

Prospects and Perspective of Hydrogen utilization in Compression Ignition Engines- A Review



Engineering

KEYWORDS : Hydrogen, sole fuel, supplemented fuel, Compression Ignition Engines.

P.S.Ranjit

University of Petroleum & Energy Studies (UPES), Dehradun

Mukesh Saxena

University of Petroleum & Energy Studies (UPES), Dehradun

ABSTRACT

Depletion of fossil fuels and increase in environmental degradation has accelerated research to use various alternative fuels, including hydrogen.

This paper reviews utilization of hydrogen as a sole fuel and investigates into hydrogen supplementation of fossil fuels as well as alternative fuels in Compression Ignition (CI) engines with respect to improvements in performance, reduction in emissions and enhancement of combustion of these engines.

It has been observed that most of the work on hydrogen utilization has taken place with respect to performance and emissions point of view and needs to be concentrated in combustion area.

Combustion of hydrogen can lead to its utilization as sole fuel in the long term perspective as well as a supplementing fuel to the conventional and alternative fuels in the short term perspective to enhance efficiency and reduce emissions of CI engines.

INTRODUCTION

Environmental pollution has reached to an alarming stage and depletion of fossil fuels makes the researchers to look into various alternative fuels in order to maintain and provide sustainable development. Hydrogen has been considered as fuel of the future due to its clean burning nature and eventually its availability from renewable sources.

Hydrogen has been considered to be the best alternative fuel as its properties could improve combustion and lead to low Green House Gases (GHG). Hydrogen used as sole fuel, could have minimal GHGs with increase in NOx emissions and could also be used under the supplemented mode with the conventional and alternative fuels.

Hydrogen in long term perspective could be used as a sole fuel, and in short term perspective it can be used as supplementing fuel to enhance thermodynamic efficiency and reduce emissions of the conventional fuels and alternative fuels: bio fuels, Compressed Natural Gas (CNG), Liquid Petroleum Gas (LPG) etc.

This paper discusses hydrogen as a fuel, its combustion as a sole fuel in long term perspective and as a supplementing fuel in a short term perspective.

HYDROGEN AS A FUEL

Hydrogen is odorless, tasteless, colorless, non corrosive and non toxic element in a combined form. Different physico and chemical properties of the conventional as well as alternative fuels along with hydrogen are as given in Table 1. [1].

It may be noted that it has higher calorific value and high flame speed with wider flammability limits as compared to conventional and alternative fuels. Further higher diffusivity of hydrogen causes better mixing process; making the heterogeneous mixture to proper local combustible mixtures in CI engines inside the combustion chamber and thereby leading to improved combustion.

As hydrogen is having wider flammability range, makes easier to use at different flammable mixtures starting from lean to rich

(i.e., $0.1 < \phi < 7.1$) needs to be understood with respect to engine power under lower & higher flammability levels and at different pressures. The diffusivity of hydrogen by mass is very high, because of this difference in upper and lower flammability limits needs to be understood.

The minimum ignition energy required for Hydrogen air mixtures is very less at atmospheric conditions i.e, 0.02 mJ, which is much lesser than other conventional fuel- air mixtures. With increase spark gap ignition energy increases and this need to be understood with respect to CI combustion environment under different hydrogen doses.

Hydrogen gas is light among all other gases. Its density is 0.081 kg/m³. Further, it is very important to understand how high volume fraction, wide flammability limits get affected by the mixtures with respect to thermal conductivity, kinematic viscosity and bulk modulus properties to get the best power out.

Auto ignition temperature of hydrogen is still under ambiguity and needs to be understood for better combustion as sole and the supplemented fuel engines to design the combustion chambers for better performance and reduction in emissions.

A mixture of 4-75% by volume of hydrogen in air at atmospheric pressure and room temperature gives a combustible mixture.

Whereas conventional Gasoline, Diesel, LPG, CNG, Di Ethyl Ether (DEE) and Bio Gas are in the range of 1.4-7.6%, 0.6-5.5%, 2.15-9.6%, 5-15%, 1.9-36% and 7.5-14% respectively. Because of this wide flammable range the use of hydrogen with different fuel mixtures should give better results in increasing engine performance and reduction in emissions of the Internal Combustion (IC) engines.

Soot is the main cause of visibility of flame, whereas the hydrogen flame not producing any sort of soot and virtually not visible. And this flame is in the range ultraviolet rays rather than normal light spectrum. Hence, the hydrogen flame is not visible in day light.

Table 1-Properties of Hydrogen and other fuels [1]

Description	Hydrogen	Gasoline	ULSD	Methane (CNG)	Ordinary Diesel	Ethanol	Jatropa oil	DEE	LPG	Biogas
Density (kg/m ³)	0.081	4.4	876	0.6512	830-850	789	917	713	2.24	1.1
Mol. Wt	2.016	107		16.043	142	46.07	800	74	44.1	25.46
Auto ignition temp (OC)	500	257	250	537	280	423		160-170	493-549	700
Boiling Point (OC) at 1 atm	-252	25-225	180-345	-162	180-340	78	286	34	-42	

Ignition energy in Air (MJ)	0.02	0.24	NA	NA				NA		
Flame temp in air (OC)	2045	2197	NA	1918					1980	1911
Lower flammability limit (vol% in air)	4	1.4	0.6	5	1	4.3		1.9-2	2.2	7.7
Upper flammability (vol% in air)	74	7.6	5.5	15	6	19		36-48	9.5	23
Buoyancy: Gas or vapor density relative to air	0.07	2-4%	4-5%	0.6	6.5	1.51	27.12	2.5	1.51	0.863
Carbon Constituent	NA	85-88		75	86	50-52			82	
Hydrogen Constituent	100	12-15%		25	13	13-15			18	
Lower heat of combustion (MJ/kg)	119.93	44.5	43	50.02	42.3	26.9	39.774	33.9	46	
Burning Velocity in air (m/sec)	2.65-3.25	0.37	NA		0-3	NA		NA		
Specific Heat Ratio of NTP gas	1.383	1.05		1.308						1.303
Diffusion coefficient in NTP air (cm ² /sec)	0.61	0.005		0.16				NA	0.11	

HYDROGEN AS SOLE FUEL: LONG TERM PERSPECTIVE

The utilization of hydrogen as a sole fuel has been studied [2-5] for hydrogen fueling vis-à-vis hydrogen combustion in CI engines. The associated performance and emissions levels are highlighted.

J.D. Naber and D.L. Siebers [2], studied ignition delay and combustion of hydrogen on a specially designed disc shaped combustion chamber with a provision to capture the combustion of hydrogen inside the combustion chamber through transparent windows.

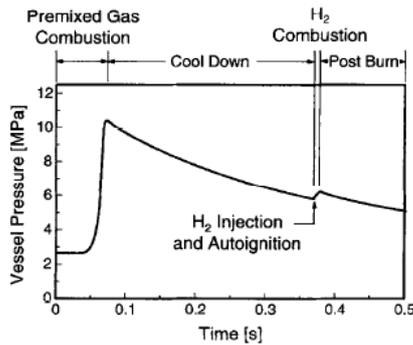


Figure 1 Pressure History of Diesel Combustion with H₂ fuel

Figure 1- explains the combustion mechanisms with respect to time at ambient gas density of 20.5 kg/m³ with hydrogen as a fuel. Studies showed that the ignition delay was shorter for ambient gas temperatures of greater than 8470 C at oxygen concentration of 5-21%. However, the effect of pressure on ignition delay was very less.

The effect of fuel temperature and ambient temperature were also studied. Ignition delay decreased with increase fuel temperature and this dependence is smaller in case of the ambient temperature (Figures 2 & 3)

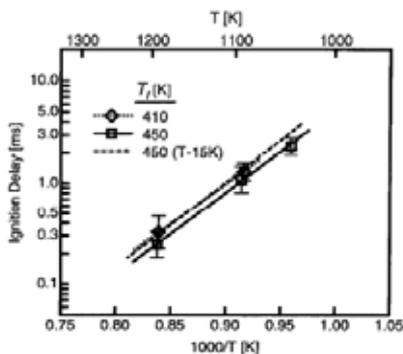


Figure 2 Effect of the fuel temperature on ignition delay

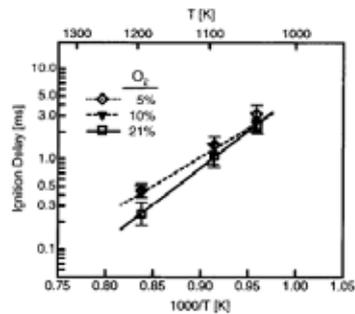


Figure 3 Effect of ambient gas O₂ concentration on ignition delay

The effect of concentration in given hydrogen combustion at constant supply of air at 20.5 kg/m³ with constant temperature of 8470 C was shown in Figure 4. It was observed that a difference of 50kPa taken place between oxygen concentration of 5%, 10% and 21%. It was recommended that, late injection of hydrogen during compression stroke in direct injection diesel engines can give less emissions without any exhaust gas after treatment processes.

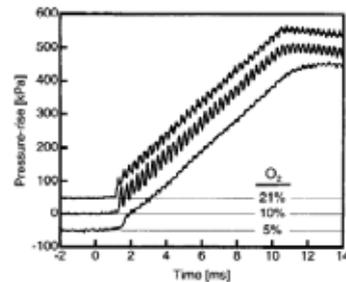


Figure 4 Effect of the ambient gas O₂ concentration on H₂ injection and combustion

S.M. Lambe et.al.,[3] have done an exhaustive study on 0.65L, 6kW, single cylinder diesel engine tested with gaseous hydrogen in a range of 65-90% on total energy basis at different speeds like 1000 and 1500 rpm. It was noticed that the efficiency increased by 15% and Green House Gases (GHG) and NO_x reduced by 30% & 70% respectively.

A.P. Kudryash et.al,[4] elucidated the mixture requirement with respect to diesel engines to understand the performance under given operating conditions with some hardware modifications. It was understood that with swirl chamber external mixture will give better performance when comparing to internal mixture formation along with glow plug.

P.C.T. De Boer et al., [5] carried out their research to understand

the differences between hydrogen and hydrocarbon operated engines. Thermal efficiency is mainly dependent on compression ratio 'r' and ratio of specific heats 'γ'. If these values increased, automatically thermal efficiency will be increased. Research on CFR engine with diesel head mounted engine, with different compression ratios undertaken to understand how increase in 'r' and 'γ' will increase the thermal efficiency and indicated mean effective pressure. But increase in 'r' and 'γ' gives the fundamental backfire problem with hydrogen. In addition to this backfire knock problems also experienced. To overcome this, they implemented the direct cylinder injection of hydrogen process.

HYDROGEN AS A SUPPLEMENT FUEL: SHORT TERM PERSPECTIVES

Various studies [6-17] undertaken with respect to hydrogen supplementation (% mass) with diesel, bio fuels, dimethyl ether, natural gas etc.. would be discussed with respect to combustion, emission and efficiency.

Jacob Wall, [6], had some observations with hydrogen mass share supplementations to the diesel and Jatropa oil. At peak load, the thermal efficiency of Jatropa oil is 27% at 0% hydrogen mass share and increased to 29% at 10% mass share. Whereas for diesel it was 30% at 0% hydrogen mass share and 32% with 5% mass share with reduction in fuel consumption and unburned hydrocarbons, because of lean mixtures formation due to hydrogen supplementation

Studies, [7], under dual fuel mode; Diesel as pilot and hydrogen as supplemented fuel with different hydrogen injection strategies showed optimum hydrogen injection was nearly about 50 BTDC with 300 CA duration. The increase in thermal efficiency by 3.2% with increase in NOx by 34% were observed as compared to baseline diesel data.

Studies [8], with and without Exhaust Gas Circulation (EGR) having diesel-hydrogen dual fuel operation at 0.15 kg/hr hydrogen mass share showed the brake thermal efficiency increase by 12.9% with smoke reduction by 42%. The brake specific energy consumption was also less as shown in Figures 5 & 6.

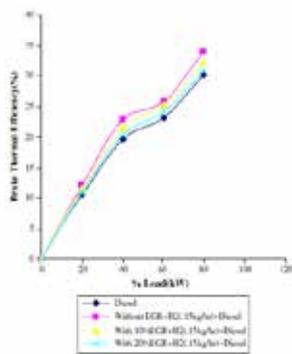


Figure 5 Brake thermal Efficiency Vs. % Load

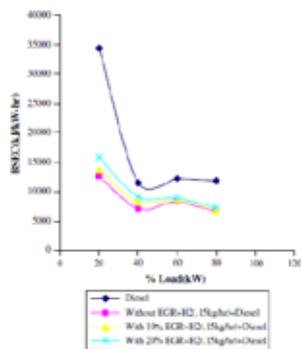


Figure 6 Brake Specific Energy Consumption Vs. % Load

Studies [9-10] with Diethyl Ether (DEE) as a pilot fuel supple-

mented with hydrogen showed thermal efficiency to increase by 30% and NOx considerably reduced. The use of DEE with Hydrogen enrichment up to 75% load was without knocking operation. In another study, [11] at 30% energy share of hydrogen, the brake thermal efficiency increased by 2.2% and Specific Energy Consumption (SEC) was reduced by 1.6% at full load conditions, whereas NOx increased up to 30%. At higher hydrogen share NOx reduced because of reduction in combustion temperature due to increase in hydrogen share. V. Edwin Geo et.al., [12] carried out experiments on diesel engine running on Rubber Seed Oil (RSO) and Rubber Seed Oil Methyl Ester (RSOME) as main fuels and hydrogen as a supplemented fuel. Maximum thermal efficiency of diesel, RSO and RSOME were 31.62%, 28.12% and 29.26% at different optimum mass shares of 10.17%, 8.37% and 8.73% respectively. These mass shares allowable up to 12.69%, 10.76% and 11.2% at full load showed increase in NOx with significant Smoke reduction.

N. Saravanan et.al. [13], claimed that, brake thermal efficiency increased from 23.6% to 29.4% at 50 ATDC with 900 CA duration under diesel-hydrogen dual fuel mode. Specific Energy Consumption (SEC) was decreased from 7.4 to 3.4 at full load under these conditions.

M. Senthil Kumar et.al., [14] carried out with Direct Injection with diesel and Straight Vegetable Oil (SVO) enriched with hydrogen as a supplemented fuel. Results with Jatropa oil and diesel with hydrogen supplementation showed that the brake thermal efficiency increased by 2.1% and 1.7% respectively fewer than 7% and 5% hydrogen mass share.

Further, smoke of Jatropa and diesel were reduced by 0.7 and 1.7 BSU respectively. Even Green House Gases also significantly reduced and NOx levels had increased by 140 and 99 ppm for Jatropa and diesel fuels. Peak cylinder pressure increased by nearly 4 bar under this dual fuel operation.

B. Hara Gopal Rao et.al., [15] had done an exhaustive study on dual fuel diesel-hydrogen mode operated diesel engine. Hydrogen share was varied in the range of 10-30% of total energy and obtained optimized hydrogen share on energy was 10%. At this optimized hydrogen share, the thermal efficiency increased at peak loads only but not at part loads. NOx also increased due to increase in combustion temperature because of faster energy release rate of hydrogen. At full load condition, increase in hydrogen share reduces the ignition delay. At 30% hydrogen energy share, engine starts knocking. Further, they extended their work by conducting the experiments in a closed vessel to understand the dual fuel engine flame propagation problems.

Timothy Gatts, Shiyer Liu et.al [16] investigated the emissions and combustion efficiency of heavy duty diesel engine unburned gaseous fuels operating under hydrogen-diesel and Natural Gas-diesel under dual fuel modes.

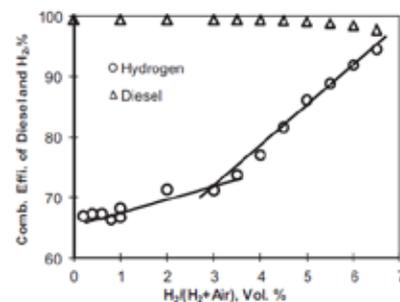


Figure 7 Effect of H₂ addition on combustion efficiency of diesel & H₂ at 15% Load

Figure 7-shows that understood that, the combustion efficiency increased linearly from 1% to 6.5% of Hydrogen share. At 1% hydrogen share, the combustion efficiency was 68% and slightly increased up to 3% hydrogen share and after this, combustion efficiency increased drastically up to 94.5% at 6.5% Hydrogen share.

S. Bari, M. Mohammed Esmail, [17] had done some experimentation work on different H₂/O₂ doses equivalent to diesel to understand the brake thermal efficiency on a constant speed 38kW Hino diesel engine under varying load conditions at 19kW, 22kW and 28kW respectively. At these loads with 4.84%, 6.06% and 6.12% of H₂/O₂ dose the increase in thermal efficiencies by 2.6%, 1.1% and 1.6% and later it could be further reduced with increased dose. It was concluded that, up to 5% of H₂/O₂ dose there is increase in performance of engine and reduction in emissions.

SUMMARY & CONCLUSIONS

Based on these studies some of the conclusions can be summarized as below.

1. A wide variety of engines varying from 5kW to 265 kW, single cylinder to multi cylinder, fueling from conventional diesel to different alternative fuels like SVO, DEE, RSO, RSOE and Natural Gas (NG) etc. using different fuel induction techniques; carburetion system to High Pressure Direct Injection system have been studied. The results are promising to represent hydrogen as good alternative fuel as sole and supplemented fuel
2. Hydrogen as sole fuel utilization would require major modifications starting from engine material compatibility to utilization of hydrogen, its safety and economical aspects.
3. In supplemented mode hydrogen gives better substitution in transition phase (short term perspective) to switch over to the sole hydrocarbon engines. The supplemented hydrogen engines would require minor hardware modifications.

4. The supplementation by hydrogen in a given engine using conventional and alternative fuels, increases efficiency. This is directly related to injection strategy of hydrogen fuel in the engine either by direct injection in the combustion chamber or the port injection in the inlet manifold. Hence, it is very essential to understand the increase in efficiency with respect to injection strategy, varying load and speed and for the considered fuel along with its properties.
5. Hydrogen supplemented CI engine operating on the conventional or alternative fuels would require an approach to be developed considering optimization of heat release with optimal proportion of hydrogen to supplement the conventional and/or alternative fuelled CI engines to enhance their performance and emissions.

ACKNOWLEDGEMENTS

Authors would like to thank UPES for the encouragement and the Ministry of New and Renewable Energy (MNRE), Government of India, New Delhi, for their support in sponsoring the project to work on "Performance Enhancement, Evaluation and Analysis of an IDI Diesel Engine Using Straight Vegetable Oil (SVO) with Hydrogen Supplementation".

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