ENGINE PERFORMANCE OF OPTIMIZED HYDROGEN-FUELLED DIRECT INJECTION ENGINE

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Abstract— The world is presently confronted with the twin crisis of fossil fuel depletion and environmental degradation. Indiscriminate extraction and lavish consumption of fossil fuels have led to reduction in underground based carbon resources. The search for an alternative fuel, which promises a harmonious correlation with sustainable development, energy conservation, management, efficiency, and environmental preservation, has become highly pronounced in the present context. For the developing countries of the world, fuels of bio-origin can provide a feasible solution to the crisis.

In the present investigation, hydrogen-enriched air was used as intake charge in a C. I. engine. Experiments were conducted in a single-cylinder, four-stroke, air-cooled, stationary direct-injection diesel engine Kirlosker TAF1 with 1500 rpm and 4.4 kW capacity coupled to an electrical generator. The injection timing and flow rate of hydrogen were varied (80, 120, 150g/hr) to find out the optimum condition for hydrogen enrichment to meet the best performance. Experiment results showed that hydrogen enriched engine gave maximum brake thermal efficiency and minimum brake specific energy consumption at 16.4% H_2 or 120g/hr flow rate with 20° CA injection timing.

Index Terms— Direct injection; Hydrogen; Enrichment; Injection timing.

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1 INTRODUCTION

Fossil fuels possess very useful properties not shared by non-conventional energy sources that have made them popular during the last century. Unfortunately, fossil fuels are not renewable (Veziroglu TN. 1987). In addition, the pollutants emitted by fossil energy systems (e.g. CO, CO2, CnHm, SOx, NOx, radioactivity, heavy metals, ashes, etc.) are greater and more damaging than those that might be produced by a renewable based hydrogen energy system (Winter CJ. 1987). Since the oil crisis of 1973, considerable progress has been made in the search for alternative energy sources.

Hydrogen is an obvious alternative to hydrocarbon fuels such as gasoline. It has many potential uses, is safe to manufacture, and is environment friendly. Hydrogen is a very efficient and clean fuel. Its combustion will produce no greenhouse gases, no ozone layer depleting chemicals, and little or no acid rain ingredients and pollution. Today many technologies can use hydrogen to power cars, trucks, electric plants, and buildings – yet the absence of an infrastructure for producing, transporting, and storing large quantities of hydrogen prevents its practical use. Hydrogen, produced from renewable energy (solar, wind, etc.) sources, would result in a permanent energy system which would never have to be changed.

A long term goal of energy research has been seek for a method to produce hydrogen fuel economically by splitting water using sunlight as the primary energy source. Much fundamental research remains to be done (Serpone N, Lawless D, Terzian R. 1992). Lowering of worldwide CO2 emission to reduce the risk of climate change (greenhouse effect) requires a major restructuring of the energy system. The use of hydrogen as an energy carrier is a long term option to reduce CO2 emissions. However, at the present time, hydrogen is not competitive with other energy carriers. Global utilization of fossil fuels for energy needs is rapidly resulting in critical environmental problems throughout the world. Energy, economic and political crises, as well as the health of humans, animals and plant life, are all critical concerns. There is an urgent need of implementing the hydrogen technology. A worldwide conversion from fossil fuels to hydrogen would eliminate many of the problems and their consequences. The production of hydrogen from non-polluting sources is the ideal way (Zweig RM. 1992).

As the fuel of the future, the expert studies indicate the hydrogen. Hydrogen may become an important energy carrier for sustained power consumption with reduced impact on the environment. It can be used in combustion devices or fuel cells without any carbon emissions and minimal emissions of other pollutant gases. When hydrogen is burned, hydrogen combustion does not produce toxic products such as hydrocarbons, carbon monoxide, oxide of sulfur, organic acids or carbon dioxide, instead its main product is water. Like electricity, hydrogen is an energy carrier and must be produced from another substance. Hydrogen is not widely used today but it has great potential as an energy carrier in the future. SI engines are suitable for hydrogen but in recent time CI engines are also in the process of modification to run with hydrogen [1]. It is important to mention here that since hydrogen has an auto-ignition temperature of about 576 °C, it is not possible to achieve ignition of hydrogen by compression alone [1]. Some sources of ignition have to be created inside the combustion chamber to ensure ignition [1]. Combustion triggering devices such as installation of glow plugs in the combustion chamber and the preliminary addition of fuel to the combustion chamber through either pilot injection or a small leak are the few solutions to the problem.

Studies by Ma et al. [2] indicated that hydrogen can be used as a sole fuel in SI engine. However a significant drop in brake power of the engine was observed due to low compression ratio. Increase in compression ratio in a SI engine would result in knocking. In compression ignition engine hydrogen can be used, but an ignition source is required. Lee et al. [3] studied the performance of dual injection hydrogen fueled engine by using solenoid in-cylinder injection and external fuel injection techniques. An increase in thermal efficiency by about 22% was observed in dual injection at low loads and 5% at high loads compared to direct injection. Lee et al. [4] observed that in dual injection, the stability and maximum power could be obtained in direct injection. However it was observed that the maximum efficiency could be obtained in the external fuel injection technique in hydrogen engine. Wang and Zhang [5] have carried out experimental tests on an internal combustion engine with mixed fuel of Diesel and hydrogen. The hydrogen flow rate is fixed and the Diesel flow is varied. The hydrogen flow rate is set at 2.29 g/min. When the engine load is 50%, the proportion of energy released from hydrogen is 13.4%, when the load is 75% and 100%, the proportion of energy released is 10.1% and 8.4% respectively. Within 20° of crankshaft angle, the combustion of hydrogen is completed while the combustion of Diesel oil prolonged for 40° after TDC, this is due to high diffuse speed of hydrogen and high-energy release rate. But the combustion of hydrogen is nearly completed almost at TDC which leads to an increase in the rate of pressure rise and peak pressure values.

Masood et al. [6] studied the effect of blending hydrogen with diesel in different proportions on combustion and emissions. It was concluded that the hydrogen–diesel co-fuelling will solve the drawback of lean operation of hydrocarbon fuels such as diesel, which are hard to ignite and results in reduced power output, by reducing misfires, improving emissions, performance and fuel economy. Heffel [7] conducted all the experiments at a constant engine speed of 1500 rpm and each experiment used a different fuel flow rate, ranging from 0.78 to 1.63 kg/h. Saravanan et al. [8] used hydrogen-enriched air as intake charge in a diesel engine adopting exhaust gas recirculation (EGR) technique with hydrogen flow rate at 20 l/min. Usage of hydrogen in dual fuel mode with EGR technique resulted in lowered smoke level, particulate and NOx emissions. The use of EGR is, therefore, believed to be most effective in improving exhaust emissions in hydrogen fuelled engine.

One alternative method is to use hydrogen in enrichment or induction, in which diesel is used as a pilot fuel for ignition. As hydrogen is a gas, it mixes well with air, resulting in complete combustion. Hydrogen-enriched engines produce approximately the same brake power and higher thermal efficiency than diesel engines over the entire range of operation [9, 10]. This work involves the enrichment of air with various percentages of hydrogen in a diesel engine using diesel as an ignition source. With a lesser pilot quantity of diesel, hydrogen-enriched engines give higher brake thermal efficiency with smoother combustion than a diesel engine. Increasing hydrogen beyond a certain quantity results in knocking; at the highest diesel flow rate, thermal efficiency is found to be the same as that of diesel engines. Hence, the overall behavior of the engine is similar to that of a diesel engine. Yi et al. [11] stated that thermal efficiency of intake port injection is clearly higher than in-cylinder injection at all equivalence ratios. Shudo et al. [12] stated that hydrogen combustion exhibits higher cooling loss to the combustion chamber wall than does hydrocarbon combustion because of its higher burning velocity and shorter quenching distance. Singh Yadav V. et al. [13] studied on Kirlosker TAF1 diesel engine with the small amount of hydrogen enrichment and found very significant improvement in the performance and emissions.

2 EXPERIMENTAL SET-UP

A single cylinder, air-cooled compression ignition engine operating on a four-stroke cycle was chosen for investigation. The technical specifications of the engine are given in table 1, and the schematic diagram of the experimental setup is shown in figure 1 and a photograph of the experimental setup in figure. 2.

Table 1- Specifications of test engine.

S. No.	**Parameters**	**Specifications**
	General Details	Single Cylinder, Air Cooled, Four Stroke, Compression Ignition, Constant Speed, Direct Injection
	Bore	87.5 mm
	Stroke	110 mm
	Rated Speed	1500 rpm
	Rated Output at 1500 rpm	4.4 kW
	Nozzle opening pressure	200 bar
	Compression Ratio	17.5:1
	Rotation	CWR/ ACWR
	SFC (gms/bhp/hr)	185
.	Start of injection	23^o bTDC

Hydrogen was supplied from a high-pressure cylinder (150 bar) at reduced pressure using a pressure regulator. The flow of hydrogen was controlled by pressure regulators and needle valves, and the flow rate was measured on mass basis by keeping the cylinder on the weighing machine. The flow of diesel fuel was measured by burette flow meter. The hydrogen was passed through a non-return valve (NRV), preventing reverse flow of hydrogen into the system. The hydrogen was then passed through a flame arrestor, in order to prevent explosions inside the hydrogen-containing system, which also acts as an NRV. Next, the hydrogen was allowed to pass through a flame trap, used to suppress flash-back into the intake manifold. The flame trap is made of cast iron that contains a sleeve to suppress the flame and water to put out the flame. Hydrogen was introduced into the intake manifold at a point close to the intake valve. The engine was started with diesel fuel and on supplying hydrogen enriched air during suction the consumption of diesel got reduced. Power developed by the engine was measured using an electric dynamometer.

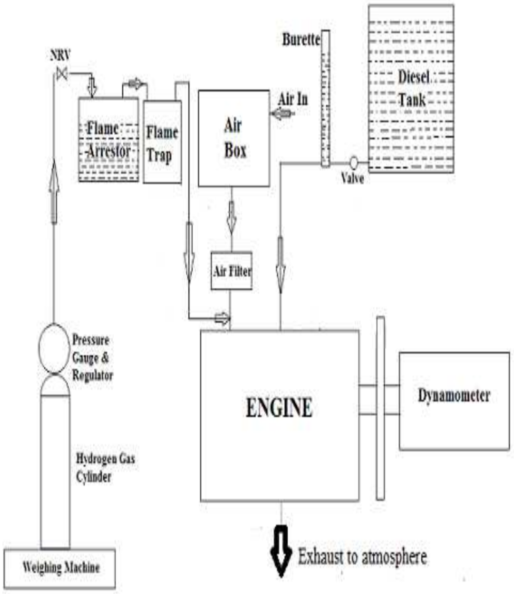

Fig. 1 Schematic diagram of the experimental setup

Fig. 2 Pictorial view of the experimental setup

3 RESULTS AND DISCUSSION

In the present experimentation, performance parameters such as brake thermal efficiency, BSEC were determined at varied hydrogen flow rates & injection timings.

3.1 Brake Thermal Efficiency

The brake thermal efficiency with load for neat diesel and with hydrogen enrichment of different flow rates and different injection timing were taken.

3.1.1 Optimum injection timing for pure diesel

The brake thermal efficiency with load for neat diesel with different injection timing is shown in figure 3. Injection timing was varied with the help of shim addition and subtraction. The thickness of 0.156 mm shim affects the 1.5° crank angle. The addition of shim will retard the injection timing and vice-versa. The optimum injection timing was found at 23° crank angle BTDC for neat diesel operation of engine.

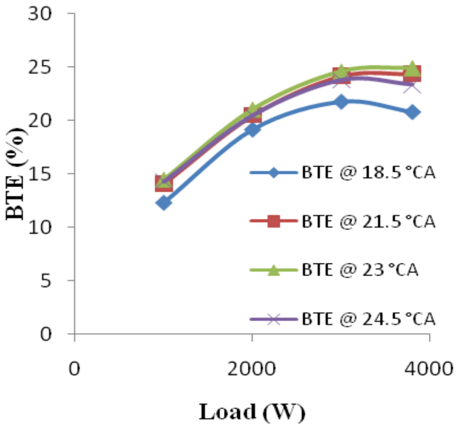

Fig. 3 Load v/s BTE (For pure diesel)

3.1.2 Optimum injection timing and flow rate for hydrogen enrichment

The brake thermal efficiency with load for hydrogen enrichment with different injection timing is shown in figure 4. It was observed that as flow rate of hydrogen started increasing, there was decrease in flow rate of diesel but at the higher hydrogen enrichment condition, engine shut down at high loads due to reduced availability of oxygen. It was observed that at 120 gm/hr was the optimum flow rate of hydrogen on which engine gave best performance. Increase in thermal efficiency is attributed to improved combustion because of enhanced combustion rate due to high flame velocity of hydrogen. After selection of optimum hydrogen flow rate, experiments were taken to find out the optimum diesel injection timing. It was found that at 20° CA BTDC and 120 gm/hr flow rate of hydrogen, engine gave slightly higher thermal efficiency in comparison to pure diesel.

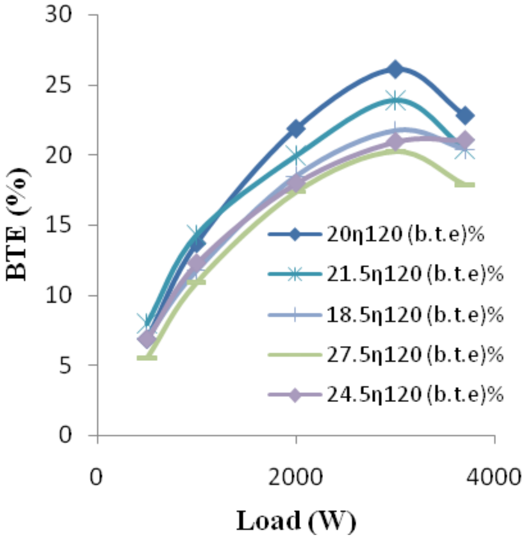

Fig. 4 Load v/s BTE (For hydrogen enrichment)

3.1.3 Brake thermal efficiency for % hydrogen enrichment at optimum injection condition

The brake thermal efficiency for % hydrogen enrichment at optimum injection condition is shown in figure 5. Figure shows that the thermal efficiency of hydrogen enrichment at 16.4 % H_2 enrichment at 70% load was maximum.

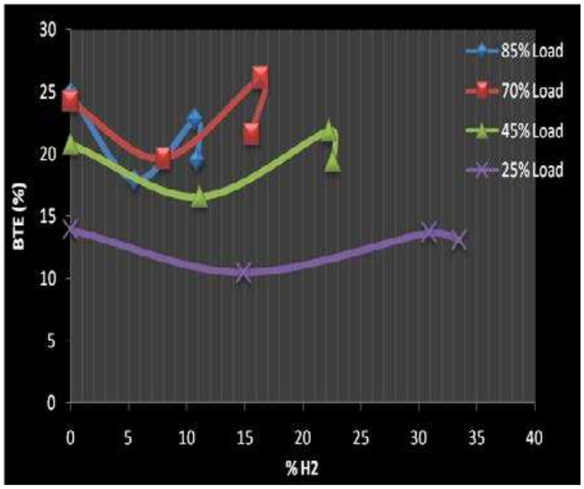

Fig. 5 % Hydrogen v/s BTE at 20° CA BTDC

3.1.4 *Comparison of Brake thermal efficiency for optimum hydrogen enriched condition v/s optimum pure diesel operation*

The brake thermal efficiency for optimized condition of hydrogen and pure diesel are shown in figure 6. Figure shows that the thermal efficiency of hydrogen enrichment at 120 gm/hr flow rate and 20° CA BTDC was slightly higher than conventional diesel fuel. This can be attributed due to better combustion characteristics of hydrogen. At around 75% of full load, BTE for 20° CA BTDC and hydrogen flow rate of 120 gm/hr was 26.07 % whereas for neat diesel it was 23.35 %.

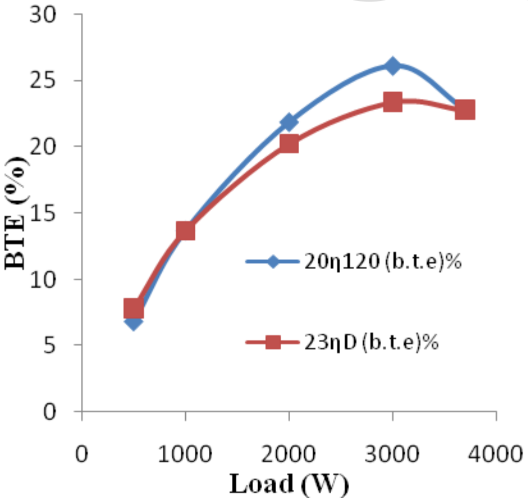

Fig. 6 Load v/s BTE

3.2 Brake Specific Energy Consumption

The brake specific energy consumption with load for neat diesel and with hydrogen enrichment of different flow rates and different injection timings were taken.

3.2.1 *Optimum injection timing for pure diesel*

The brake specific energy consumption with load for neat diesel with different injection timing is shown in figure 7. At optimum injection timing 23° crank angle BTDC, the bsec was found minimum for neat diesel operation of engine.

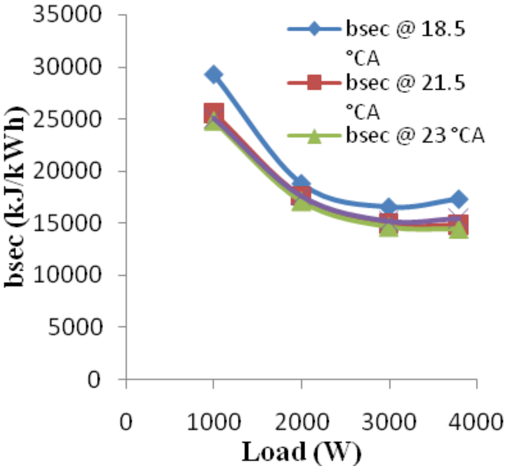

Fig. 7 Load v/s bsec (For pure diesel)

3.2.2 *Optimum injection timing and flow rate for hydrogen enrichment*

The brake specific energy consumption with load for hydrogen enrichment with different injection timings is shown in figure 8. At optimum 120 gm/hr flow rate of hydrogen, bsec was analyzed at different injection timings. It was found that at 20° CA BTDC and 120 gm/hr flow rate of hydrogen, engine gave minimum brake specific energy consumption.

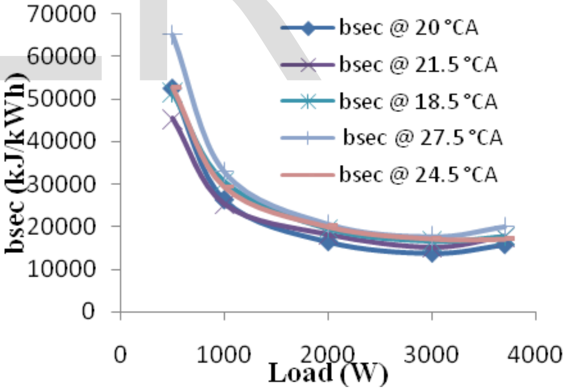

Fig. 8 Load v/s bsec (For hydrogen enrichment)

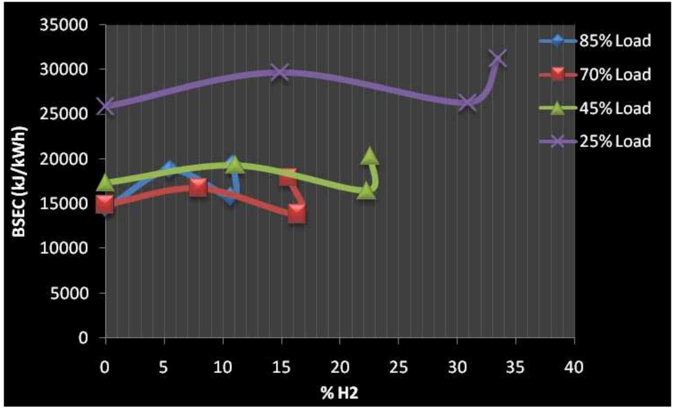

Fig. 9 % Hydrogen v/s BSEC at 20° CA BTDC

3.2.3 Brake specific energy consumption for % hydrogen enrichment at optimum injection condition

The brake specific energy consumption for % hydrogen enrichment at optimum injection condition is shown in figure 9. Figure shows that the brake specific energy consumption of hydrogen enrichment at 16.4 % H_2 enrichment at 70% load was minimum that denotes the just reverse pattern of the BTE.

3.2.4 Comparison of Brake thermal efficiency for optimum hydrogen enriched condition v/s optimum pure diesel operation

Figure 10 shows the variation of brake specific energy consumption with load for neat diesel at optimum injection timing 23 °CA BTDC and hydrogen fuelled engine with optimum injection condition of 120gm/hr at 20 °CA BTDC. It was observed that BSEC (kJ/kWh) for hydrogen enriched fuelled engine was minimum in compare to conventional diesel fuel. At around 75% of full load, BSEC for neat diesel and hydrogen enrichment was 19754.81kJ/kWh and 15797.18kJ/kWh respectively.

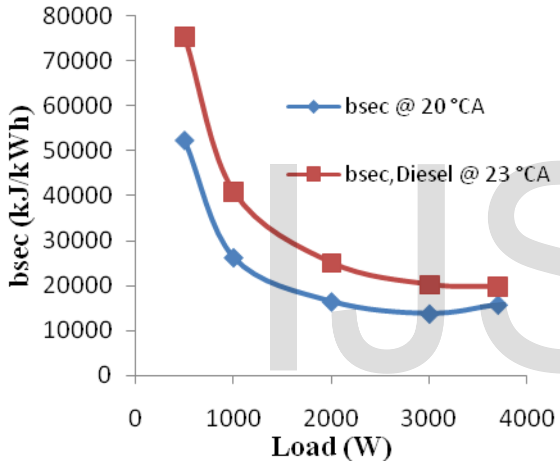

Fig. 10 Load v/s bsec

3.3 Exhaust Gas Temperature

The exhaust gas temperature with load for neat diesel and hydrogen enrichment of different flow rates and different injection timings were taken.

3.3.1 Optimum injection timing and flow rate for hydrogen enrichment

The exhaust gas temperature with load for hydrogen enrichment with different injection timings is shown in figure 11. At optimum 120 gm/hr flow rate of hydrogen, EGT was analyzed for different injection timing. It was found that at 20° CA BTDC and 120 gm/hr flow rate of hydrogen, engine gave maximum exhaust gas temperature. This increase in exhaust gas temperature in case of hydrogen enrichment is due to enhanced combustion rates of hydrogen.

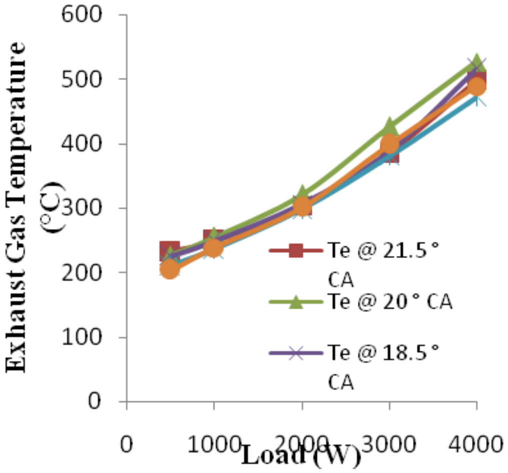

Fig. 11 Load v/s EGT (For hydrogen enrichment)

3.3.2 Comparison of Brake thermal efficiency for optimum hydrogen enriched condition v/s optimum pure diesel operation

Figure 12 shows the variation of exhaust gas temperature with load for neat diesel at optimum injection timing 23 °CA BTDC and hydrogen fuelled engine with optimum injection condition of 120 gm/hr at 20 °CA BTDC. It can be observed that EGT for hydrogen enriched fuelled engine was maximum in comparison to conventional diesel fuel due to enhanced combustion rates of hydrogen.

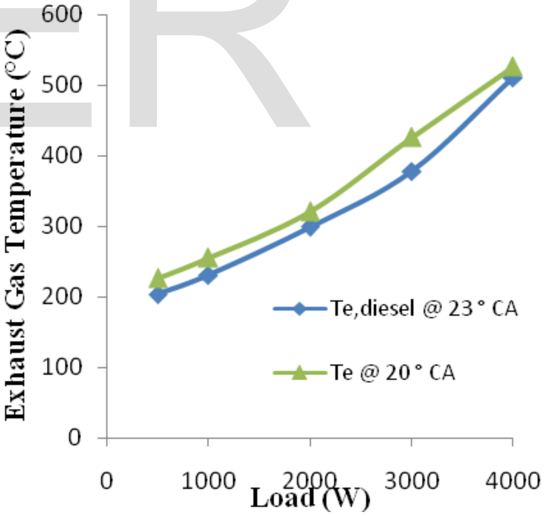

Fig. 12 Load v/s EGT

4 CONCLUSION

A successful operation of a compression ignition engine with hydrogen enrichment over a wide range of load and injection timings was observed without causing any undesirable combustion phenomena. The following conclusions were drawn on the basis of experimental results:

- The optimum injection timing of hydrogen fuelled engine was found at 20° CA BTDC with the flow rate of 120 gm/hr.
- It was found that hydrogen enriched engine gave maximum efficiency with 16.4% hydrogen addition.

- It was also found that hydrogen enriched engine gives maximum efficiency at around 70% of full load whereas when operated with diesel this values come close to 80 %of full load.
- At 70% of full load, the brake thermal efficiency was increased by 11.6% with the supply of 120 gm/hr of hydrogen at optimum injection timing in comparison to neat diesel due to better combustion characteristics of hydrogen. However, at high flow rates of hydrogen the availability of oxygen in combustion got reduced so the thermal efficiency decreased.
- BSEC in case of hydrogen enrichment was 31.8 % less compared to that of neat diesel operation at 70% of full load. The reason for reduction in BSEC was due to the higher calorific value of hydrogen at mass basis and operation of hydrogen fuelled engine under lean burn conditions.
- Due to enhanced combustion rate of hydrogen exhaust gas temperature was high in case of hydrogen enrichment.

At the optimum condition of injection, the emission and combustion analysis can be done. Due to high exhaust temperature, there will be increment in NOx emission that can be reduced by EGR technique. Other emission will reduce due to the lack of availability of carbon particle in hydrogen gas. Overall, hydrogen is an acceptable and environment friendly fuel for future use to meet the excess need of conventional fuel.

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