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Investigation of Using Hydrogen as an Internal Combustion Engine Fuel

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Abstract: With the growing rate of depletion of the non - renewable fuels, the quest for an appropriate alternative fuel has gathered great momentum. Hydrogen is one of the best alternatives for conventional fuels. Experiments are conducted in a single-cylinder, four-stroke, water - cooled, direct - injection diesel engine coupled with an electrical generator having a compression ratio of 17:1 and a capacity of 3.7kW at a rated speed of 1500RPM. Performance parameters such as specific fuel consumption (SFC) and brake thermal efficiency (η_{bth}) are determined and emissions such as oxides of nitrogen (NOX), hydrocarbon (HC), carbon monoxide (CO), particulate matter, smoke and exhaust gas temperature are measured. In this investigation, the hydrogen was fed to the engine through the inlet manifold at the end of the compression stroke of the cycle. In order to maintain safety, the flame t rap, flame arrestor and solenoid valve were also used in the experimental setup. The results show that there is an increase in thermal efficiency and reduction in carbon monoxide emission when, the hydrogen is used as a dual fuel, in the operation of the diesel engine.

Key words: Compression · Ignition engine · Hydrogen · Emission · Combustion rate

INTRODUCTION

The fuels derived from crude oil are critical sources of energy for fueling vehicles. In the fast moving world, hydro carbon based fuels have become significant for a country's development. However, crude oil based fuels are non renewable. Though diesel engines are the most trusted power sources in the transportation industry, due to stringent emission norms and rapid depletion of petroleum resources there has been a continuous effort to use alternative fuels. Hydrogen has its own benefits and limitations in its use as a conventional fuel in an automotive engine system. At the current and projected rate of consumption of crude oil, it is estimated that these reserves will be badly depleted in due course and it may become impossible to meet the requirements [1]. It is therefore, important to develop alternative energy sources. Gaseous fuels are best suited for IC engines since physical delay is almost nil [2]. However, as fuel displaces equal amount of air the engines may have poor volumetric efficiency [3]. Hydrogen is one of the most promising fuels. Its clean burning characteristic and better performance derives more interest over the hydrogen fuel, compared to other alternative fuels[4,5].

Properties of hydrogen compared to other fuels are listed in Table 1 and 2. Many researchers have tried to use hydrogen as a fuel in SI engine [6, 7]. When using hydrogen in SI engine, the power output of the engine is reduced to about 30% and apart from that, problems like pre - ignition, back firing and knocking occurs at high loads. When using hydrogen as a sole fuel in the compression - ignition engine, the compression temperature is not enough to initiate the combustion of the hydrogen due to higher self – ignition temperature of hydrogen [5]. So, when using hydrogen in CI engine, an ignition source is required [4]. In dual fuel operation mode, the diesel acts as an ignition source for the hydrogen fuel. Hydrogen has a wide flammability range in comparison to all other fuels. Wider flammability limits allow its utilization over extremely wide air/fuel ratio without misfire. The wider ignition limits of hydrogen makes it possible to use lesser throttling when compared to operation on gasoline. It has fast burning rates. The high burning velocity of hydrogen facilitates the operation of CI engines at higher speeds. The high auto - ignition temperature of hydrogen makes it a very good knock resistant. Its low emissivity allows lesser heat loses to cylinder walls, thereby increasing the thermal

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Table 1: Comparison of Properties of Hydrogen with Other Hydrocarbon Fuels

SNo	Property	Hydrogen(H_2)	Methane(CH_4)	Gasoline (C_8H_{18})	Diesel($C_{12}H_{26}$)
1	Kinematic viscosity at 300K (mm^2/sec)	110	17.2	1.18	4.3
2	Molecular mass[kg/kmol]	2.016	16	114	168
3	Density (liquid) [kg/m^3]	0.0898	799	702	840
4	Density (gas) [kg/m^3]	0.0899(STP)	0.717(STP)	737(at 15°C)	820-950 (at 15°C)
5	Octane number	› 130	› 120	90 - 98	30
6	Cetane number	-	-	Below 14	40 - 50
7	Higher heating value (kJ/kg)	141800	55500	47300	44800
8	Normal boiling point (K)	22.3	111.6	310 - 478	643
9	Theoretical air fuel ratio (kg/kg comb.)	34.32	17.2	14.5	18 - 70
10	Quenching gap at NTP (mm)	0.64	2.03	2.0	2.1
11	Stochiometric air fuel ratio (kg/kg)	34.3	17.2	14.7	14.6

Table 2: Comparative Combustion Properties of Hydrogen with Other Fuels

SNo	Property	HydrogenH_2	MethaneCH_4	GasolineC_8H_{18}	Diesel$C_{10}H_{22}$
1	Flammability limits in air at 20°C and 760 mm Hg(% by volume)	4.1 - 75.6	5.3 - 15.0	1.48 – 7.00	0.6 - 0.8
2	Minimum ignition energy in air (MJ)	0.02	0.29	0.24	20
3	Laminar flame speed at NTP (m/s)	1.90	0.38	0.37 - 0.43	0.23
4	Adiabatic flameTemperature (k)	2525	1446	2470	2295
5	Auto ignition temperature (k)	858	813	501 - 744	550
6	Specific gravity(60F and 15.6C)	0.070(for gas)	0.89	0.74	0.82 - 1.08
7	Energy density (MJ/m^3) at LHV and at atm.pressure	10,783	18000	31200	36500
8	Thermal conductivityat 300K (MW/mK)	17.58	34	11.2	0.15
9	Lower heating value(gas at 0°C and 760 mm Hg) (kJ/kg)	119960	19900	42690	41900

efficiency of the engines. The ignition energy required for hydrogen is very low. It's nearly 10 times lesser than that of gasoline. So it is very easy to ignite the hydrogen with a relatively weak spark.

Combustive Properties of Hydrogen: The properties that contribute to the use of hydrogen as a combustible fuel are:

- High auto ignition temperature
- High diffusivity
- Low density
- Low ignition energy
- Small quenching distance
- Wide range of flammability limits
- High flame speed

High Auto Ignition Temperature: AIT is the important factor to find out the maximum compression ratio of the engine, because temperature rise during the compression process is related to compression ratio only. Larger compression ratio can be used in hydrogen engine than in hydro carbon engine because of its high AIT. Hydrogen has a relatively high auto ignition temperature. This has an important implication when a hydrogen - air mixture is compressed. In fact, the auto ignition temperature is an important factor in determining, what compression ratio an engine can use, since the temperature rise during compression is related to the compression ratio. The temperature may not exceed hydrogen's auto ignition temperature otherwise causing pre - mature ignition. The high auto ignition temperature of hydrogen allows larger compression ratios which can be used in a hydrogen engine than in a hydrocarbon engine[8].

High Diffusivity: The gas is highly diffusive and buoyant which makes quick dispersant of fuel during leaks, reducing the fire and explosion hazards associated with hydrogen engine operation. Hydrogen has very high diffusivity. This ability to disperse 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. Second if a hydrogen leak develops, the hydrogen disperses quickly [9].

Low Density: Without compressing or converting into liquid, large volume of hydrogen gas cannot be stored for automobile propulsion. This is the most important implication of hydrogen's low density. It means fuel - air mixture has low energy density which in turn reduces power output. Hydrogen at 200 bar, at atmospheric pressure and temperature has mainly around 5% of the energy of gasoline of the same volume. This is the major setback for transport applications. Hydrogen has low density. This results in two problems, first a very large volume is necessary for storing system and the second is the low energy density of a hydrogen - air mixture which reduces the power output of the hydrogen fueled engine. Since the density of hydrogen is lesser than air, calorific value of hydrogen - air mixture reduces. So the homogeneous mixture formation is not efficient: storage and refilling of cylinder with fresh mixture is difficult (insufficient refilling) [10].

Low Ignition Energy: Hydrogen has very low ignition energy. The amount of energy needed to ignite hydrogen is about one third order of magnitude less than that of gasoline. This enables hydrogen engines to ignite lean mixtures and ensures prompt ignition. Low ignition energy means that hot gases and hot spots on the cylinder can serve as sources of ignition, creating problems of premature ignition and flashback. Preventing this is one of the challenges associated with running an engine on hydrogen [11].

Small Quenching Gap: It is the distance from internal cylinder wall where the flame extinguishes. Hydrogen has the quenching distance of 0.64 mm whereas gasoline has 2.03 mm. Compared to other fuels, it is more difficult to quench hydrogen flame which has the tendency to backfire, since it can escape through nearly closed intake valve. The burning speed of hydrogen is 2.37 - 3.25 m/s which is higher than methane or gasoline at stochiometric conditions. Hydrogen flame is relatively short lived since it catches fire and burns quickly.

Wide Range of Flammability: Hydrogen can be combusted in an internal combustion engine over a wide range of fuel - air mixtures. A significant advantage of this is that hydrogen can run on a lean mixture [12, 13]. A lean mixture is one, in which the amount of fuel is less than the theoretical, stochiometric or chemically ideal amount for combustion with a given amount of air. Safe handling of hydrogen is very important, because it has wide flammability limits (4 - 75% vs. 1.4 - 7% volume in air for gasoline) over other fuels. Running an engine with a lean mixture allows greater fuel economy due to complete combustion of the fuel. Due to lower combustion temperature exhaust NO_X emissions are reduced.

High Flame Speed: Hydrogen has high flame speed at stochiometric ratio. The hydrogen flame speed is nearly an order of magnitude higher than that of other fuels. This means that combustion in hydrogen engines closely approach the ideal engine cycle. At leaner mixture however, the flame velocity decreases significantly. Hydrogen engines are more closely approach thermodynamically ideal cycle engine because it burns with high flame speed when stochiometric fuel mixture is used. Flame speed will be reduced when engine runs with lean operation in order to obtain fuel economy. The properties like adiabatic flame temperature and flame velocity influence the engine parameters like thermal efficiency, combustion stability, emissions and etc.

Experimental Setup: An experimental setup was made with necessary instruments to evaluate the performance, emission and combustion parameter of the compression ignition engine at different operating conditions. The overall view of the engine setup is shown in Figure 1. The engine used for the investigation was a four stroke, water cooled, single cylinder vertical diesel engine, developing a rated power 3.7kW at a rated speed of 1500 rpm. The engine was coupled with an eddy current dynamometer for loading. High speed diesel fuel was used

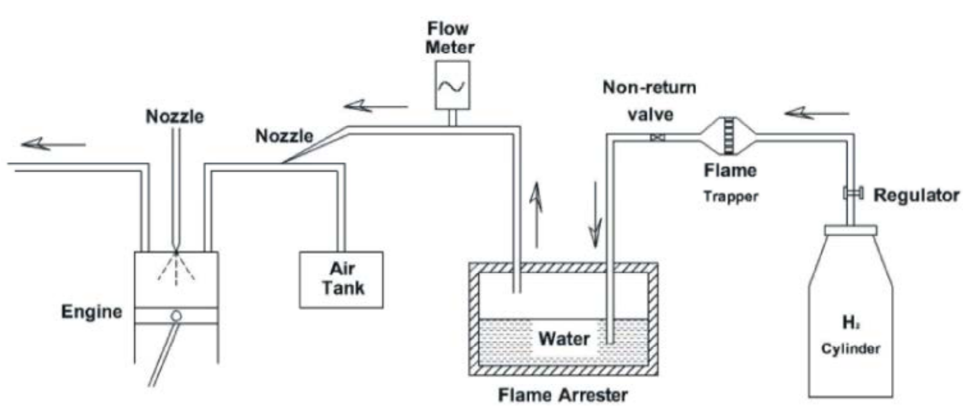

Fig. 1: Experimental Setup

as a pilot fuel in the test engine and the hydrogen was inducted through the inlet manifold. First base line reading was taken by using diesel fuel and dual fueled with hydrogen combustion was taken to evaluate the engine characteristics for the various flow rates.

RESULTS AND DISCUSSION

Fig. 2 compares the specific fuel consumption for the various flow rates of hydrogen. It can be seen that the SFC is highest in the case of 3lpm of hydrogen flow rate followed by base line engine and is least in the case of 9lpm of hydrogen flow rate. It was also evident that the SFC of the engine at the hydrogen flow rate of 5lpm and 7lpm is in between the other two ranges. This decrease in SFC is due to fast burning velocity of hydrogen [10] and its high calorific value.

Fig. 3 compares the brake thermal efficiency for the various flow rate of hydrogen. The efficiency of the hydrogen dual fuel operation is quite higher than the diesel fuel operation over the entire brake power range. In 9lpm flow rate of hydrogen, brake thermal efficiency is the highest due to increase in calorific value of the overall fuel mixture. The high value of brake thermal efficiency can be attributed to the better mixing of hydrogen with air which results in better combustion [11, 14]. The flame velocity of hydrogen is about 9 times as that of diesel, this may cause a higher brake thermal efficiency.

The variation of carbon monoxide emission with respect to brake power is shown in Figure 4. Here, the carbon monoxide content is decreasing in the order of base line engine, 3lpm, 5lpm, 7lpm and 9lpm. The CO emission is lowest, when the flow rate of hydrogen is 9lpm and is nearly 70% lower than the base line reading of the engine. This reduction in CO emission is due to high rate of combustion [4] associated with high diffusion rate of hydrogen and its non carbonadoes nature of species in its molecular structure [15].

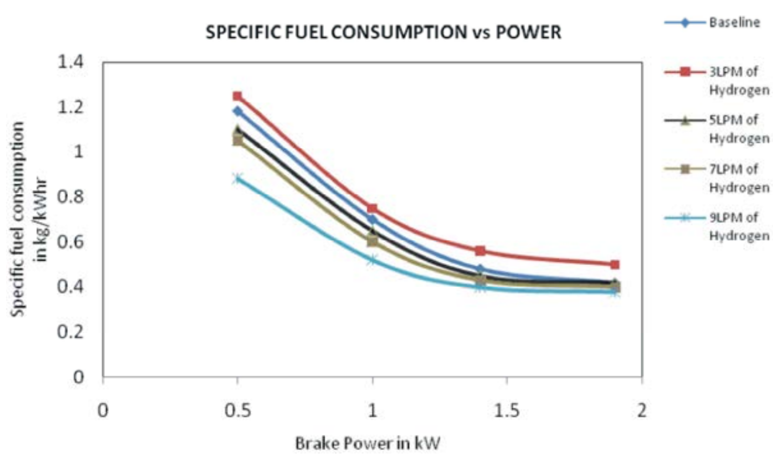

Fig. 2: Brake Power Vs Specific Fuel Consumption

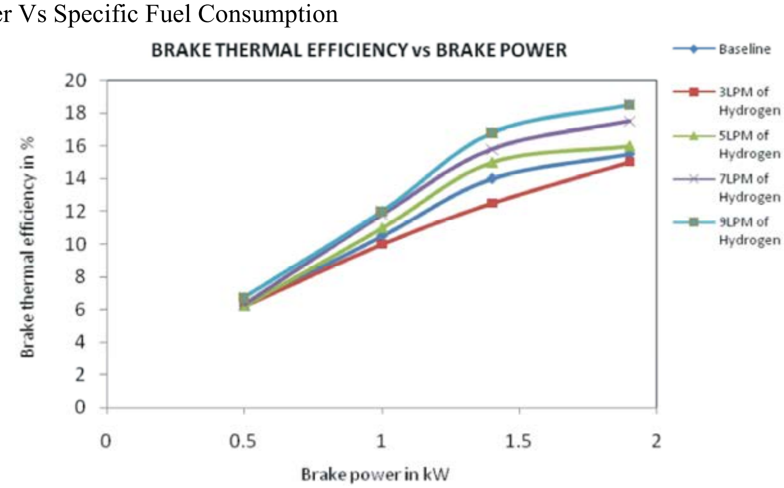

Fig. 3: Brake Power Vs Brake Thermal Efficiency

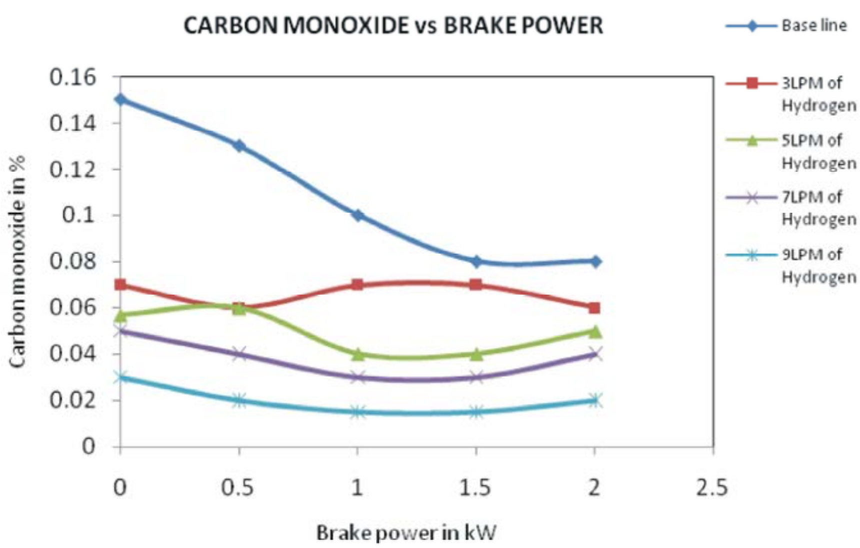

Fig. 4: Break Power Vs Carbon monoxide emission

CONCLUSION

- The performance and emission characteristics of a single cylinder compression - ignition engine were experimented successfully by various quantity of hydrogen, to study the test engine. The experimental results of this investigation are concluded as follows.
- When hydrogen was used as dual fuel, 50% decrease in CO emission was obtained.
- When the hydrogen flow is 5 lpm, 7 lpm and 9 lpm the brake thermal efficiency of the hydrogen dual fuel operation was quite higher than the diesel fuel operation.
- When the hydrogen flow is 5 lpm, 7 lpm and 9 lpm the specific fuel consumption of hydrogen with diesel will be decreases when compared to the base line operation whereas it increases when the flow rate is 3 lpm.
- The smoke intensity decreases by 38% compared to neat diesel operation. The reduction in smoke is due to the absence of carbon in hydrogen fuel.

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