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RESEARCH ARTICLE

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Performance, emission and combustion characteristics of CI engine fuelled with diesel and hydrogen

Abstract Hydrogen (H_2) is being considered as a primary automotive fuel and as a replacement for conventional fuels. Some of the desirable properties, like high flame velocity, high calorific value motivate us to use hydrogen fuel as a dual fuel mode in diesel engine. In this experiment, hydrogen was inducted in the inlet manifold with intake air. The experiments were conducted on a four stroke, single cylinder, water cooled, direct injection (DI), diesel engine at a speed of 1500 r/min. Hydrogen was stored in a high pressure cylinder and supplied to the inlet manifold through a water-and-air-based flame arrestor. A pressure regulator was used to reduce the cylinder pressure from 140 bar to 2 bar. The hydrogen was inducted with a volume flow rate of 4l pm, 6l pm and 8l pm, respectively by a digital volume flow meter. The engine performance, emission and combustion parameters were analyzed at various flow rates of hydrogen and compared with diesel fuel operation. The brake thermal efficiency (BTE) was increased and brake specific fuel consumption (BSFC) decreased for the hydrogen flow rate of 8l pm as compared to the diesel and lower volume flow rates of hydrogen. The hydrocarbon (HC) and carbon monoxide (CO) were decreased and the oxides of nitrogen (NO_x) increased for higher volume flow rates of hydrogen compared to diesel and lower volume flow rates of hydrogen. The heat release rate and cylinder pressure was increased for higher volume flow rates of hydrogen compared to diesel and lower volume flow rates of hydrogen.

Keywords hydrogen, brake thermal efficiency, crank angle, compressed ignition (CI)

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1 Introduction

In the modern and fast moving world, the petroleum-based fuel has become important for a century's development. Products derived from crude oil continue to be the major and critical source of energy for fuelling vehicles all over the world. However, petroleum reserves are limited and are non-renewable. During the last decade, the use of alternative fuel in diesel engines has received renewed attention. The uncertainty of petroleum-based fuel availability has created a need for alternative fuels [1]. At the current and projected rate of consumption of crude, it is estimated that these reserves will be badly depleted in due course and it may become impossible to meet the requirements. Diesel engine is the most efficient type of internal combustion engines. In the past few decades, research efforts have been focused largely on better engine design from the perspective of reducing pollutants emission without sacrificing performance and fuel economy. In recent years, an emphasis on reducing pollutant emissions from petroleum-based engines has motivated the development and testing of several alternative fuels. The main pollutants from diesel engines are NO_x (NO — nitric oxide and NO_2 — nitrogen dioxide), particulate matter and smoke (visible product of combustion) [2]. Various fuels have been considered as substitutes for hydrocarbon-based fuel. Alternative fuels that aspire to replace petroleum-based fuels include alcohols, liquefied petroleum gas (LPG), compressed natural gas (CNG), hydrogen, vegetable oils, bio gas, producer gas and liquefied natural gas (LNG). Of these, hydrogen is a long-term renewable and less-polluting fuel. In addition, hydrogen is non-toxic, odorless and results in complete combustion [3]. Hydrogen can be used as a fuel in internal combustion engines either pure or blended with other hydrocarbon fuels. Due to these characteristics, researchers are focusing their attention on hydrogen as an alternative fuel in internal combustion engines (ICEs) and in the development of fuel cell powered vehicles and hybrid electric vehicles (HEVs). Hydrogen can be used as a sole fuel in spark ignition (SI) engine, either by carburation or by direct injection [4]. Researchers have also performed experimental studies on burning hydrogen-diesel oil mixture and have found that increasing compression ratio is an effective method to improve the combustion characteristics of hydrogen fueled engine. Hydrogen can be commercially produced from electrolysis of water and by coal gasification. It can also be produced by several other methods such as the thermo-chemical decomposition of water and solar photo-electrolysis, although these are currently still in the laboratory stage. Hydrogen fueled ICE vehicles built with current technology are not competitive with synthetic gasoline or methanol vehicles on the basis of coal consumption or fuel cost [5]. The concept of using hydrogen as an alternative fuel for diesel engines is recent. The self-ignition temperature of hydrogen is 858 K, so hydrogen cannot be used directly in a compressed ignition (CI) engine without a spark plug or glow plug. This makes hydrogen unsuitable as a sole fuel for diesel engines [6]. Hydrogen-enriched engines produce approximately the same brake power and higher thermal efficiency than diesel engines over the entire range of operation [7,8]. With a lesser pilot quantity of diesel, hydrogen-enriched engines give higher brake thermal efficiency with a smoother combustion than diesel engines [9]. 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 [10]. Many researchers have been directed toward the development of alternative fuels to achieve this goal. Among the various probable alternative fuels, hydrogen is found to be the most promising due to its clean burning and better combustion properties. Researchers have also experimentally studied hydrogen as an air enrichment medium with diesel as an ignition source in a stationary diesel engine system to improve engine performance and reduce emissions. However the high self-ignition temperature of hydrogen limits its use in compression ignition engines since the cylinder temperature rise due to compression alone is not enough to initiate combustion; hence an ignition source is required. Summing up, it is concluded that the optimal hydrogen enrichment with diesel is 30% [11–14], which shows that it has less smoke, less particulates emission, a higher brake thermal efficiency and hence a lower specific energy consumption. Hydrogen is used in the dual fuel mode with diesel and shows the highest brake thermal efficiency of 30% at a compression ratio of 24.5:1 [15,16]. The performance of dual injection hydrogen fueled engine by using solenoid in-cylinder injection and external fuel injection technique has also been studied. An increase in thermal efficiency by approximately 22% is noted for dual injection at low loads and 5% at high loads compared to direct injection [17]. Hydrogen is widely regarded as a promising transportation fuel because it is clean and renewable. While electrochemically reacting hydrogen in fuel cells is considered to be the cleanest and most efficient means of using hydrogen, it is believed by many to be a technology of the distant future [18]. One of the main obstacles that plague the successful utilization of hydrogen as a fuel in an ICE has been backfire which is caused by the undesirable combustion of the air/fuel charge in the intake manifold [19]. The combustion duration is reduced due to the higher flame speed of hydrogen. Additionally, a higher premixed combustion rate has been observed with hydrogen induction [20]. The hydrogen engine is a possible solution to improving the engine performance at idle and lean conditions. Since the flame speed of hydrogen is five times as large as that of gasoline, hydrogen engines can get a high degree of constant volume combustion which not only benefits the engine thermal efficiency but also reduces the engine cyclic variation. Additionally, neat diesel has also been combusted to compare with the H_2/diesel mixture. The results of these tests have been compared with the data obtained from previous numerical research with different code [21]. Besides, the low ignition energy of hydrogen also enables hydrogen-air mixture to be easily ignited under lean conditions and helps engines gain a smooth starting process. In this paper, hydrogen is inducted with air in the inlet manifold with a volume flow rate of 4 L/min, 6 L/min and 8 L/min, respectively. The pilot fuel is diesel.

2 Materials and methods

2.1 Combustion and properties of hydrogen

Hydrogen on burning produces only water. It is non-toxic, non-odorant and also results in complete combustion. Hydrogen has a high self-ignition temperature (858 K); therefore it is difficult to ignite hydrogen with the help of only compression. Due to this property, hydrogen cannot be used in a diesel engine system without an ignition source. So to start combustion, some kind of ignition source is required during the compression stroke. Before top dead centre (TDC), a small charge of diesel fuel is injected through the conventional injection system which acts as a source of ignition. Combustion of hydrogen is fundamentally different from the combustion of hydrocarbon fuel. Hydrogen has a wider flammability limit of 4%–75% by volume in air compared to diesel fuel which is only 0.7%–5% by volume. The burning velocity is so high that very rapid combustion can be achieved. The limit of flammability of hydrogen varies from an equivalence ratio of 0.1 to 7.1.

Hydrogen at ordinary temperature and pressure is a light gas with a density of only 1/14th that of air and 1/9th that of natural gas. By cooling to the extreme temperature of 253°C at atmospheric pressure, the gas is condensed to liquid with a specific gravity of 0.07. The standard heating value of hydrogen gas is 12.1 MJ/kg compared with the average value of 38.3 MJ/kg for natural gas. The flame speed of hydrogen burning in the air is such greater than the natural gas, and the energy required to initiate the combustion is less. The mixture of hydrogen and air or combustible over an exceptionally wide range of compositions the flammability limits at ordinary temperatures extends from 4% to 74% by volume of hydrogen in the air. Table 1 gives the various properties of hydrogen at 25°C and 1 atm.

Table 1 Properties of hydrogen

Properties	Hydrogen
Auto ignition temperature/K	858
Minimum ignition energy/MJ	0.02
Flammability limits (volume in air)/%	4–75
Stoichiometric mixture (volume in air)/%	29.53
Molecular weight/g	2.016
Density/(kg·cm^{-3})	0.0838
Mass ratio	34.4
Flame velocity/(cm·s^{-1})	270
Specific gravity	0.091
Adiabatic flame temperature/K	2318
Quenching gap/cm	0.064
Heat of combustion/(kJ·kg^{-1})	120000
Octane number	130
Cetane number	—
Boiling point/K	20.27

2.2 Hydrogen enrichment

The inlet air was enriched with H_2 with three different flow rates of 4 L/min, 6 L/min and 8 L/min. The corresponding percentage of H_2 in the inducted air is 1.2%, 1.8% and 2.5% respectively as listed in Table 2. Due to the enrichment of the intake air with hydrogen, the quantity of diesel consumed is reduced for all loads. Figure 1 shows the percentage of diesel replaced due to the addition of H_2 in intake air. From Fig. 1, it is evidently seen that the percentage of diesel replaced increases with the increase of the H_2 flow rate at any given load. Similarly, for a fixed flow rate of H_2, the percentage of diesel replaced by H_2 increases with decreasing loads. For lower load, the replacement is more compared to higher load. This trend resulted from the fact that the flow rate of H_2 is fixed at all loads, while the consumption of diesel decreases with decreasing loads.

Figure 2 depicts the energy released by hydrogen for different flow rates with different loads. Comparing Figs. 1 and 2 at full load at 4 L/min of H_2 flow rate, the energy released is 5.26% for a diesel replacement of 2%. Similarly, at the same H_2 flow rate of 4 L/min at 20% load, the energy content of H_2 is 10% for the diesel replacement of 4%. The same trend is observed for all flow rates of H_2 at different loads. This is caused by the higher calorific value of the H_2 replacing the diesel and its superior combustion with higher flame speed.

Table 2 Percentage of H_2 in intake mixture

Hydrogen flow rate /(L·min^{-1})	Percentage of H_2 in intake mixture/%	Percentage of air in intake mixture/%
4	1.2	98.8
6	1.8	98.2
8	2.5	97.5

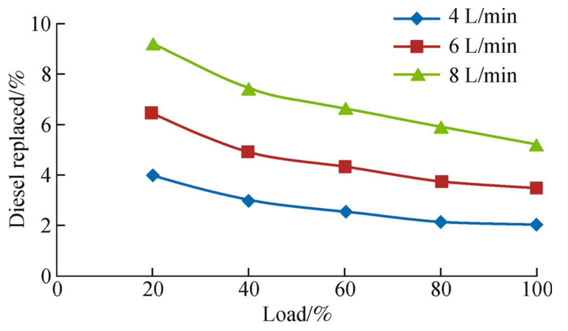

Fig. 1 Percentage of diesel replaced for different H_2 flow rates

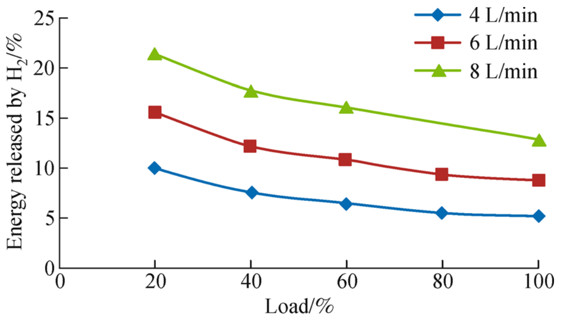

Fig. 2 Percentage of energy released by H_2 for different H_2 flow rates

2.3 Uncertainty analysis

Any experimental measurements, irrespective of the type of instrument used, possess some uncertainty due to fixed or random errors. As fixed errors are repeatable, they can be easily accounted for to get the true value of the measurement. However, random errors must be estimated analytically. Percentage uncertainties of various parameters such as brake power, brake-specific fuel consumption and brake thermal efficiency (BTE) were calculated using the percentage uncertainties of various instruments used in the experiment. The typical values of errors of various parameters are given in Table 3.

Table 3 Average uncertainties of some measured and calculated parameters

Measurement	Accuracy	Uncertainty/%	Measurement technique
Load	±10 N	±0.2	Strain gauge type load cell
Speed	±10 r/min	±0.1	Magnetic pickup principle
Weighing instrument	±0.1 g	±1	Mass measurement
Time	±0.1 s	±0.2	Manual stop watch
CO	±0.02%	±0.2	NDIR technique
HC	±10 ppm	±0.1	NDIR technique
NO_x	±12 ppm	±0.2	NDIR technique
Exhaust gas temperature (EGT) indicator	±1 C	±0.15	K-type thermocouple
Pressure pick up	±1 bar	±0.15	Magnetic pickup principle
Crank angle encoder	±1°	±0.2	Magnetic pickup principle

Using the principle of propagation of errors, the total percentage uncertainty of an experimentally found trial can be computed as ±2.12%.

3 Experimental setup and procedure

The schematic and photographic view of the experimental setup is demonstrated in Figs. 3 and 4, respectively.

The experiments were conducted in a single cylinder, four stroke, water-cooled, diesel engine (Make: Kirloskar AV-1). The engine was coupled to an eddy current dynamometer. The engine was run at a constant speed of 1500 r/min. The specifications of the engine used are tabulated in Table 4.

A crank angle encoder was fitted to the crank shaft to measure the crank angle. The cylinder pressure was measured by a piezoelectric pressure transducer (Make: Kistler, Type 6056A) mounted on the cylinder head. The pressure signal was sent to the data acquisition system where the combustion data like cylinder pressure and heat release rate (HRR) were obtained. The oxides of nitrogen

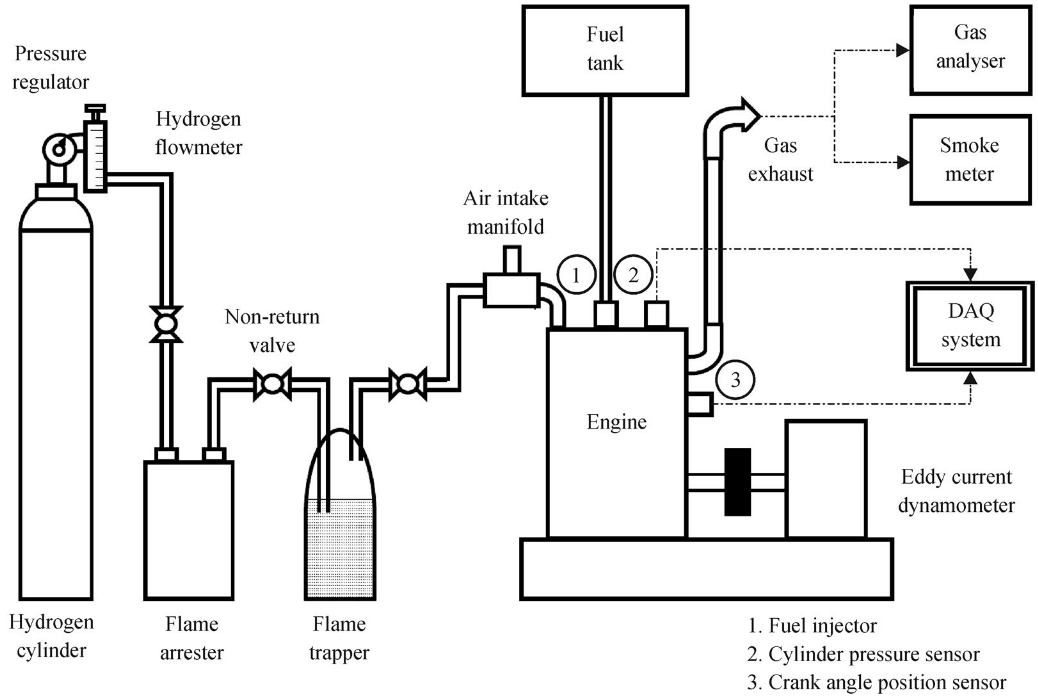

Fig. 3 Schematic of experimental setup

Fig. 4 Photographic view of experimental setup

Table 4 Specification of the engine

Engine make	Kirloskar AV-1
Type	Vertical, single cylinder, water cooled
Max. power	3.7 kW at 1500 r/min
Displacement	550 CC
Bore × Stroke	80 mm × 110 mm
Compression ratio	16.5:1
Fuel injection timing	21° BTDC
Loading device	Eddy current dynamometer

(NO_x), carbon monoxide (CO) and hydrocarbon (HC) emissions were measured with non-dispersive infrared analyzers (NDIR) (Make: HORIBA-Japan). The gas analyzers were calibrated with standard gases before test. Initially, the engine was operated with neat diesel fuel to obtain reference data. Further, the engine was tested with dual fuel mode like addition of hydrogen with inlet air in addition to pilot diesel injection. The hydrogen gas was inducted in the inlet manifold in different flow rates of 4 L/min, 6 L/min and 8 L/min respectively. The hydrogen flow line consists of hydrogen cylinder, pressure regulator, flame arrester, flow meter and flow control valve, as displayed in Figs. 3 and 5.

Fig. 5 Hydrogen flow line

The pressure of hydrogen stored in a high-pressure storage tank at 250 bar was reduced to a pressure 2 bar by using a pressure regulator. The hydrogen was then passed through a flame arrestor and flame trap which arrest any backfire of the engine. It also acts as a non-returnable valve. Then the hydrogen is passed through the digital gas flow meter which has a flow range of 0–10 L/min. The combustion, performance and emission characteristics were evaluated for different hydrogen flow rates and compared with neat diesel fuel operation.

4 Results and discussion

4.1 Performance analysis

4.1.1 Brake thermal efficiency

Figure 6 shows the variation in BTE with brake power for different flow rates of hydrogen. The 8 L/min hydrogen addition gives the highest BTE (39.42%) compared to diesel (35.21%) at full load. The BTE increases with higher hydrogen enrichment. In the experiment, it is observed that the share of hydrogen started increasing with decreasing load. This indicates that hydrogen participates in the combustion and increases the thermal efficiency which is attributed to enhanced combustion rate due to the high flame velocity of hydrogen. The increase in BTE is caused by hydrogen's higher calorific value and better mixing with air in addition to its faster burning rate characteristics [22]. It was observed that the hydrogen addition with inlet air showed an improved performance compared to normal neat diesel operation.

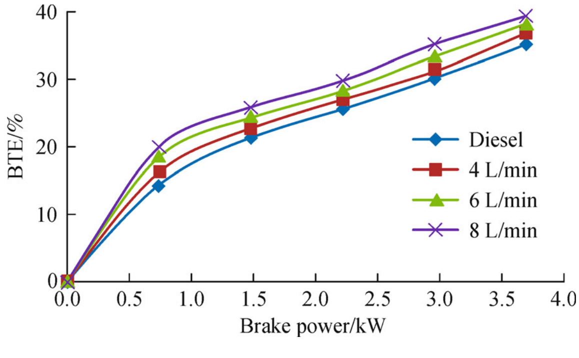

Fig. 6 Comparison of BTE

4.1.2 Brake specific fuel consumption

Figure 7 shows the variation of brake specific fuel consumption (BSFC) with brake power for different flow rates of hydrogen. The BSFC decreases with an increase in hydrogen addition rate with air. The lowest BSFC of 0.21 kg/kWh was obtained for 8 L/min hydrogen enrichment at 3.7 kW compared to diesel of 0.31 kg/kWh. This results from the premixing of hydrogen fuel with air due to its high diffusivity and uniform mixing with air resulting in

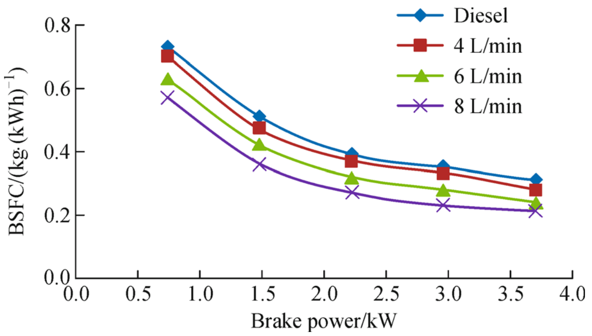

Fig. 7 Comparison of BSFC

improved combustion. The percentage of reduction of BSFC was observed to be 32% at full load between diesel and a hydrogen flow rate of 8 L/min.

4.2 Emission analysis

4.2.1 Nitrogen oxides

Figure 8 exhibits the variation of nitrogen oxides with load. NO_x forms at peak combustion temperature and higher oxygen concentrations [23,24]. NO_x formation is higher with 8 L/min compared to neat diesel and other flow rates of hydrogen. NO_x formation is dependent on combustion temperature. During the combustion process, NO_x forms in both flame-front and post flame charge. In diesel engine especially with hydrogen fuel, higher peak pressure combustion generates very thin flame reaction zone that shortens the residence time of combustion. This causes burned gases produced early in the combustion process to be compressed to higher temperature than they reached immediately after combustion. As a result, NO_x formation in the post-flame gases is more dominant as compared to flame front NO_x. As the hydrogen percentage increases, the flame speed and hence combustion efficiency increase [25]. The percentage of increase of NO_x is 25% at full load when compared to neat diesel.

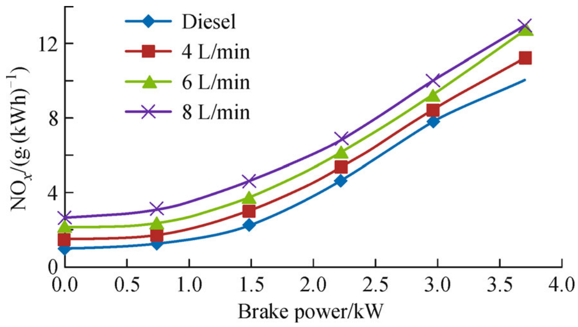

Fig. 8 Comparison of NO_x

4.2.2 Hydrocarbon

Unburned hydrocarbon decreases significantly because hydrogen fuel does not contain carbon. The variation of HC emissions with brake power for different values of hydrogen enrichment is presented in Fig. 9. It is observed that the HC emission of the hydrogen flow rate of 4 L/min, 6 L/min and 8 L/min with diesel fuel operation are 0.1841 g/kWh, 0.1801 g/kWh and 0.1741 g/kWh respectively at full load. The lowest HC emission was obtained to be 0.1741 g/kWh with a hydrogen flow rate of 8 L/min compared to 0.1881 g/kWh for diesel. The reduction in HC is caused by the higher burning velocity of hydrogen, which enhances the diesel burning. The HC post-flame oxidation was promoted by the increased combustion temperature as hydrogen addition. The factors discussed above were responsible for the reduced exhaust HC concentration with the increasing hydrogen fraction. The absence of carbon in hydrogen fuel also reduces HC emissions to a greater extent [25,26]. Similar results can be found in previous studies [27].

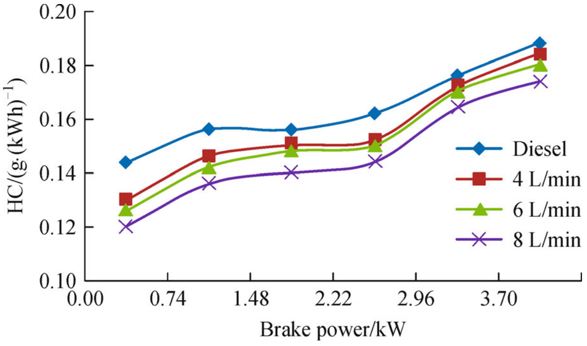

Fig. 9 Comparison of HC

4.2.3 Carbon monoxide

The variation of carbon monoxide with engine brake power and different proportions of hydrogen enrichment is shown in Fig. 10. The lowest CO emission was obtained as 0.0015 g/kWh with a hydrogen flow rate of 8 L/min when compared to 0.00179 g/kWh for diesel. With a hydrogen flow rate of 8 L/min, the CO emission is lower than other hydrogen flow rates and neat diesel operation. The reduction CO in a hydrogen flow rate of 8 L/min in hydrogen-operated dual fuel engine resulted from the absence of carbon in hydrogen fuel. At no load, since the engine is operated at a lean equivalence ratio, a reduction in CO is observed for hydrogen dual fuel operation. In the combustion reaction, the addition of hydrogen reduced the carbon content and increased the temperature. Therefore, the reduction in CO emission is significant for all flow rates of H_2. But at higher loads, the oxygen concentration

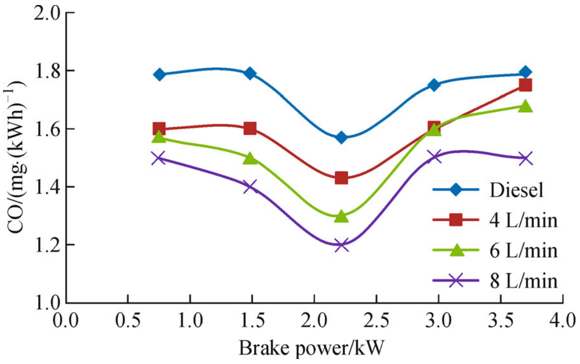

Fig. 10 Comparison of CO

reduces and, in addition, due to lesser reaction time, it results in a slight increase in CO formation rate, which makes the overall CO concentration to increase at full load compared to the same at medium load.

4.2.4 EGT

The variation of EGT with brake power and different proportions of hydrogen enrichment is demonstrated in Fig. 11. It is observed that the EGT for a hydrogen flow rate of 4 L/min, 6 L/min and 8 L/min and diesel fuel operation increased averagely compared to diesel at, full load respectively. The highest exhaust temperature was obtained to be 467°C with a hydrogen flow rate of 8 L/min compared to 425°C for diesel. This is due to the better mixing of hydrogen with air resulting in complete combustion of fuel with the increase in temperature around the combustion chamber [28]. Figure 11 confirms that the increase in NO_x emission is caused by the higher combustion temperature and O_2 availability. The H_2 fed into the engine can increase the peak of gas temperature. It can be explained that more H_2 induced into the cylinder increases the releasing energy from the combustion process. Thus, the combustion gas has a higher pressure and temperature. Hence this results in increased EGT.

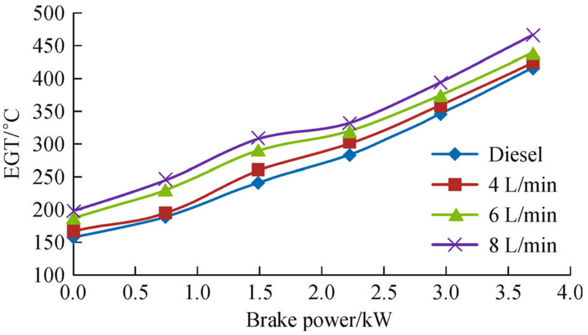

Fig. 11 Comparison of EGT

4.3 Combustion analysis

4.3.1 Cylinder pressure

Figure 12 shows the variation of cylinder pressure with crank angle. It is observed that hydrogen (8 L/min) and diesel fuel mode gives a higher peak pressure compared to diesel fuel operation at full load. With diesel, the peak pressure is 66.60 bar while with hydrogen it is 68.58 bar. The peak pressure of hydrogen occurs 5°CA later than that of diesel. The pressure rise is always lower in the case of diesel operation due to its slower burning characteristics [29].

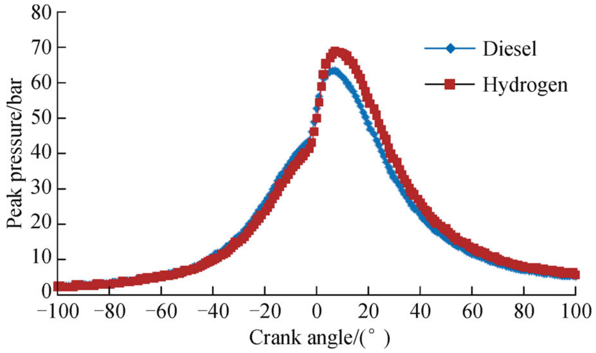

Fig. 12 Comparison of cylinder pressure

4.3.2 Heat release rate (HRR)

Figure 13 depicts the variation of heat release rate for hydrogen diesel combustion with 8 L/min hydrogen enrichment at full load. It is evident that heat release for hydrogen is more rapid than for diesel. The ignition of hydrogen with 8 L/min hydrogen enrichment operation takes place only after the injection of diesel at 23° BTDC. It can also be observed that the highest heat release rate is 52.79 J/°CA for 8 L/min hydrogen enrichment compared to neat diesel of 48.84 J/°CA. This is due to the instantaneous combustion (constant volume) that takes place with hydrogen fuel. The premixed fuel burns rapidly and releases an enormous amount of heat followed by the controlled heat release. The HRR during the premixed combustion is responsible for the high peak pressure [30,31].

5 Conclusions

Based on the experiments conducted on a hydrogen-enriched air-inducted diesel (dual fuel) engine system, the following conclusions are drawn:

1) The brake thermal efficiency of the hydrogen and

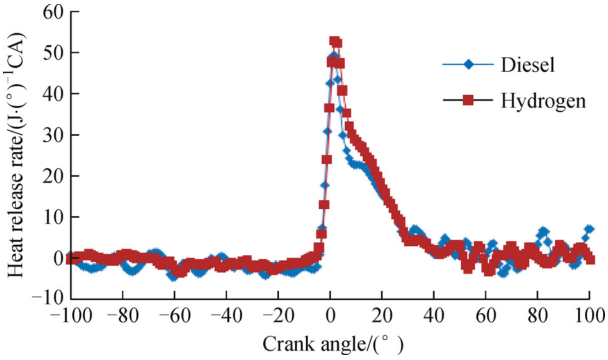

Fig. 13 Comparison of heat release

diesel fuel operation was quite higher than the diesel fuel operation over the entire brake power range. At a hydrogen flow rate of 8 L/min, the brake thermal efficiency was increased due to the addition of hydrogen fuel.

2) The brake specific fuel consumption decreased with the increase in hydrogen percentage over the entire range of operation.

3) The NO_x concentration increased with higher enrichment of hydrogen (8 L/min) compared to lower hydrogen enrichment and diesel.

4) The carbon monoxide emission decreased at part load and increased at full load. The lowest CO emission was obtained to be 0.0015 g/kWh with 8 L/min hydrogen addition, compared to 0.00179 g/kWh for diesel.

5) The HC emission for all additional hydrogen rates decreased averagely compared to diesel at full load, respectively. The lowest HC emission was obtained to be 0.1741 g/kWh with 8 L/min addition hydrogen with diesel, compared to 0.1881 g/kWh for neat diesel.

6) The exhaust gas temperature increased for all additional hydrogen flow rates averagely compared to diesel at full load, respectively.

7) The cylinder pressure increased for a hydrogen flow rate of 8 L/min compared to neat diesel at full load, respectively.

8) The HRR were higher for a hydrogen flow rate of 8 L/min compared to neat diesel fuel. The HRR for a hydrogen flow rate of 8 L/min was 52.79 J/°CA and 48.84 J/ °CA for neat diesel fuel at full load.

On the whole, it was concluded that hydrogen-enriched diesel engines perform well and emit less pollution compared to neat diesel fuel. Hence, hydrogen enrichment in a CI engine can be regarded as an eco-friendly alternative fuel to diesel.

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