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Hydrogen in IC engines as a promising option for high engine power and efficiency with low emissions

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ABSTRACT: Hydrogen is gaining worldwide importance as a combustion fuel with low emissions. In combustion hazard assessment, consideration should be given towards mixture formation, flammability, sensitivity of ignition, deflagration propagation, detonation, and effects of temperature and overpressure. Based on the extensive studies of many researchers, this paper is opting hydrogen as an energy carrier and main fuel because of its carbon-free content, wide limits of flammability and fast flame speeds. It emphasizes the impact of hydrogen properties on facility design.

Keywords: CO2 emissions; Cetane number; flammability; ignition sensitivity; internal combustion engines.

I. INTRODUCTION

Fossil fuels are the most commonly used sources of energy in the world especially China, USA and India. They are found in majority of items using each day. One major use of these products is as fuel, gasoline for cars, jet fuel, heating oil and natural gas to generate electricity. When burned, they produce huge quantities of carbon dioxide. Carbon emissions trap heat in atmosphere and lead to climate change resulting health hazards. There is a need to stop burning of fossil fuels. Some alternative fuels are bio-diesel, bio-alcohol (methanol, ethanol, and butane), chemically stored electricity (batteries and fuel cells), hydrogen, non-fossil methane, non-fossil natural gas, vegetable oil, propane and other biomass sources.

Realization of an IC engine to run well on hydrogen is one of the most challenging tasks. In 1820, Cecil has developed a hydrogen engine. He has operated on the vacuum principle to produce power. The vacuum is created by burning of a hydrogen-air mixture. It is allowed to expand and then cool. The engine performance is reported as satisfactory. However, vacuum engines are yet to become practical (http://www3.eng.cam.ac.uk/DesignOffice/projects/cecil/index.html). After 60 years, Otto has performed experiments on combustion engines using a synthetic producer gas for fuel (having 50% hydrogen content) and noticed to work with it as dangerous. He has initiated the development of practically feasible carburettor using gasoline (https://en.wikipedia.org/wiki/Otto_engine). NASA has relied upon hydrogen gas as rocket fuel to deliver crew and cargo to space. Expertise is developed for hydrogen propellant transportation, storage, system design, training, safety standards, hazard analysis, testing, vehicle demonstration, technology transfer and outreach (https://www.nasa.gov/content/space-applications-of-hydrogen-and-fuel-cells). For pollution control and cleaner air, there is a renewed interest in hydrogen as a vehicular fuel.

Regarding the combustive properties, hydrogen has a **wide flammability range**, which can run on a lean mixture leading to greater fuel economy and more complete combustion reaction. The low final combustion temperature reduces the amount of pollutants emitted in the exhaust. Appropriate lean operation can significantly reduce the power output due to reduction in the volumetric heating value of the air/fuel mixture. Hydrogen has very **low ignition energy**. Hydrogen engines promptly ignite lean mixtures. **Small quenching distance** of hydrogen makes the flames to travel closer to the cylinder wall prior to extinguish and increase the tendency for backfire. Hydrogen has a relatively **high auto-ignition temperature** due to high compression ratio. The absolute final temperature (T_2) is expressed in terms of the

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compression ratio $\left(\frac{V_1}{V_2}\right)$, absolute initial temperature (T_1), and the ratio of specific heats (γ) as

$$T_2 = \left(\frac{V_1}{V_2}\right)^{\gamma-1} \times T_1 \qquad (1)$$

Hydrogen has **high flame speed** at stoichiometric ratios. Hydrogen engines can approach closely the thermodynamically ideal engine cycle. At leaner mixtures, significant decrease in the flame velocity is reported. Hydrogen has very **high diffusivity** facilitating the formation of a uniform mixture of fuel and air. If leak develops, it disperses rapidly. It is better to avoid or minimize unsafe conditions. **Low density** of hydrogen used in an IC engine demands the necessity of huge volume to store sufficient hydrogen in the vehicle for an adequate driving range. The power output will be reduced due to the energy density of a hydrogen-air mixture.

Alternative fuels such as natural gas, CNG, biodiesel, gasoline can reduce pollution to a certain extent but not completely. Gaseous fuels (such as CNG and natural gas) in vehicles are not fully satisfactory. Customers demand low cost and high performance. H_2 can be extracted from water, which can be used as an alternative fuel. Electrolysis is a process of producing H_2 from water using electrodes and electrolytes. A minimum of 1.23 volts energy is required to split H_2 atom from H_2O.

Biodiesel refers to vegetable oil or animal fat-based diesel fuel consisting of alkyl esters. Acetylene used in chemical processes emits harmful substances like carbon monoxides [1].Natural gas consists of 90% methane, 3%ethane, 3% nitrogen and 2% propane [1]. Ethanol is generally produced from biomass and live feedstock. It has low flame speed and difficult to use in winter. It can be mixed with gasoline, which can serve as an alternative fuel [1].

Hydrogen is a gas at ambient conditions. It is considered as the cleanest fuel producing zero emission, which has more advantages when compared to other fuels. It has high flame speed with high auto-ignition temperature (see Table-1) well suited for use in IC engines. Hydrogen is 57 times lighter than gasoline vapor and 14 times lighter than air [2]. It can rise in 20 m/s and disperse rapidly in an open environment. This buoyancy is a built-in safety advantage in an outside environment. Human senses are unable to detect colorless, odorless and tasteless hydrogen. The asphyxiant non-toxic and non-poisonous hydrogen is flammable and explosive over a wide range of concentrations. It should be safely stored by keeping away from heat, flames, and sparks. It is non-corrosive. But, it can embrittle some metals causing significant deterioration in properties [2].

Table-1: Properties of petrol, diesel, gasoline and hydrogen

Property	Petrol	Diesel	Gasoline	Hydrogen
Chemical Formula	C_nH_{2n+2}	C_nH_{2n}	C_4–C_{12}	H_2
Flame speed (m/s)	1.9	0.86	>0.2	7.7
Boiling temperature (K)	523–623	633	310–470	20–25
Density (kg/m^3)	770	832	719.7	832*
Flash point (K)	230	>325	230	-
Auto-ignition temperature (K)	553	483.15	553	773.15
Lower heating value (MJ/kg)	43.4	42.6	43.4	120
Cetane number	0 - 5	37 - 56	0 – 5	
Octane number	87	15 – 25	91 – 94	>130
Carbon content (%)	83–85	82.6	75	-

*At291K and 0.1 MPa pressure

Dr. Michael Swain (2001) with the University of Miami at Coral Gables has made experimental simulations on two car fires (one by creating 1.6mm puncture in a gasoline fuel line and the other by leaking of hydrogen connector) to examine the impact on leaks ignition (https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/30535be.pdf).

Figure-1 shows a picture from a video of the two car fires from the leak at one minute after ignition. The gasoline fire is intensifying, whereas the hydrogen flame has begun to subside. Hydrogen fire was over in 100 seconds. The gasoline car continued to burn for long-time and

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totally damaged (see Figure-2). No damage is noticed in the hydrogen-tank equipped test car (see Figure-3).

Motivated by the work of many researchers [3-7], this paper presents the methods of extraction of hydrogen, responsible factors in engine performance, safety precautions, and requirement of design modifications to opt for hydrogen IC engines for high engine power and efficiency with low emissions.

Figure-1: A picture from a video of the two car fires from the leak at one minute after ignition (https://www.youtube.com/watch?v=OA8dNFiVaF0).

Figure-2: Picture showing the intensifying of gasoline fire and the hydrogen flame subsiding (https://www.youtube.com/watch?v=OA8dNFiVaF0).

Figure-3: Picture showing no damage after hydrogen fire was over in 100 seconds (https://www.youtube.com/watch?v=OA8dNFiVaF0).

II. METHOD OF EXTRACTION OF HYDROGEN

Hydrogen can be produced from diverse, domestic resources including fossil fuels, biomass, and electrolysis of water using electricity. The resulting synthesis gas contains hydrogen and carbon monoxide, which is reacted with steam to separate the hydrogen (https:// afdc.energy.gov/ fuels/). Other methods include using microbes that use light to make hydrogen, converting biomass into gas and separating hydrogen, using solar energy to split hydrogen from water molecules. But above all the cheap and best method is electrolysis (https://en.wikipedia.org/wiki/Hydrogen_production). The process of extracting hydrogen and oxygen from water using electricity is known as electrolysis which requires two electrodes. Both silver and nickel can be used as electrodes (see Table-2).Though gold and platinum are considered as the best electrodes for production of hydrogen, they are costly when compared to silver and nickel [8, 9]. Further research has taken place in coating of these with activated carbons to improve electrolysis process more efficiently [10]. An electrolyte solution is required for better conduction. For splitting one H_2O atom into H_2 and O_2 requires 1.23 volts electricity. Non-renewable sources such as solar cells can be utilized to minimize the electricity cost. Major hurdles are in trapping and storing of hydrogen being highly flammable. Factors effecting production of hydrogen are [8, 11]: Electrolyte quality; Electrode material; Electrical resistance of the electrolyte; Space between electrodes; Size and alignment of electrode; Temperature; Pressure and applied voltage. Table-3 gives characteristics of hydrogen. Table-4 gives the advantages of hydrogen.

Table-2: Electrodes with different solutions to produce hydrogen (ml) within 30 minutes

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	H_2So_4	HCL	KOH	NaCl
Silver	28.55	45.00	27.50	17.50
Aluminium	40.50	24.00	22.45	20.65
Copper	36.50	25.85	28.45	17.65
Steel	32.50	24.50	28.50	21.50
Nickel	54.80	48.65	28.85	20.85

Table-3: Characteristics of hydrogen

Molecular weight	2.015 g
Specific gravity	0.090
Lower heating value	120 MJ/Kg
Heat of vaporization	
Boiling point	20K
Octane number research	106
Flammability limits/ CO_2 emissions	0
Adiabatic flame temperature	2383 K

Table-4: Advantages of hydrogen

	Hydrogen	Natural gas	Gasoline	Diesel
Vapour density(mg/L)	0.07	0.55	4.0	3.0
Combustion Temperature (K)	1131.5	1085.15	778.52	643.15
Flammability range (mJ)	0.02	0.29	0.24	0.20

Water requirement to make 1kg of hydrogen is assessed using the Stoichiometric equation: $2H_2O \rightarrow 2H_2 + O_2$. 1 mole of H_2O produces 1 mole of H_2 as a result 18 grams of H_2O gives 2grams of H_2 at STP conditions. 1000 grams of H_2 is 500 moles of H_2 gas. Hence, 500 × 18 grams = 9 kgs of water is required to make 1 kg of hydrogen. This could be the cheapest way of production of high amount of hydrogen [11].1 kg of hydrogen contains 33.33 kWh of usable energy, whereas in case of petrol and diesel, it is 12 kWh. A full tank of hydrogen (7kg capacity) vehicle can go up to 480 Km.

III. FACTORS RESPONSIBLE FOR ENGINE PERFORMANCE

The factors observed from petrol and diesel engines are: Compression ratio (The ratio of the maximum to minimum volume in the cylinder of an internal combustion engine); Coolant temperature; Friction between piston ring and cylinder ring; Valve resistance; Valve timing; and Heat transfer. Hydrogen has relatively high compression ratio than other IC engines (34:1 to 180:1) so it can be used as a fuel in IC engines [12].

In IC engines, fuel undergoes combustion. Air in the engine releases chemical energy in fuel as heat and convert it into mechanical work. Combustion of fuel raises temperature and pressure of the gases inside the engine. These gases constitute the working fluid. Hydrogen is considered to be long term potential alternative both as a fuel for IC engines and fuel cell powered vehicles. It can be produced from fossil and non-fossil sources. H_2 can be produced by conventional process like natural gas but CO_2 is emitted. Electrolysis is the best process being used in most of the industries. Production of H_2 is very expensive due to high electricity consumption, which can be minimized using solar energy [13]. Table-5 gives the comparison of emissions of hydrogen engine and standard IC engines.

Table-5: Emissions of hydrogen engine (g/mile) and standard IC engine [13]

	NOx	CO	NMHC
SULEV standards	0.02	1.0	0.01
H_2 IC	<<0.02	0.0036	0.006

Diesel engines are designed to operate at high compression ratios of 15-20, whereas petrol engines have 8-10. High compression ratio yields high thermal efficiency. Diesel engines have fuel efficiency 15-25% better than petrol engines. For example, an Indian car of 1.2 liter engine capacity (i.e., 1200cc of air fuel mixture): (1200*1)/(1+14.7) = 76cc of petrol. Energy requirement for diesel, petrol and hydrogen are 45.5, 45.8 and 120-140 MJ/kg respectively. CO_2 emission when 1 kg of fuel burned for diesel is 2.65 kg, whereas it is 2.3 kg for petrol and 9-litres of water in case of hydrogen.

IV. SAFETY PRECAUTIONS WITH HYDROGEN

Hydrogen is highly flammable and generates more heat using in IC engines. High temperature resistant materials should be used in construction of engine valves and container. Coolant plays a very important role taking necessary steps to overcome the backfiring problem. Hydrogen tanks must protect from leaking and damaging at any unexpected events. Hydrogen fuel cell vehicles use tanks to store hydrogen. Such type of tanks in vehicles should be preferred to store hydrogen. Pre-ignition problem is very high in hydrogen IC engines.

V. DESIGN MODIFICATIONS

Hydrogen has low energy ignition limit. Seeping of hydrogen by piston rings to the crankcase has a possibility of igniting. Crankcase ventilation is must for hydrogen engines to prevent

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accumulation of un-burnt hydrogen. Installation of a pressure relief valve can relieve the sudden pressure rise due to hydrogen ignition in the crankcase. Calorific value of hydrogen is high. Special crystalline materials should be utilized for storing hydrogen at lower pressures and greater densities. Engine should be designed in such a way to bear the heat and overcome pre-ignition problems. Fuel delivery system must be redesigned. The simplest method of delivering fuel to hydrogen engines is through carburettor or central injection system [10]. Hydrogen engine performance can be improved by injecting hydrogen directly into the cylinder during the compression stroke [14, 15]. These specifications will definitely enhance the engine cost.

VI. CONCLUSION AND FUTURE SCOPE

Hydrogen is gaining worldwide importance as a combustion fuel with low emissions. It is a gas at ambient conditions, and considered as the cleanest fuel producing zero emission. It has more advantages when compared to other fuels. It has high flame speed with high auto-ignition temperature well suited for use in IC engines.Safety culture must be adopted for minimizing workplace hazards, protecting environment, thereby protecting the health, safety and welfare of the personnel involved and general public. Any project dealing with hydrogen demands a well-designed workplace. A well-designed workspace is a necessary for projects involving hydrogen to mitigate hazards by taking into account the characteristics of hydrogen. Construction materials must be selected to withstand the intended operating conditions. Design of hydrogen piping systems should minimize the potential for leaks and allow for their easy detection. Design must include safety-related maintenance requirements such as correct valve placement, electrical isolation, equipment accessibility, and built-in condition monitoring. Safety of the workspace should have interlock systems working in unison with hydrogen and fire detectors.

Japan is at the forefront of developing hydrogen technologies and opened recently a large green hydrogen plant (https:// www.rechargenews.com/transition/japan-opens-worlds-largest-green-hydrogen-plantnear-fukushima- disaster-site/2-1-769361). The EU (European Union), the US (United States), Australia and China are on the deployment of hydrogen technologies in sectors such as steel, shipping, petrochemicals and power. India is committed to the rapid expansion of the hydrogen economy, ensuring the cost- effective deployment of low carbon hydrogen technologies across the transport, industry and power sectors by 2030 (https:// www.teriin.org/sites/default/files/2020-06/Hydrogen-Policy-Brief.pdf).

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