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Analysis thePerformance and Emission Characteristics on Dual Fuel Diesel Engine using Hydrogen with Safflower Methyl Ester

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Abstract: In the present study, hydrogen utilization as diesel engine fuel at various load operation was investigated. Hydrogen cannot be used directly in a diesel engine due to its auto ignition temperature higher than that of diesel fuel.One alternative method is to use hydrogen in enrichment or induction. Hydrogen was introduced to the intake manifold using a mixer before entering the combustion chamber. To investigate the performance and emission characteristics of this dual fuel single cylinder research engine was converted to utilize hydrogen with safflower methyl ester as fuel. The enginehas run with different proportions (B25,B75,B100;S100+H2,S100+H4,S100+H6,S100+H8)of fuel blends by volume basis and readings arerecorded. These tests are carried out over entire range ofengine operations at varying conditions of load.
Keywords: Dual fuel engine, Combustion Modelling, Alternative fuels**,** Hydrogen and Safflower methyl ester.

Introduction

Owing to the growing price of the oil and its restricted resources, the engine manufacturers use other energy resources instead of oil fuels. Alternative fuels are very important since they can be extracted from renewable resources, and their emissions levels are lower than those of traditional fossil fuels. The advantage of using Safflower oil and Hydrogen fuels is that they emit lesser air pollutants in comparison to diesel fuel and most of them are more economical compared to the oil as well as they are renewable [1-3].The advantages of using hydrogen as fuel for internal combustion engine is among other a long-term renewable and less polluting fuel, non-toxic, odourless, and has wide range flammability. Other hydrogen properties that would be a challenge to solve when using it for internal combustion engine fuel, i.e.: low ignition energy, small quenching distance, and low density [4]. The Safflower oil-hydrogen dual fuel engine can be operated with less fuel than neat diesel operations, resulting in lower smoke level and higher brake thermal efficiency [5]. Hydrogen induction, particularly when its energy share increased above 15% resulted in a sharp decrease in ignition delay, very high peak pressure rates, increase in smoke and loss in fuel efficiency [6].

Dual fuel operation without full diesel resulted in the lowest smoke and unburned HC. It reduces the NOx emission effectively [7]. Using port-injected hydrogen, there was an increase in brake thermal efficiency of the engine with a greater reduction in emissions [8]. Any decrease of emission, especially NOx is likely due to enhancement of turbulent mixing in the cylinder caused by the injection of pressurized hydrogen through the intake valve [9]. Timed manifold injection (TMI) of hydrogen gave higher thermal efficiency and avoided undesirable combustion [10-12] Hydrogen induction with TMI coupled with EGR results in lowered emission level and improved performance level compared to the case of neat diesel operation [13]. The aim of the work presented here is to investigate the effect of hydrogen enrichment on the safflower oil combustion process in a stationary diesel engine at a various load. To that end, experiments were performed to investigate the combustion process of a Safflower oil-hydrogen dual fuel engine at various hydrogen flow rates and various mixing of safflower oil with Diesel.

Experimental setup and procedure

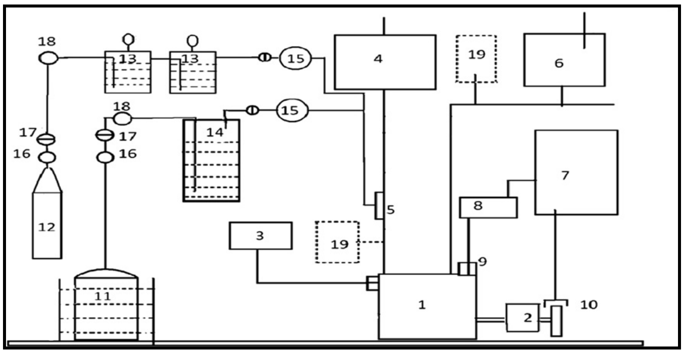

Fig. 1 Experimental setup.1- Engine, 2- Gen-set, 3- Diesel tank and measurement system, 4- Air tank and measurement system, 5- Gas mixture, 6- Gas analyser, 7- PC based data acquisition system, 8- Charge amplifier, 9- Cylinder pressure sensor, 10- Crank angle encoder, 11- Safflower oil cylinder, 12- Hydrogen gas cylinder, 13- Hydrogen gas flame trap, 14- Safflower oil flame trap, 15- Gas flow meter, 16- Gas cylinder control valve, 17- Pressure regulator, 18- Solenoid switch valve, 19- Temperature and Pressure measurement locations.

The experimental setup to carryout experimentation in the present paper is same as in references [14-16], but LPG cylinder is replaced by the Safflower oil cylinder. A schematic layout of the diesel engine test setup used during the experiments is shown in **Fig. 1. Table 2**shows the engine geometry and operating parameters for the present work. The diesel engine is modified to work on dual fuel mode by attaching hydrogen and Safflower oil cylinders in connection with the intake manifold through flame traps, mass flow meters, followed bya one-way non-return valve and common flame arrestor by keeping turbocharger and its bypass active. The engine was coupled to a 62.5 kW D.C. generator. The load on the engine was varied by using electronic loading. The power is based on the electrical output of the installation. The engine was run at a constant speed of 1500 RPM [14-16]. Exhaust gas emissions namely, CO, NOx and un-burnt hydrocarbons (UHC) were measured by an AVL 5000 DI Gas analyser. The CO was measured in volume percentage basis where as NOx and UHC were measured in ppm units. The cylinder pressure was measured by piezoelectric pressure transducer (pressure range 0-250 bars) and a charge amplifier.

Fig.2 Photographic view of experimental setup

The pressure data were transferred to data acquisition system for further analysis. A crank angle encoder (Kistler make) with an accuracy of 1 was used for angle measurement. The mass flow rate of hydrogen and Safflower was measured by mass flow meters in litters per minute. To ensure repeatability the experiments were carried out for three times.

Table .1 The produced biodiesel attributes comparison with the standard Biodiesel

Fuel Properties	Safflower	ASTM
Kinematic viscosity (40°C)	4.52	1.9-6.10
Density (15 °C), g/cm^3	0.87	-
Flash point, (°C)	167	>130
Pour point (°C)	-10	-
Cloud point (°C)	-7	-
Freezing point (°C)	-12	-
Boiling point (°C)	326	315 - 356

The experiments were performed on the test engine under the following four conditions.

(i) Case I : engine runs on diesel only.
(ii) Case II : engine runs on diesel as pilot fuel and Safflower as secondary fuel.
(iii) Case III : engine runs on Safflower as pilot fuel.
(iv) Case IV : engine runs on Safflower as pilot fuel and hydrogen as secondary fuel.

Table.2 Engine Specifications

Sr. No.	Parameter	Engine specification
1.	Make and model	BAJAJ ALUWO4CT Turbocharged, inter-cooler, Gen-Set
2.	General details	Four stroke, compression ignition, constant speed, vertical, water-cooled, direct injection, turbo charger, intercooler, Gen-Set
3.	No. of cylinder	4
4.	Bore mm	104
5.	Stroke mm	113
6.	Rated speed rpm	1500
7.	Swept volume cc	3839.67
8.	Clearance volume cc	84.90
9.	Compression ratio	17.5:1
10.	Injection pressure bar	260
11.	Injection timing BTDC	16^0
12.	Rated power kW at 1500 rpm	62.5
13.	Inlet pressure bar	1.06
14.	Inlet temperature K	313
15.	Nozzle diameter mm	0.285

Results and discussion

Emissions

Carbon monoxide (CO)

The development of carbon monoxide depends on post oxidation reaction. In common diesel engine, the carbon oxidation reaction is almost completed due to the presence of more excess air. The considerable amount of CO is not produced until the smoke limit is reached. The variation in CO with different load conditions is shown in **Fig. 3(a), (b)** respectively. At various load condition Cases II, III and IV shows decrease in CO emission, respectively, as compared to Case I operation. Higher concentration of CO in the exhaust is a clear indication of incomplete combustion of the premixed mixture. The CO levels were higher due to combustion inefficiencies. At various loading condition fuel-air mixture near the pilot is burned due to less turbulence. Thus some partial oxidation product like carbon monoxide may come out in the exhaust. At higher concentration of safflower oil and Hydrogen gas fuel, the concentration of the partial oxidation product could decrease [7,9].

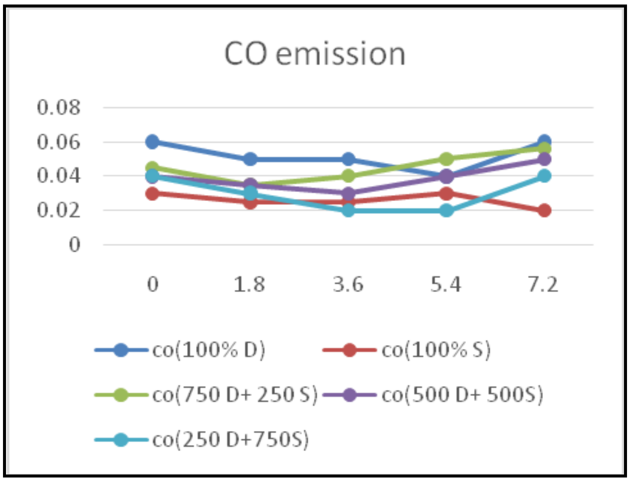

Fig. 3(a)The variation in CO with different load conditions

This is considered to be the reason for the decrease in CO emissions. So there is decrease in CO emission for the Cases II, III and IV respectively, as compared to Case I. It is observed that the CO emission in Case IV is less than Case II and III due to minimum mean gas temperature and combustion rate **Fig. 3(a), (b)**. In Cases IV hydrogen shows different behaviour in dual fuel engine due to presence of liquid hydrocarbon.

In general, the presence of hydrogen reduces CO because it does not contain any carbon particle and whatever the small percentage of CO is present in the exhaust is due to the burning of lubricating oil and incomplete combustion of diesel fuel and safflower oil. In diesel engine, the diesel fuel is injected at the end of compression process in the atmosphere of high temperature and high-pressure air. Further, CO emission is increased at both load conditions due to delayed ignition period.

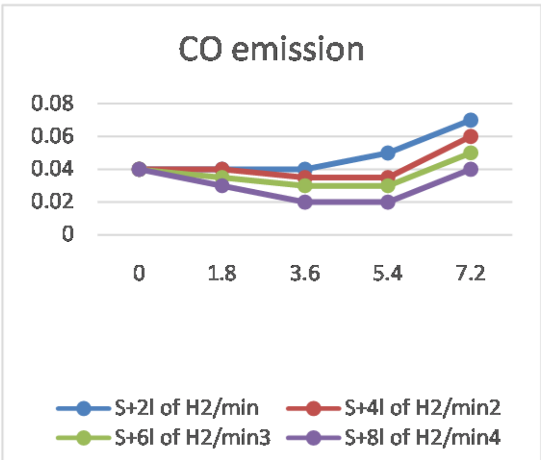

Fig. 3(a)The variation in CO with different load conditions

Carbon dioxide (CO_2)

The development of carbon depends on oxidation reaction. In common diesel engine, the carbon oxidation reaction is almost completed due to the presence of more excess air. The considerable amount of CO_2 is not produced until the smoke limit is reached. The variation in CO_2 and mean cylinder oil and gas temperature is shown in **Fig. 4(a), (b)** respectively. At various load condition Cases II, III and IV shows decrease in CO_2 emission, respectively, as compared to Case I operation. Higher concentration of CO_2 in the exhaust is a clear indication of incomplete combustion of the premixed mixture. The CO_2 levels were higher due to combustion inefficiencies. At various loading condition fuel-air mixture near the pilot is burned due to less turbulence. Thus some partial oxidation product like carbon monoxide may come out in the exhaust. At higher concentration of safflower oil and Hydrogen gas fuel, the concentration of the partial oxidation product could decrease [7,9]. This is considered to be the reason for the decrease in CO_2 emissions. So there is decrease in CO_2 emission for the Cases II, III and IV respectively, as compared to Case I. It is observed that the CO_2 emission in Case IV is less than Case II and III due to minimum mean gas temperature and combustion rate. Different behaviour in dual fuel engine due to presence of liquid hydrocarbon. In general, the presence of hydrogen reduces CO_2 because it does not contain any carbon particle and whatever the small percentage of CO_2 is present in the exhaust is due to the burning of lubricating oil and incomplete combustion of diesel fuel and safflower oil. In diesel engine, the diesel fuel is injected at the end of compression process in the atmosphere of high temperature and high-pressure air. Further, CO_2 emission is increased at both load conditions due to delayed ignition period

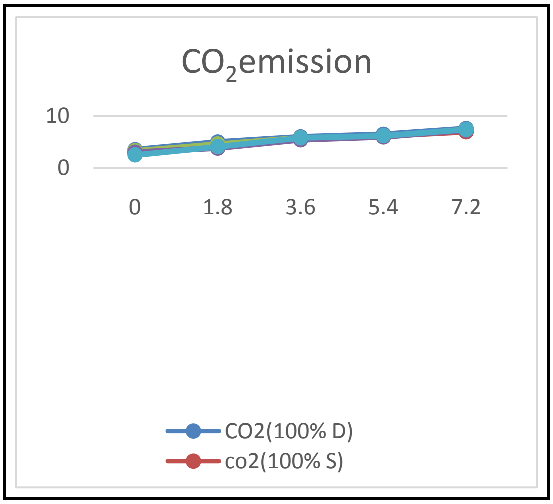

Fig. 4(a)The variation in CO_2 with different load conditions In Cases IV hydrogen shows

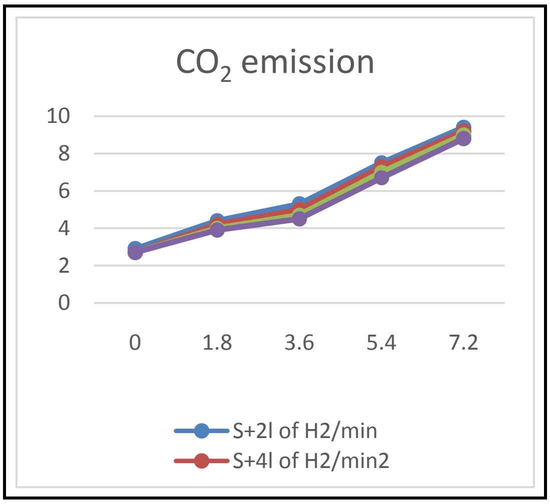

Fig. 4(b)The variation in CO_2 with different load conditions Hydrocarbons (HC)

Fig. 5(a) and (b) depicts variation in unburned hydrocarbon at various load conditions for the Cases I, II, III and IV respectively. The extra leaning and improper mixing are responsible for HC emission in diesel engine.At various load condition, Cases II, III and IV exhibits minimum HC emissions, as compared to Case I. Reduction in pilot fuel quantity, which causes poor ignition of gaseous fuel and inducted mixture is too lean to burn could be the reason for this. Also, shows that the exhaust gas temperature is low, at low loads, while at higher load this rises due to quicker burning of hydrogen. This leaves diesel fuel injected toward the end of injection period, scarce in oxygen. Moreover, during the compression process, the homogeneously mixed gaseous fuel undergoes chemical reactions before diesel pilot fuel injection and the rate of these chemical reactions may become high due to higher charge temperature.

When diesel pilot fuel is injected into this situation, the traveling of flame front is complete. Decrease in oxygen concentration would cause an increase in total unburned HC [5]. Therefore, rate of HC emissions is more. At various load condition, Cases I show maximum HC emission as compared to case II, III, and IV operation. At higher load condition due to a low pilot quantity, HC emission is high at diesel fuel. High load condition results in increased ignition delay and cylinder gas temperature which may lead to spreading of the pilot fuel prior to ignition. This will lead to poor combustion of the gaseous fuel-air mixture. It is observed that HC emission in Case IV is less than Case II and III due to fact

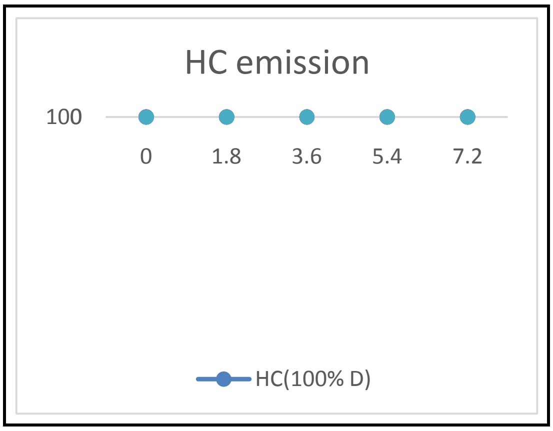

Fig. 5(a)The variation in HC with different load conditions

That the mean gas temperature of Case IV is as compared to Case II and III which **Fig 5(a), (b).** The lower cylinder gaseous charge temperature in Case II and III combined with slower burning rate leads to increase in fuel which does not burn completely, hence more HC emission is found.

The exponential increase in HC was reported by Singh et al. [4] with the use of Safflower oil and Hydrogen gas mixture at lower loads, due to pre-mixed mixture is very lean.

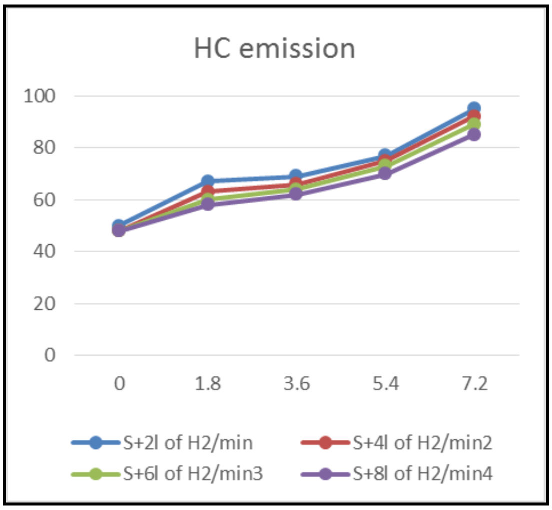

Fig. 5(b)The variation in HC with different load conditions.

NOx

Nitrous oxide (NO) and a small amount of nitrogen dioxide (NO_2) are the main constituents of nitrous oxides, mostly formed by the oxidation of atmospheric nitrogen in the combustion chamber. NO formation mainly control by combustion temperatures and the availability of oxygen. Whereas, formation of NOx in the dual fuel engine mostly depends on diesel pilot spray region. The formation of NOx increases with the increase in the size and amount of pilot diesel fuel. Also, the nitrogen oxide emission rises with the increase in cylinder temperature, oxygen concentration and combustion duration [1]. **Fig. 6(a) and (b)** exhibits variation of NOx and mean cylinder gas temperature for the Cases I, II, III and IV at various load conditions.

It is observed that dual fuel operation produces less NOx at all load conditions than Case I operation.

At various load condition drop in NOx emission were observed for the Cases II, III and IV, respectively, as compared to Case I. This could be because increase in hydrogen substitution simultaneously increases the mole fraction of H_2O i.e. the moisture increases which finally NOx Nitrous oxide (NOx) and a small amount of nitrogen dioxide (NO_2) are the main constituents of nitrous oxides, mostly formed by the oxidation of atmospheric nitrogen in the combustion chamber. NO

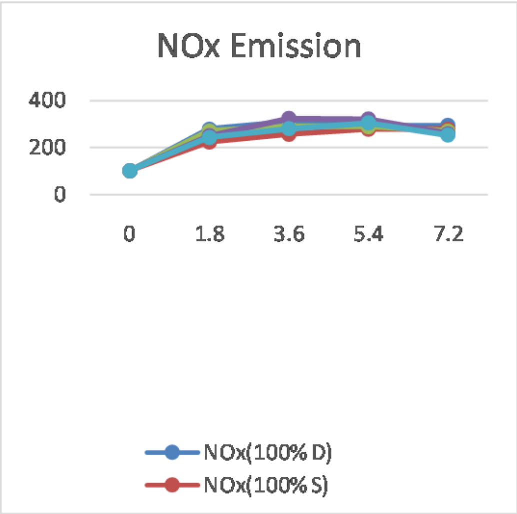

Fig. 6(a)The variation in NO_X with different load conditions.

Formation mainly control by combustion temperatures and the availability of oxygen. Whereas, formation of NOx in the dual fuel engine mostly depends on diesel pilot spray region. The formation of NOx increases with the increase in the size and amount of pilot diesel fuel. Also, the nitrogen oxide emission rises with the increase in cylinder temperature, oxygen concentration and combustion duration [1]. **Fig. 6(a) and (b)** exhibits variation of NOx and mean cylinder gas temperature for the Cases II, III and IV at various load conditions. It is observed that dual fuel operation produces less NOx at all load conditions than Case I operation. This could be because increase in hydrogen substitution simultaneously increases the mole fraction of H_2O i.e. the moisture increaseswhich finally brought down the peak temperature. Hence NOx decreases with the increase in hydrogen substitution [5].

For Case IV reduction in NOx may be due to the lower adiabatic flame temperature of producer gas and absence of organic nitrogen in producer gas [15,17]. Dual fuel operation reduces the amount of pilot safflower fuel during diffusion-controlled combustion phase. Further, the initiation of combustion and lesser period of premixed combustion phase may result in lower nitrous oxide emissions due to lower in cylinder temperature [27]. It is observed that the NOx emission in Case IV is less than Case II and III due to lower mean gas temperature

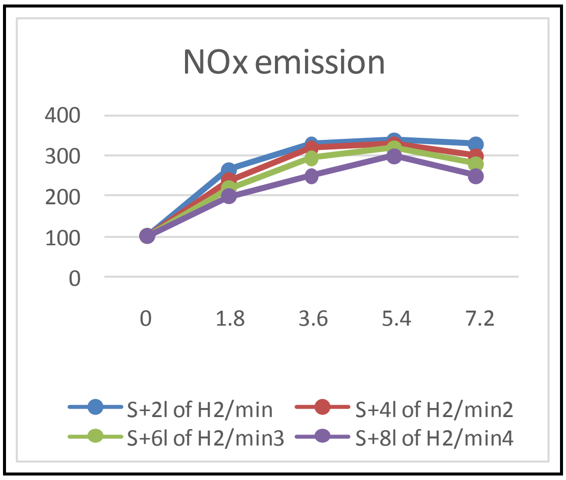

Fig. 6(b) The variation in NO_X with different load conditions

Thermal efficiency

The deviation of thermal efficiency at. various load conditions and for different substitution of Diesel (Case I), mixture of diesel Safflower oil (Case II), Safflower oil(case III) and mixture of Safflower oil and Hydrogen(Case IV) are shown in Fig. 7(a), (b) respectively.It is seen that the thermal efficiencies of the Cases II, III and IV are lesser than pure diesel operation (Case I) at lower load conditions, fuel results in lesser brake thermal efficiency. The efficiency of Case II is less due to high cooling losses because of shorter quenching distance and more thermal conductivitywhereas in Case III and IV, it may be due to rise in ignition delay of diesel [17]with the presence of Safflower oil in dual fuel mode and also due to the lower burning rate of producer gas itself [18-24]. When the load is raised, the efficiencies are still less compare to Case I operation. It is known that the laminar

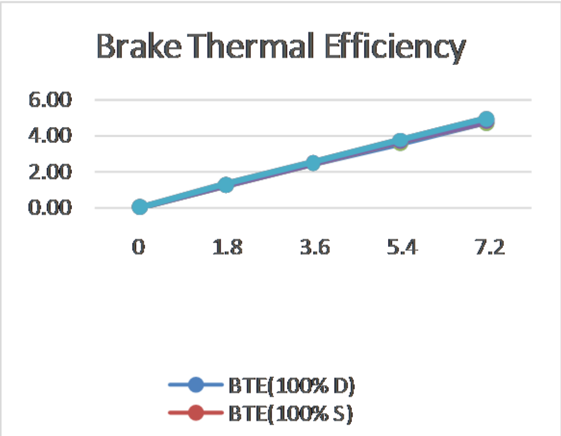

Fig. 7(a) The variation in BTE with different load conditions

flame velocity of diesel, hydrogen and safflower oil are 4.8 cm/s, 117 cm/ s and 6 cm/s [27]respectively at overall equivalence ratio of 0.6 [19]. It means gaseous fuels have larger flame velocity and diffusivity than diesel, uses most part of the oxygen from the entrained air during main part of the combustion . Also, the amounts of oxygen necessary for complete burning of each of the combustible components of safflower oil during Case III and Case IV as presented are not fulfilled, Hence, engine emits more smoke gives an indication of incomplete combustion of fuel.

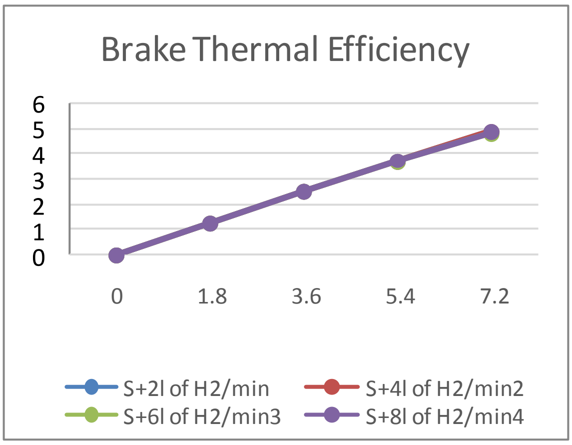

Fig. 7(b) The variation in BTE with different load conditions

At various load conditions, maximum efficiency for Case II becomes higher as compared to Case I. This might be due to increase in combustion rate with larger pilot diesel (56.33 mg/cycle/cylinder) which leads to stronger ignition source and hence, more comprehensive and better combustion of gaseous fuel Hydrogen shows the higher pre-ignition energy rate at higher concentration and loads [30]. It was observed by Borreti[24]that the thermal efficiency increases up to 40% as compared to original diesel engine. However, during Case III and IV efficiencies are low as compared to Case I. The decrease may be attributed to the lesser energy content and reduction in the amount of fresh air entering the combustion chamber leading to incomplete combustion with the increase concentration of Safflower oil [18-24]. It is observed that as the percentage of hydrogen in the mixture increases, the efficiency get increases up to 40% of hydrogen substitution due to the fact that laminar burning velocity of producer gas is 0.5 m/sec as compared to 2.65 m/sec of hydrogen.

The presence of hydrogen enhances the burning velocity of mixture and thus efficiency increases [31]. Also, producer gas flame tends to become unstable, while, hydrogen-air flames likely to be stable. Therefore by increase in hydrogen fraction leads to stabilization of flame [32]. However, further addition of hydrogen beyond 60:40 reduces the efficiency viz 50:50. It might be due to increase in hydrogen fraction, flame destabilization takes place because of reduction in Markstein length (Markstein length measures the effect of curvature on a flame; larger the Markstein length, greater the effect of curvature on burning velocity). In addition, the hydrogen consumes most part of the oxygen available for combustion and other hydrocarbons do not have enough oxygen to burn.

Conclusions

On the basis of the results and discussions presented above, the following conclusions could be drawn.

- The performance study of CI engine operated on diesel, hydrogen and Safflower oil in dual fuel mode as CI engine fuels indicates no major modification required in an existing diesel engine.
- Use of hydrogen as secondary fuel enhances the brake thermal efficiency at high load conditions while it produces opposite effect at low load conditions.
- Use of hydrogen as secondary fuel reduces the brake thermal efficiency for all combinations of diesel-producer gas under all load conditions
- A mixture combination of Safflower oil and hydrogen as secondary fuel exhibits better brake thermal efficiency in comparison with other proportions of the same mixture. This is more than pure diesel and diesel- Safflower oil combination but, when compared with diesel-producer gas combination, the brake thermal efficiency is much improved.
- Un-burnt HC/CO emissions for all type of the fuel combinations in duel fuel mode are found to be less than neat diesel fuel engine operation.
- NO_x emissions for all type of the fuel combinations in duel fuel mode are found to be lower than single diesel fuel engines.
- The best performances of the engine employed for investigation are obtained by the substitution of 20% of hydrogen.

Overall, the investigation shows that beyond 40% load condition, Case IV operation i.e. a mixture of safflower oil- hydrogen(6 lit/min) is always considerable. Though, it reduces the brake thermal efficiency slightly, however, drops down the formation of NO_x as compared to pure diesel and diesel-Safflower oil operations. Furthermore, its use avail wide scope for the unused biomass for the generation of producer gas which ultimately reduce burden over the use of fossil fuel.

It is significant to add here that there is a need to develop safflower oil generating and storing provisions suitable to use more conveniently as of other oils and hydrogen which are at present in use because of its convenience so that existing diesel engines may be easily adapted for dual fuel operation.

In short, the resourceful and eco-friendly performance of the engine is offered by the secondary fuel made by a mixture of safflower oil and hydrogen.

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