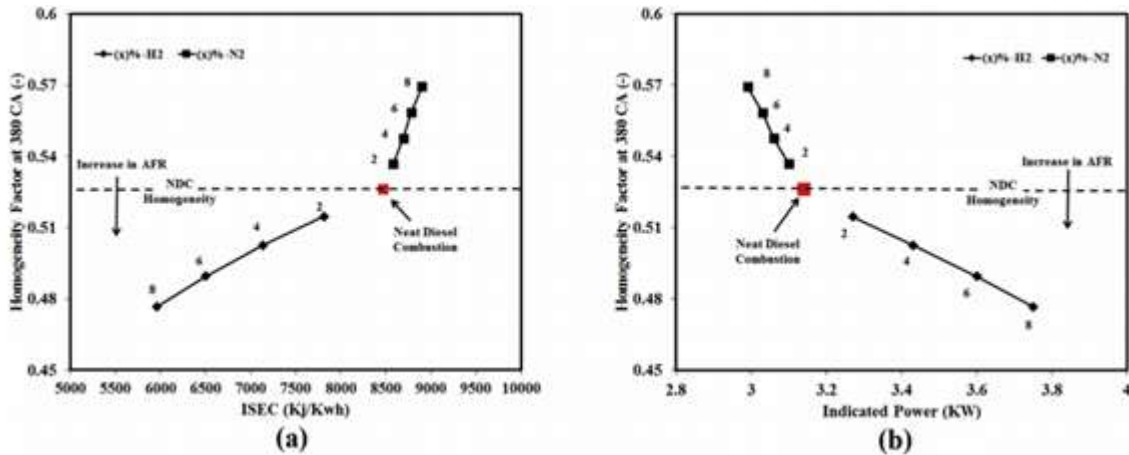


Figure 11: Variation of ISEC and IP with % variation of N2 and H2 [27]

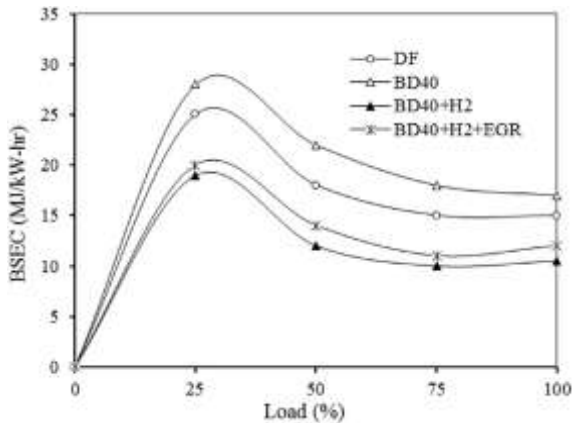


Figure 12: BSEC variation with % load [26]

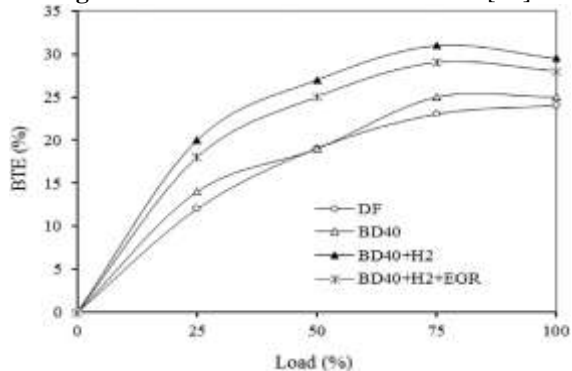


Figure 13: BTE variation with % load [26]

g) Combustion characteristics using dual fuel

Deb M et al. carried out experiments on KirloskarTV1-Single cylinder water cooled CI engine with hydrogen injector running at 17.5:1 compression ratio [25]. Hydrogen share was varied and it was found that the BTE increased and BSEC decreased with increase in the hydrogen share, with 33.28 % BTE at 42 % hydrogen energy share in diesel as compared to 28.74 % with only diesel fuel operation. BSEC decreased by 18.60% as compared to diesel fuel operation. Rahman M.A. et al. compared variation of BTE with load for various fuels that included diesel, biodiesel, biodiesel+H₂, and Biodiesel+H₂+EGR. It was found that BTE was the highest for biodiesel and H₂ blend for all loads, with highest BTE at 75% load. BSEC was the lowest for this fuel. Fig. 11 and 12 show the variation of BTE and BSEC with load for various fuels.[26]

h) Emission Characteristics

Deb M et al. found that increasing the % of hydrogen in diesel decreased the CO₂ emission [25]. They found out that the CO₂ emission reduced to 247.4 gm/kW-h at 42% hydrogen blend as compared to 623.5 gm/kW-hr for diesel fuel operation. For CO emissions too they found out that CO content decreased considerably with an increase in hydrogen content in fuel. They concluded that the high flame speed of hydrogen increases the cylinder pressure which increases the efficiency of engine thus reducing CO emissions. The figures 15 show the variation of CO vs the % of H₂. Similar results were given by Mobasheri et al. [27] in which they found that increasing hydrogen decreases CO content while the particulate emissions also reduced as the hydrogen percentage was increased. Thus the Rahman et al. in their work concluded that the CO₂ increased with the increase in load for hydrogen and biodiesel blend, but when EGR was used the CO₂ content increased as compared to BD40+H₂ for the same load.

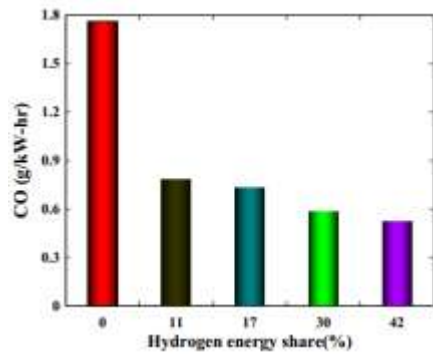


Figure 14: Variation of CO vs Hydrogen energy share [25]

This was because of the fact that CO₂ gas entered the engine through the inlet which increased the percentage of CO₂. In case of unburned HCs, the biodiesel blend had the lowest emission as compared to diesel, and biodiesel with minimum emission at 50% load. The fig below shows the graph of HC vs load.

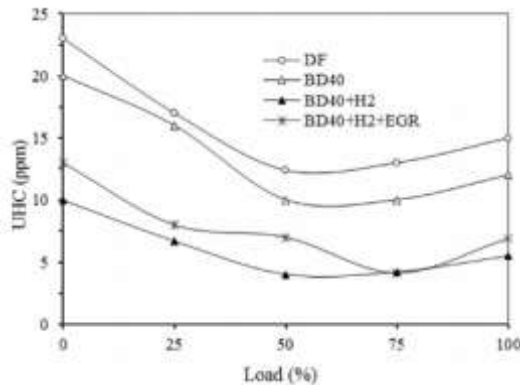


Figure 15: UHC VS LOAD

3. Conclusions and Future Scope

It is evident from the emerging trends that the diesel and gasoline powered engines will be history in the near future. In the scenario of electric powered cars the hydrogen powered engines can be also considered a potential option if used with utmost care. The electric powered cars are considered as the best replacement for conventional fuels but they come with their own problems of waste disposal. Here, hydrogen fuelled engines can come into the main frame and efficiently be used if proper precautions are taken care of.

Hydrogen as a fuel plays a great role in the reduction in exhaust emissions in both SI as well as CI engines in the present scenario of stringent emission norms. The emission control technologies for both engines have reached to their minimum level using various techniques and hydrogen can have a greater potential considering future emission norms. The better BTE as well as BSFC also further adds more weight to the claim of hydrogen substitution.

Although hydrogen reduces emissions considerably, care must be taken to reduce NO_x emissions to a significant level. There is a good scope of research work in this area. The main problem with hydrogen as a fuel in IC engines is the safety aspects and storage problems. If a good method of storage is found out then there will not be any other concern

that will be able to stop hydrogen from replacing the conventional duo of gasoline and diesel.

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