

Hydrogen Fueled Internal Combustion Engine: A Review

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Abstract: Continuous and fast depletion of the fossil fuels and exponential growth in the industrial demand for conventional fuels are increasing sharply. This is demanding the circumstances to carry out research in order to find out the viable alternate fuels, for meeting sustainable energy demand with minimum environmental hazards, cost effective and safe. All the above challenges can be addressed by the use of hydrogen as an alternate fuel. In this paper the fundamentals of the hydrogen as a fuel in the internal combustion engine has been discussed. Fuel properties such as combustion, performance and emission characteristics of hydrogen fuelled engine are been described.

I. INTRODUCTION

From many years, hydrocarbon fuels have played a leading role in the transportation and power generation. Due to increase in destruction in the environment by emission and depletion of the worldwide petroleum resources, research must be carried out to find an alternate fuel to overcome the major problems. As a result of various alternative fuels like liquefied compressed gas (LPG), compressed natural gas(CNG), vegetable oil, bio gas, producer gas, hydrogen etc, have been considered as substitute for the hydrocarbon based fuels [1]. An internal combustion engine, hydrogen can be used as a sole fuel. The higher self-ignition temperature of the hydrogen (858) needs external source to initiate the combustion in the combustion chamber. Emission such as HC, CO, CO₂, SO_x and smoke are either not observed or very much lower than the hydrocarbons used as fuels [2]. The unburned hydrogen may come out of the engine, through the exhaust but it is not considered as hydrogen is non-toxic in nature and does not involve in any smog reaction. This paper provides a brief summary of the combustion, performance and emission characteristics of the hydrogen fuel in an internal combustion engine with respect to the other traditional fuels.

II. COMBUSTIVE PROPERTIES OF HYDROGEN

There are several important characteristics of hydrogen that greatly influence the technical development of the internal combustion engine. Important properties are discussed in the following section.

Property	Hydrogen	Methane	Gasoline
Limits of flammability in air (vol %)	4-75	5,3-15	1-7,6
Laminar burning velocity in air* (cm/s)	200-230	37-43	37-43
Minimum energy for ignition in air (mJ)	0,02	0,29	0,24
Autoignition temperature (K)	858	813	501-744
Quenching gap in air* (mm)	0,64	2,03	2
Diffusion coefficients in air* (cm ² /s)	0,61	0,16	0,05
Density* (kg/m ³)	0,0838	0,7174	700-750
Flame temperature in air at $\lambda=1^*$ (K)	2318	2148	2470
Lower heating value (MJ/kg)	120	53	44
Research octane number	>130	>120	90-100
Normal boiling point (K)	20,3	111,6	310-478

*273K 1013hPa

Table 2.1: properties of hydrogen, gasoline and methane.

2.1 FLAMMABILITY FACTOR

Flammability is the ability of a substance to burn or ignite, causing fire or combustion. For fuels, the flammability factor is an important aspect for the power generation. The Flammability range in air at 298K at 1 atm for hydrogen is 4%- 75% and for the gasoline it is 1%-7.6%. for an internal combustion engine, it is better to give the flammability range in terms of equivalent ratio, it is evident that hydrogen fuelled IC engine is amenable for stable operations, which allows more control over engine operation of both emission reduction and fuel metering [3].

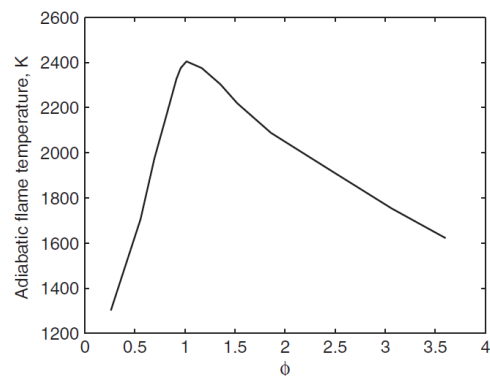


Figure 2. Flame temperature change for hydrogen air blend [12].

2.2. FLAME PROPERTIES

Flame velocity and adiabatic flame temperature are important properties for engine operation and control, in particular thermal efficiency, combustion, stability and emission. The burning velocity of hydrogen is six times greater than gasoline enhances the brake thermal efficiency of it. By increase in hydrogen percentage in the mixture, the resultant laminar burning velocity as well as the flammability limits increases [4]. Stockhausen *et al.* [5] found a pre-ignition limit of, $\phi = 0.6$ for a 4-cylinder engine at an engine speed of 5000 rpm. But however, the engine peak power output was reduced by 50% compared to engine operation with gasoline. Ilbas *et al.*[6] observed when hydrogen content was increased the burn duration decreases and no knocking and backfire phenomenon was observed during engine operation for all the fuel conditions for gasoline and air mixture [7,8].

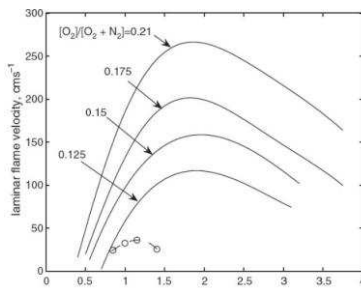


Figure 3. Laminar flame velocities for H₂, O₂, N₂ mixtures (-o-) for gasoline and air mixture[8]

MINIMUM IGNITION SOURCE ENERGY

The minimum ignition source energy is minimum energy required to ignite a fuel-air mixture by an ignition source such as a spark discharge. For hydrogen-air mixture the minimum ignition source energy is an order of 0.02MJ in magnitude and is lower than the petrol-air mixture, 0.24MJ in magnitude- and is approximately constant over the range of flammability. Unfortunately low minimum ignition energy of the hydrogen-air mix means that a much lower energy spark is required for spark ignition. That means hot gases and hit spots on the cylinder can serve as source of ignition, creating problem of premature ignition.[9,10]

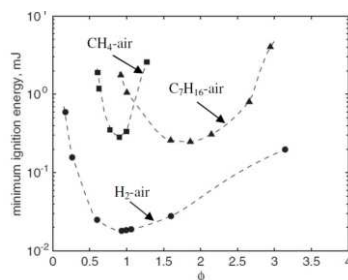


Figure 4. Minimum ignition energy of hydrogen in air [11]

2.4 HIGH DIFFUSIVITY

Diffusivity is the ability of dispersing of fuel in air. Hydrogen has very high diffusivity. Diffusivity of hydrogen is considerably greater than gasoline and is advantageous for two main reasons. Firstly, it facilitates the formation of a uniform mixture of fuel and air. Secondly, if a hydrogen leak develops, the hydrogen disperses rapidly. Thus, unsafe conditions can either be avoided or minimized. It also ensures prompt ignition of the charge in the combustion chamber. [12,13].

2.5 LOW DENSITY

Hydrogen has very low density. This results in two problems when used in an internal combustion engine. Firstly, a very large volume is necessary to store enough hydrogen to give a vehicle an adequate driving range. Secondly, the energy density of a hydrogen-air mixture, and hence the power output, is reduced. [14]

2.6 HIGH AUTO IGNITION TEMPERATURE

The auto ignition temperature of a substance is the lowest temperature at which it will spontaneously ignite in a normal atmosphere without an external source of ignition, such as a flame or spark. This temperature is required to supply the activation energy needed for combustion. The auto ignition temperature of hydrogen is 536°C. The temperature may not exceed hydrogen's auto ignition temperature without causing premature ignition. Thus, the absolute final temperature limits the compression ratio. But the high auto ignition temperature of hydrogen allows larger compression ratios to be used in a hydrogen engine than in a hydrocarbon engine. [7]

2.7 SMALL QUENCHING DISTANCE

Hydrogen has a small quenching distance, 0.6mm for hydrogen and 2.0mm for gasoline, which refers to the distance from the internal cylinder wall where the combustion flame extinguishes. This implies that it is more difficult to quench a hydrogen flame than the flame of most other fuels, which can increase backfire (i.e., ignition of the engine's exhaust). [15]

III. ENGINE POWER OUTPUT

Hydrogen fueled internal combustion engine peak power output is primarily determined by volumetric efficiency, air-fuel ratio and fuel injection. The stoichiometric air-fuel ratio for hydrogen is 34:1. At this ratio, hydrogen takes 29% of the combustion chamber leaving 79% of air in it. As a result, the energy content of this mixture will be less than it would be if the fuel was gasoline. The stoichiometric heat of combustion per standard kg of air is 3.37MJ and 2.83MJ for hydrogen and gasoline. It follows that maximum power density of

a pre-mixed relative to the power density of the identical engine. The mixing of fuel and air prior to its entering the combustion chamber, these system limits the maximum theoretical power obtained to approximately 85% of that of gasoline engine. At a stoichiometric fuel ratio, the combustion temperature is very high and as a result it will form a large amount of nitrogen oxides (NO_x), which are the criteria of pollutant. If the equivalence ratio is below the lean flammability of gasoline/air mixture the resulting ultra-lean combustion produces low flames temperature and lead directly to lower heat transfer to the walls, higher engine efficiency and lower exhaust of NO_x emission. Since one of the reason for using hydrogen is low exhaust emission and better performance. Higher the compression ratio, is higher the indicated thermodynamic efficiency of the engine.

IV. BRAKE THERMAL EFFICIENCY

Brake thermal efficiency is one of the key factors in determining the engine performance and is defined as the fuel consumption rate to generate unit power. The high research octane number [RON] and low lean-flammability limit of hydrogen helps in attaining high brake thermal efficiency in an IC engine. Ji and Wang [18] plotted the brake thermal efficiencies against the excess air ratios for three different hydrogen volume fractions [0%, 3% and 6%] from their experimental data. It shows that brake thermal efficiencies of the hydrogen enriched engines are higher than the gasoline, especially at lean conditions. The peak brake thermal efficiency under the test conditions designed to run at a stoichiometric air-fuel ratio increases from 26.4% at $\phi = 1.09$ for the original engine, to 31.6% at $\phi = 1.31$ for 6% hydrogen addition. Brake thermal efficiencies change with excess air ratio between 14% and 26.4% without hydrogen addition and increases between 29.2% and 31.6% with 6% hydrogen addition under the experimental conditions.

Hydrogen-enriched engines can produce roughly constant brake thermal efficiencies in a wide range of excess air ratio compared with the pure gasoline engine. Lucas and Richards found that if hydrogen is induced in to the cylinder by mixing with gasoline at a constant flow rate, the engine thermal efficiency increased by 10%. According to Lyon's research, the engine efficiency can be increased till 6%, under no cycle variation. Meanwhile, lean combustion has been proved to be an effective way for obtaining a higher engine thermal efficiency [17]. For a gasoline SI engine, high efficiency combustion occurs near the stoichiometric in a narrow range of excess air ratio. So with the increase of excess air ratio a gasoline engine goes into more and more serious incomplete combustion, producing much lower power output

and brake thermal efficiency. On the other hand, Tang *et al.*[18] presented a plot for brake thermal efficiency [BTE] against BMEP which shows a drop-off at high loads is likely due to increasing heat transfer losses.

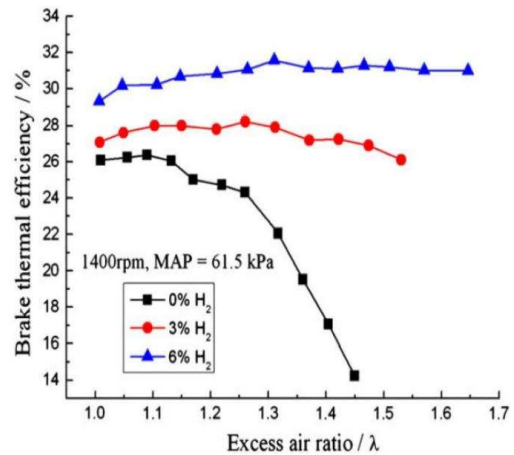


Figure 5. Variation of BTE against excess air ratio [18]

V. EMISSION ANALYSIS

The major toxic pollution in the exhaust of internal combustion engine constitute of HC, CO and NO_x along with CO₂

5.1 NO_x EMISSION

The combustion of hydrogen with oxygen produces only water when the combustion of hydrogen with air takes place it produces oxides of nitrogen. The oxides of nitrogen are created due to high temperature generated within the combustion during combustion. NO_x emission are found to increase with increase in hydrogen fractions in the mixture NO_x emission depends upon

- The air/fuel ratio
- The engine compression ratio
- The engine speed
- The ignition timing
- Whether thermal dilution is utilized

Ji *et al.*[19] Showed that with increase in hydrogen content to the relevant excess air ratio for the minimum NO_x emission slightly increases as with higher hydrogen addition fraction. More air is needed for fully burning hydrogen to produce higher in-cylinder temperature. Ultra-lean combustion (i.e., $\phi \leq 0.5$), which is adequately synonymous with low temperature combustion, is an effective means for minimizing NO_x emissions in internal combustion engine. [20]

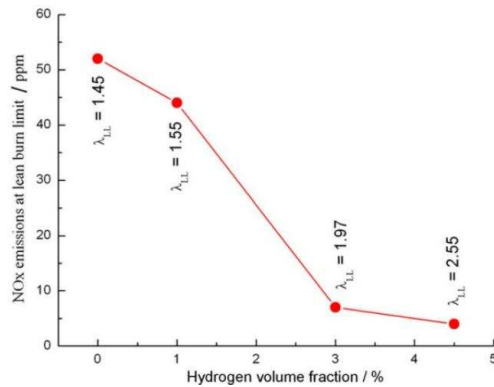


Figure 6. NOx emission variation at lean burn limit vs. Hydrogen Volume fraction at 1400 rpm and 61.5 KPa [19]

5.2 HC EMISSION

The principal cause of HC in SI engines is incomplete combustion of the fuel-air charge, resulting in part from flame quenching of the combustion process at the combustion chamber walls, and engine misfiring. Engine variables that affect HC emissions include the fuel-air ratio, intake air temperature, and cooling water temperature. The HC emission gradually decreases with increase in hydrogen present in the mixture. As increase in hydrogen formation of OH⁻ radicals, they are accelerated and results in decrease in HC emission. The small quenching distance of hydrogen (three times smaller than gasoline) between the position of flame extinguishment and the cylinder wall helps to reduce HC emissions with increase in hydrogen fractions. The HC emission are effectively reduced with the increase of hydrogen blending ratio, in a spark ignition ethanol engine and reach the minimum value of 1019ppm of h₂=5.949% [15]. Hydrogen addition in fuel reduces unburnt hydrocarbon depending on fuel consideration [20]. Jiet *al.* [21] found that for normal gasoline fuel, the HC emission abruptly increases after a certain value of excess air ratio [$\lambda = 1.36$] which, can be decreased by increasing hydrogen content, as the high flammability of hydrogen helps in complete combustion of the fuel. The works of Dimopouloset *al.* [22] state that hydrogen addition in fuel reduces unburnt hydrocarbons to an extent of 6 to 20% depending on fuel consideration. The above said fact can be clearly observed from the figure 7 which has been taken from their works.

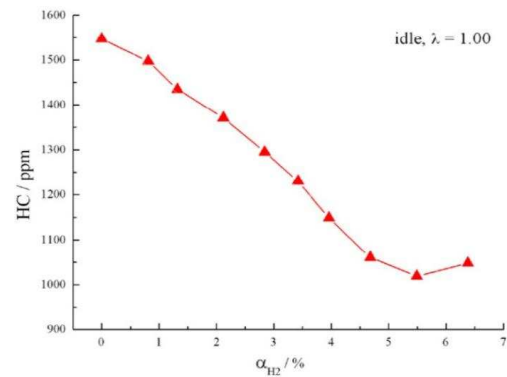


Figure 7. HC emission variation with hydrogen fraction for SI Hydrogen-ethanol engine.[22]

5.3 CO AND CO₂ EMISSION

Carbon monoxide CO is a colourless, odourless, and tasteless gas that is highly toxic to humans. CO is produced due to the incomplete combustion of hydrocarbon fuels. One of the main sources of CO production in SI engines is the incomplete combustion of the rich fuel mixture that is present during idling and maximum power steady state conditions and during such transient conditions as cold starting, warm-up, and acceleration. Uneven fuel distribution, poor condition of the ignition system, very lean combustion, and slow CO reaction kinetics also contribute to increased CO production in SI engines. CO emission increases with the hydrogen addition fraction when the excess of air ratio is near stoichiometric condition. As air/fuel ratio is more in hydrogen, combustion of hydrogen in cylinder can cause lean oxygen area due to the in homogeneity of the fuel air mixture which reduces the oxidation rate for CO into CO₂. The increase in cylinder temperature after hydrogen addition also contribute to stimulating the oxidation reaction of CO into CO₂. The results for the work of Ji and Wang [18] has been plotted to show the variation of emission with change in hydrogen fraction.

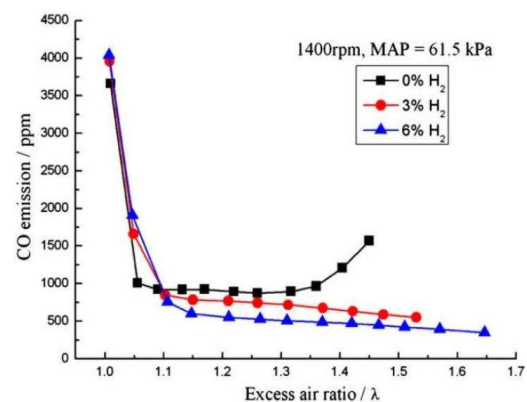


Figure 8. CO emission variation vs. excess air ratio [18]

VI. CONCLUSION

It is evident from the study that it is advantageous to use hydrogen enriched air as a fuel in internal combustion engines. Power and torque loss occurs at low speed hydrogen operation. At high speed hydrogen gives better performance as compare to gasoline operation. Similarly Thermal efficiency and Brake mean effective pressure of hydrogen is more at higher speed. NO_x emission in internal combustion engine reduces to the maximum considerable amount. This makes it possible to run the engine leaner, resulting in lower emissions of CO₂, CO and HC. Short time of combustion produces lower exhaust gas temperature for hydrogen. Hydrogen is a very good candidate as an engine fuel. Appropriate changes in the combustion chamber together with better cooling mechanism would increase the possibility of using hydrogen across a wider operating range.

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