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Hydrogen Fuelled Internal Combustion Engine: A Review

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Abstract: Owing to the depletion of fossil fuels is urgently demanding a research to be carried out to find out the reliable alternative fuels for meeting sustainable demand. Hydrogen can transform fossil-fuel dependent economy into hydrogen economy as an energy carrier which can provide a nearly free emission transportation level. Hydrogen in the form of gas can be used in both Spark ignition and Compression ignition engine for propelling purpose. Hydrogen fuelling system provides a much cleaner combustion and fuel efficient than conventional one, as hydrogen reacts with oxygen to generate energy, the resultant product is water vapour. This paper review the scope and production of hydrogen, combustion fundamentals, fuel strategy, performance and emission of hydrogen fuelled IC Engines which gives idea for researchers who all are working on hydrogen as a fuel in IC Engine.
Keywords: IC Engine, Hydrogen, Ignition, Performance, Emission.

I. INTRODUCTION

India is a very vast country in terms of area with large number of population. Most of the people use the different modes of transportation which demands the large amount of fuel. Fossil fuel is the primary source of fuel which meets most of the demand today. Petroleum and its derivatives are in the phase of depletion. The combustion of the fossil fuels releases CO_2, 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 discover now itself and this fuel should have low emission and good performance. Many engineers and scientists agree that the solution to these problems can be made with the clean hydrogen fuelling system. Hydrogen is much cleaner and efficient energy system. Utilisation of hydrogen as a fuel liberates mainly water. Hydrogen, produced from water, thus represents a closed cycle energy carrier system. On the other hand hydrogen is the fuel of the future. Hydrogen based IC engine will be able to close the gap between the carbon based economy and hydrogen based. Many researchers considered hydrogen to be the ideal energy carrier of the future i.e., hydrogen can be utilised as the medium for storing and distributing energy for final use in a wide variety of applications. The research study that has been carried out for ease of storage, distribution, utilization & range of production suggest that hydrogen has tremendous scope as a fuel in Internal Combustion Engine. Hydrogen can be produced from water and any sorts of primary energy source. Hydrogen can therefore be manufactured independent of supplies of non-renewable primary energy sources like as coal, petroleum, nuclear energy, natural gas. Renewable energy sources such as solar, wind, hydro-electric, Ocean used to produce hydrogen from water represents a potentially sustainable source of fuel for the future that can be used in an IC Engine. Hydrogen as a renewable fuel resource can be produced through the expenditure of energy to replace increasingly the depleting sources of conventional fossil fuels.

II. HYDROGEN AS A FUEL

Hydrogen has a unique property that makes it remarkable well suited in principle, to engine applications. With comparison to other fuels over wide range of pressure and temperature, hydrogen has very high flame propagation rates within the cylinder. The range of flammability of hydrogen varies from an equivalence ratio (φ) of 0.1 to 7.1. Even in the lean mixtures, the flame propagation rates will be sufficiently high. Hence the hydrogen fuelled engine can be operated with a wide range of Air/fuel ratio. The minimum energy required for ignition of hydrogen–air mixture is 0.02 mJ only. This enables hydrogen engine to run well on lean mixtures and ensures prompt ignition. The density of hydrogen is found to be 0.08988 kg/m^3 which is lighter than that of air so it can easily spread over the atmosphere. As the self-ignition temperature for hydrogen is 858 K, compared to diesel of 453 K, it allows a larger compression ratio to be used for hydrogen in internal combustion engine. But it is not possible to achieve ignition of hydrogen by compression only. Some sources of ignition have to be created inside the combustion chamber to ensure ignition. One of the most important features of hydrogen fuelled engine is that it produces less exhaust emission comparing to other fuels. It restricts the production of CO, CO_X, SO_X and other particulate matter. Thus the emission product will be NO_X and water vapour.

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$$2H_2 + O_2 = 2H_2O$$

Due to this typical behaviour, researchers are concentrating their attention on hydrogen as an alternative fuel in Internal Combustion Engine.

Table 1: Properties of Hydrogen

Properties	Hydrogen	Unleaded Gasoline	Diesel
Formula	–	$C_nH1.87n$ (C_4–C_{12})	$C_nH1.8n$ (C_8–C_{20})
Density at 16°C and 1.01 bar (kg/m^3)	0.0838	721-785	833-881
Auto Ignition Temperature (K)	858	533-573	530
Flammability limits (vol. % in air)	4-75	1.4-7.6	0.7-5
Min. ignition energy (mJ)	0.02	0.24	–
Stoichiometric air fuel ratio on mass	34.3	14.6	14.5
Net heating valve (MJ/kg)	119.93	43.9	42.5
Limits of flammability (equivalence ratio)	0.1-7.1	0.7-3.8	–
Flame velocity (cm/s)	265-325	37-43	30
Diffusivity in air (cm^2/s)	0.63	0.08	–
Quenching gap in NTP air (cm)	0.064	0.2	–
Cetane number	–	13-17	44-55
Octane number	130	92-98	30

A. Hydrogen Production Methods

Hydrogen can be easily produced in school classrooms by electrolysis of water, using Hofmann Voltameter. 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 in widely used. Other methods of hydrogen production from fossil fuels include partial oxidation, plasma reforming, petroleum coke and coal. Hydrogen can be generated from water using electrolysis, radiolysis, photo catalytic water splitting, thermolysis and so on. 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 economically.

Table 2: Methods to Produce Hydrogen

Methods	*Process*	*Implementation*
Steam Reforming of Methane gas	In presence of nickel catalyst & at 700 – 1100 °C: CH4(g) + H2O(g) → CO(g) + 3H2(g) Next reaction at lower temperature: CO(g) + H2O(g) → CO2(g) + H2(g)	Current major source of Hydrogen
Electrolysis of water	Electric current will pass through water: Reaction: 2H2O(l) →2H2(g) + O2(g)	Don't used widely due to cost of electricity
Hydrogen from Coal (Gasification)	At high temperature and pressure: Coal + H2O(g) + O2(g) → syngas Syngas = H2 + CO + CO2 + CH4	Current method of mass production of hydrogen
Solar – Hydrogen System	Electric current passed through water: 2H2O(l)→ 2H2(g) + O2(g)	Don't used widely due to cost of renewable source of energy

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B. Combustion Properties

The properties of hydrogen that contribute to its use as a combustible fuel are discussed below.

1) *Wide Range of Flammability:* Hydrogen has a wide flammability range of 4-75% in comparison with all other fuels. The figure shows the range of flammability with respect to the concentration of hydrogen in air.

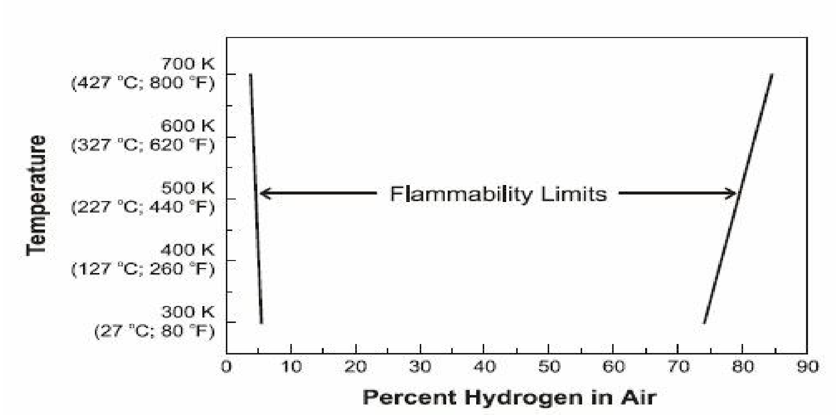

Figure 1: Flammability Limits for % of hydrogen in air

Thus it can be ignited over a wide range of air-fuel mixtures in an IC Engine. While talking to the advantages, hydrogen fuel allow the engine to run on a lean mixture generally gives greater fuel economy due to complete combustion of fuel. Addition to this, it also allows for a lower combustion temperature which reduce the emissions of criteria pollutants such as NO_X.

2) *Low Ignition Energy:* Ignition energy refers to the amount of energy which is required to ignite a combustible vapour or gas mixture in an IC Engine. Hydrogen has very low ignition energy at atmospheric condition. The minimum ignition energy of a hydrogen and air mixture is 0.02mJ which is an order of magnitude lower than that required for gasoline. This enables hydrogen engines to ignite lean mixtures and ensures prompt ignition.

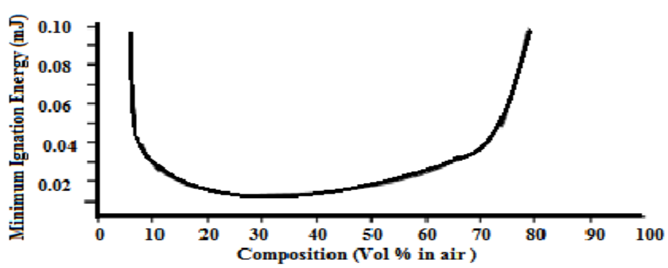

Figure 2: Minimum Ignition Energy of Hydrogen in Air

If the minimum ignition value will be low for hydrogen-air mixture, it suggests that low value of spark energy will be required for spark ignition. This means that ignition can be initiated with a resistance hot wire.

3) *High Auto-Ignition Temperature:* Auto ignition temperature is the value of minimum temperature which is required to initiate self-sustained combustion in a combustible fuel mixture without any external ignition. Hydrogen has relatively high auto ignition temperature of 858k. The auto ignition temp gives the idea about compression ratio. The high value of auto ignition temp allows larger compression ratios to be used in hydrogen engine than in hydrocarbon engine. This leads to the higher thermal efficiency of engine. On the other hand, hydrogen is difficult to ignite in diesel engine because the temp needed for those types of ignition are relatively high.
4) *Small Quenching Distance:* Comparatively hydrogen has a small quenching distance of 0.64mm against 2.0mm of gasoline. Quenching distance measures how hydrogen flames can travel closer to the cylinder wall before they extinguish. This means that it is much difficult to quench a hydrogen flame than a flame of another fuel which consequently increases the tendency of backfire.
5) *High Flame Speed:* Hydrogen burns with a high flame speed at stoichiometric ratios of nearly 2.65m/s which is an order of

magnitude faster than of conventional fuels. This means that hydrogen is more closely approach to the thermodynamically ideal engine cycle. With leaner mixture, the velocity of

6) *High Diffusivity:* Hydrogen possess very high diffusivity, considerably greater than gasoline with a value of 0.61cm^2/s. This property has two advantages. Firstly, it facilitates the formation of uniform mixture of air and fuel. Secondly, if leakage will occur, the hydrogen dispersed rapidly. So that as a result, unsafe conditions can be either avoided or minimized.
7) *Low Density:* The density of hydrogen is very low with 0.082kg/m^3. This gives rise to the two problems in an IC Engine. Firstly, without significant compression a very large volume is necessary to store enough hydrogen to give a vehicle an adequate driving range.

C. Stoichiometric Air/Fuel Ratio

The minimum amount of air required for complete combustion of a fuel is known as Stoichiometric or Theoretical fuel. This is defined as the ratio of mass of air to fuel m_a/m_f, which is required for stoichiometric combustion. That is the quantity of air which is required for complete combustion of 1kg of fuel without any oxygen appearing in the products of combustion. The theoretical or stoichiometric combustion of hydrogen and oxygen is given as:

$2H_2 + O_2 = 2H_2O$

Moles of H_2 required for complete combustion = 2 mole

Moles of O_2 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 N_2 in air = Moles of O_2 x (79% N_2 in air / 21% O_2 in air)
= 1 mole of O_2 x (79% N_2 in air / 21% O_2 in air)
= 3.762 moles N_2

Number of moles of air = Moles of O_2 + Moles of N_2
= 1 + 3.762
= 4.762 moles of air

Weight of O_2 = 1 mole of O_2 x 32 g/mole
= 32 g

Weight of N_2 = 3.762 moles of N_2 x 28 g/mole
= 105.33 g

Weight of air = weight of O_2 + weight of N_2
= 32g + 105.33 g
= 137.33 g

Weight of H_2 = 2 Moles of H_2 x 2 g/mole
= 4 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 g / 4 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.

D. Combustion Anomalies

Hydrogen fuelled internal combustion engine has some anomalies during the combustion events. Generally the properties like wide flammability limits, high flame speed and low ignition energy gives rise to undesired combustion in engine. These abnormal combustions include pre-ignition, backfiring, auto-ignition and knocking. Minimization of these combustion problems in a hydrogen engine is quite challenge and measures taken during engine design, mixture formation and load control to avoid abnormal combustion.

1) *Pre-Ignition:* The premature combustion of the fuel-air mixture in an internal combustion engine is termed as pre-ignition. The figure shows the combustion inside the cylinder under normal and premature condition.

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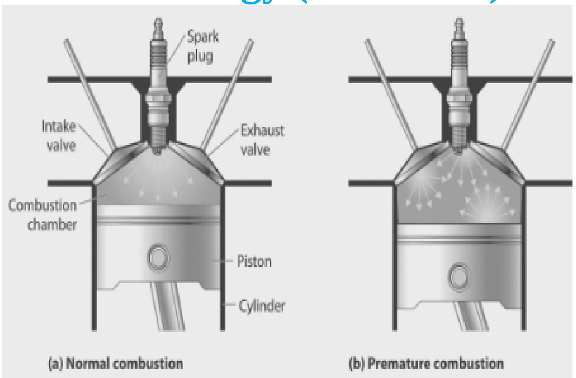

Figure 3: Normal and Premature Combustion

The low ignition energy and wide flammability property of hydrogen engines result the pre-ignition. The mixture burn mostly during compression stroke due to premature ignition so that temperature of combustion chamber rises which cause to the hot spot that leads to the pre-ignition to increasing in temperature, resulting in another earlier pre-ignition in next cycle. These anomalies continue until the suction stroke and causes backfire.

2) *Backfire:* The explosion or combustion produced by an IC Engine during its operation that occurs in air inlet system rather than inside the combustion chamber. The backfire can be obtained as shown in the figure inside the engine.

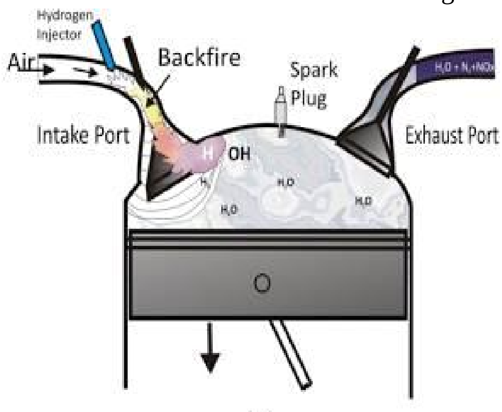

Figure 4: Backfiring in Intake port

When the valve is open, the presence of pre-ignition at a point near the inlet valve makes enflame charge travel through the valve and into the inlet manifold resulting in backfire. The backfire is dangerous in pre-mixed fuel induction strategies where there is possibility of presence of ignitable fuel-air mixture in inlet manifold. Any measures that help to avoid pre-ignition can also reduce the problem of backfiring in engine.

3) *Auto Ignition and Knock*: Knocking is a common problem that can be found in hydrogen fuelled engine. When the temperature of fuel and oxidizer inside the cylinder reaches its extremes, then end gas ignites spontaneously without the aid of spark is termed as auto-ignition. In addition to this high amplitude pressure waves will generate due to the release of remaining energy defined as Knocking. It can cause engine damage due to increased mechanical and thermal stress created by pressure waves inside the combustion chamber.

III. FUEL INJECTION SYSTEM

Pre-ignition problem can be reduce or eliminate after adapting or re-designing the fuel delivery system. Hydrogen fuel delivery system can be divided into 3 major types: Central (carburetted) injection, Port injection and direct injection. The fuel-air mixture will be injected during the intake stroke in central and port injection. The injection is at inlet of air intake manifold in carburettor while at the inlet port in Port injection. In Direct cylinder injection, the air-fuel mixture is form inside the combustion cylinder after the air intake valve has closed.

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A. Central Injection or Carburetted System

This is the simplest method of delivering fuel to hydrogen engine. In the case of central injection or a carburettor, the injection is made at the inlet of the air intake manifold. Carburetted injection system has mainly two advantages. Firstly, carburetted system doesn't require high value of hydrogen supply pressure to be as high as for other methods. Secondly, standard gasoline engine can be easily converted in to hydrogen engine. After all having these advantages, it has some disadvantages i.e. it is susceptible to irregular combustion due to pre-ignition and backfire. A schematic diagram illustrating the operation of Carburetted injection system is shown in fig5.

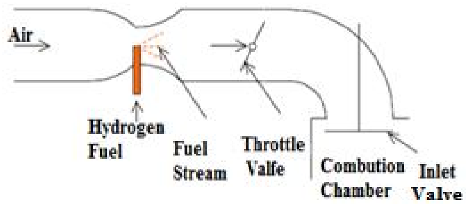

Figure 5: Carburetted Injection System

B. Port Injection System

The port injection fuel delivery system consists of an injection of fuel directly into the intake manifold at each intake port rather than drawing fuel in at a central point. After the beginning of the intake stroke, the hydrogen is injected into the manifold. The air is injected separately at the beginning of intake stroke to dilute the hot residual gases results the less pre-ignition. The inlet supply for port injection is higher than for central injection but less than for direct injection systems. A schematic diagram illustrating the operation of inlet port injection is shown in fig6.

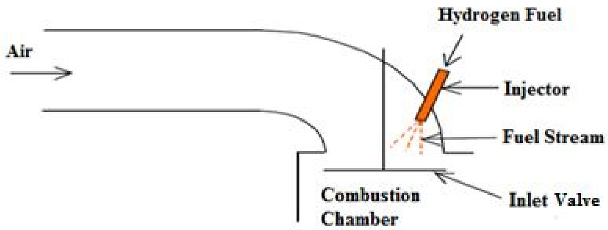

Figure 6: Port Injection System

C. Direct Injection System

Sophisticated hydrogen engines use direct injection system. In Direct Injection, air-fuel is injected into the combustion cylinder during the compression stroke when the intake valve is closed. Thus, the premature ignition during the intake stroke is avoided and consequently the engine cannot backfire into the intake manifold. The power out of a direct injection hydrogen engine is 42% more than a hydrogen engine using a Central or Carburetted Injection System. A schematic diagram illustrating the operation of direct injection is shown in fig7.

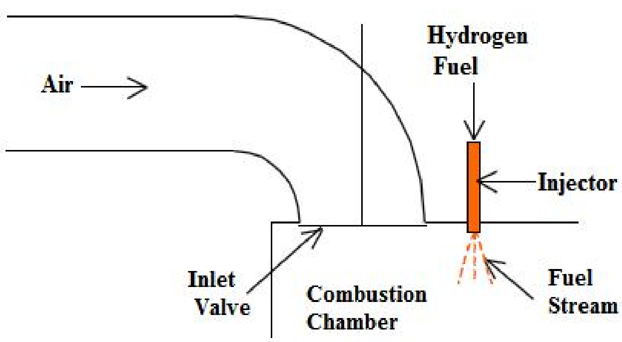

Figure 7: Direct Injection System

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IV. IGNITION SYSTEM

As hydrogen has a low ignition energy limit, hydrogen can be easily ignited using gasoline ignition. Ignition systems which use a waste spark system must not use to ignite hydrogen. These waste sparks acts as a source of pre-ignition for hydrogen engines. The plugs used for ignition of hydrogen engine have non-platinum tips to avoid oxidization with air as platinum as catalyst. A cold rated plug with shorter insulator nose is used which liberates heat from the plug tip to the cylinder head comparatively quicker than a hot rated spark plug. Due to smaller surface area of insulator nose of spark plug, the chances of the plug tip igniting the air-fuel charge is reduced. The hot rated spark plugs are useful only when the carbon deposits accumulate. But hydrogen doesn't contain carbon, hot rated spark plugs doesn't serve a useful function in Hydrogen fuelled IC Engine.

V. PERFORMANCE PARAMETERS

A. *Thermal Efficiency*

The theoretical thermodynamic efficiency of an Otto cycle engine is based on the compression ratio of the engine and the specific-heat ratio of the fuel as shown in the equation:

$\eta th = 1 - 1/(V_1/V_2)^{\gamma-1}$

Where,

V_1/V_2 = the compression ratio

γ = ratio of specific heats

ηth = theoretical thermodynamic efficiency

The higher value of compression ratio or the specific-heat ratio will give the higher indicated thermodynamic efficiency of the engine. The compression ratio limit of an engine is based on the fuel's resistance to knock. The less complex the molecular structure, the higher the specific-heat ratio. Hydrogen (γ=1.4) has a much simpler molecular structure than gasoline and therefore its specific-heat ratio is higher than that of conventional gasoline (γ=1.2-1.3).

B. *Power Output*

Theoretical maximum power output from a hydrogen engine depends on two functions i.e. the air/fuel ratio and fuel injection strategies. As mentioned in above, the theoretical or stoichiometric air/fuel ratio for hydrogen is 34:1. In this condition, hydrogen will displace 29% of the combustion chamber leaving only 71% for the air. As a result, the energy content of air and hydrogen mixture will be less than it would be if the fuel were gasoline. Gasoline is liquid so it will occupy a very small volume of the combustion chamber, and thus allows more air to enter in chamber. The air and fuel will mix prior to the combustion chamber due to central and port injection strategies which results the system to limit maximum theoretical power obtainable to approximately 80-85% that of gasoline engines. In case of direct injection system, the fuel mix with air after the intake valve has closed so that maximum output of the engine can be approximately 15-20% higher than that for gasoline engines. Thus depending on how the fuel is metered, the maximum power output for a hydrogen engine can be varied as either 15-20% higher or 15-20% lesser than that of gasoline under stoichiometric air-fuel ratio. But as a theoretical air/fuel ratio, large amount of NO_X will form due to high combustion temperature. The emission of NO_X can be reduced to nearly zero when the air supply will be twice than that of theoretical air-fuel mixture. But this reduce the power output to about half that of a similarly sized gasoline engine. Designing the hydrogen engine larger than gasoline engine and equipped with turbochargers or superchargers can recover the power loss.

VI. EMISSION

The product of combustion of air fuel mixture contains carbon monoxide (CO), unburned hydrocarbons (HC), and oxides of nitrogen (NO_X). The concentration of gaseous emissions in the engine exhaust gases are usually measured in parts per million (ppm) or percentage (%) by volume. There are several techniques developed for the reduction of these pollutants.

The combustion of hydrogen with oxygen produces water as its only product:

$2H_2 + O_2 = 2H_2O$

The combustion of hydrogen with air however can also produce oxides of nitrogen (NO_X):

$H_2 + O_2 + N_2 = H_2O + N_2 + NO_X$

The high temperature that developed inside the combustion chamber is the cause for NO_X emission. Lean mixture combustion, which promotes good thermal efficiency, also results in less emission of HC and CO but causes high levels of NO_X emission. If air fuel ratio will increase to reduce NO_X, it will result to increase in HC and CO emission. Two methods are adopted to reduce these

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emissions. Firstly concentrates on engine design and fuel modifications and the second involves treatment of exhaust gases after leaving the IC engine.

Figure 8 illustrates a typically NO_X curve relative to equivalence ratio for a hydrogen engine. A similar graph including other emissions is shown in Figure 9 for gasoline.

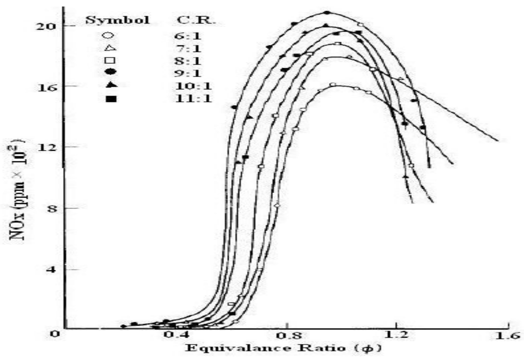

Figure 8: Emissions for Hydrogen Engine

The composition of the combustion products is significantly different for fuel-lean and fuel-rich mixtures, and because the stoichiometric fuel/air ratio depends on the fuel composition, the ratio of the actual fuel/air ratio to the stoichiometric ratio (or its inverse) is a more informative parameter for defining mixture composition. The fuel/air equivalence ratio φ:

Fuel-air Equivalence ratio, $\varphi = (F/A)_{actual} / (F/A)_{st}$

For fuel lean mixtures: $\varphi < 1$

For stoichiometric mixtures: $\varphi = 1$

For fuel rich mixtures: $\varphi > 1$

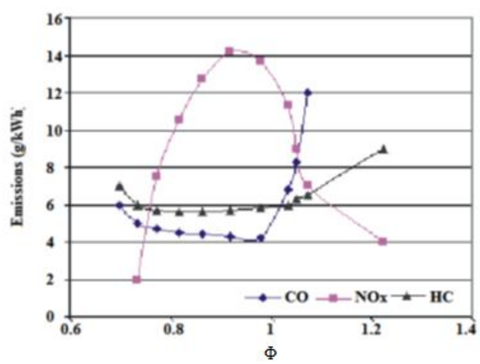

Figure 9: Emissions for Gasoline Engine

The NO_X for a gasoline engine is reduced as equivalence ratio decreases (similar to a hydrogen engine) as shown in Figure 8. In case of a gasoline engine the reduction in NO_X is compromised by an increase in carbon monoxide and hydrocarbons as Figure 9.

VII. CONCLUSIONS

It is evident from the study, it is advantageous to use hydrogen enriched air as a fuel in internal combustion engines. The key results that made after this study are summarized below:

1) Hydrogen can be used as a fuel either as pure or blended with gasoline engine.
2) Anomalies like pre-ignition can be avoided by adopting proper design of injection method and providing cold rated no platinum type spark plug.
3) Backfiring in hydrogen engines is limited to external mixture formation operation and can be avoided with direct injection operation.
4) Due to the wide range of ignition, hydrogen engine can be used without throttle valve which can reduce loss during engine pumping.

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5) Hydrogen operated engine has higher thermal efficiency than gasoline and diesel operated engines.
6) Hydrogen engine may achieve lean-combustion in its actual cycles which reduce NO_X emission. Hydrogen fuelled IC Engine reduce global warming and local pollutions problems.

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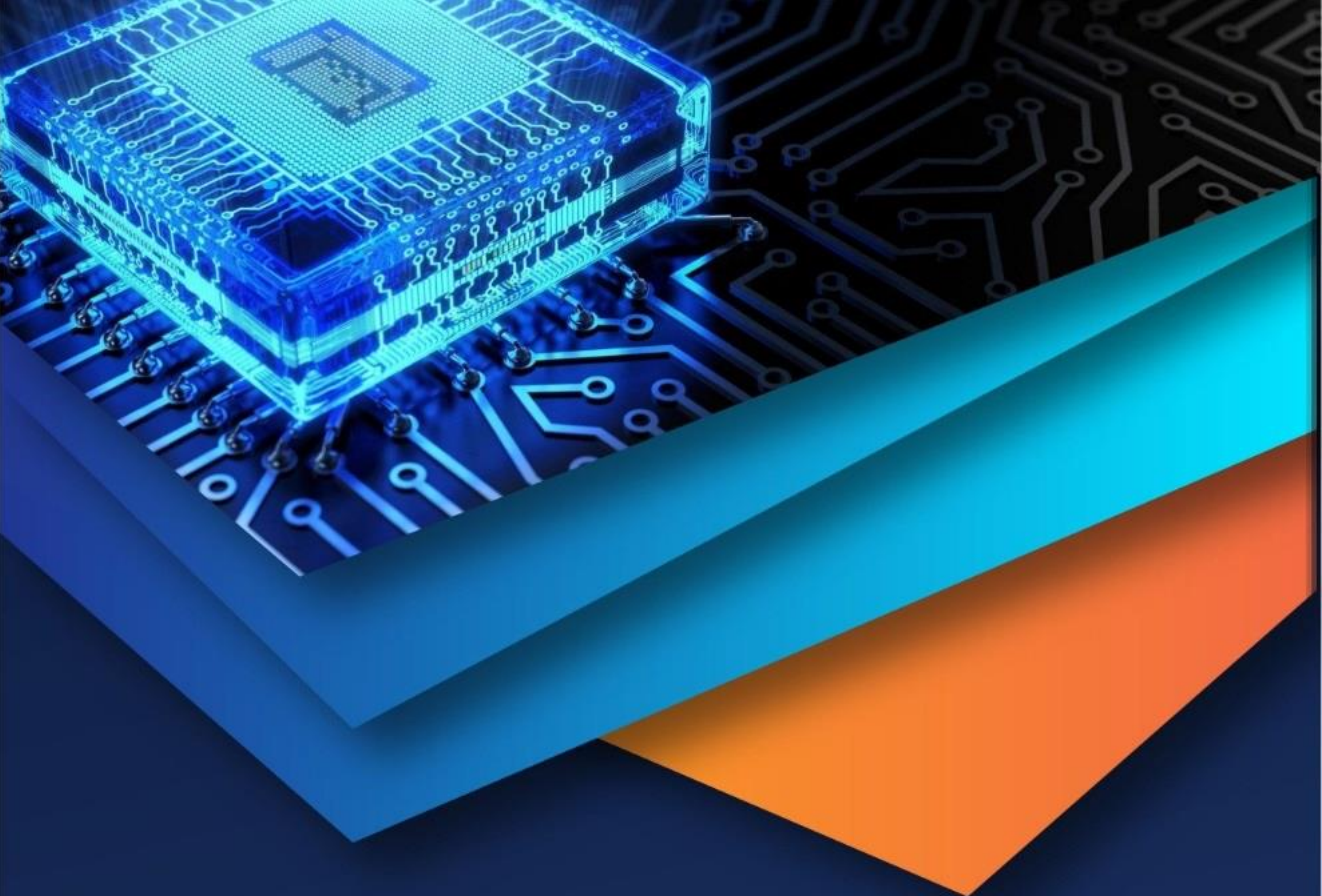

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