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Effect of pilot fuel injection operating pressure in hydrogen blended compression ignition engine: An experimental analysis

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ABSTRACT

As the reduction of fossil fuel resources, environment threat, aggrandizement in energy demand and escalation in the cost of hydrocarbon fuels has caused interests in the evolution of alternative fuels for existing IC engines. Several researchers are promoting novel ideas and cutting edge technology which would eventually lead to leap fogging innovation and breakthrough in the area of alternative fuels. In this, concern hydrogen is increasing in demand because of its wide flammability limits, minimum ignition energy, high calorific value and high flame velocity. Apart from that it does not demand much modifications in the mechanism of the normal diesel engine to run as dual fuel and also it does not contain any carbon atom which eliminate emissions of CO_2, unburnt and partially burnt hydrocarbons such as aldehydes and other greenhouse gases concerned with combustion. In the present experimental investigation 10% and 20% of hydrogen by mass of fuel is inducted into the combustion chamber in conjunction with air in hydrogen–diesel dual fuel mode. The variation in injection operating pressure is done to optimize the performance characteristics and emissions. Experimentations were conducted on three different injection operating pressures (IOP) i.e. 200, 220 and 240 bar at full load condition and the performance characteristics were calculated. The effect of IOP on emissions were measured and reported. The rate of heat release and pressure release were also measured.

1. Introduction

Over the past decades the fossil-fuel reserves in the world are diminishing at an alarming rate and a lack of crude oil is expected at the early decades of this century. As a well-known fact, the energy resources for the major prime movers are discounting from the world, leaving toxic and fatal foot prints on the environment and human health. Diesel is one of such a fossil fuel which is used in the compression ignition engines, where compression ignition engines are the majorly used prime movers in medium and heavy vehicles, generators, pumps and machineries in most of the developed countries. But the amount of pollutants such as CO_2, CO, NO_x and unburnt hydrocarbons that are thrown out into the atmosphere through the exhaust emission of automotive vehicles is also increasing. So the compression ignition engines have occupied irreplaceable designation whereas replacement of fuel has been found. Hydrogen is one such fuel which has already shown off itself as a remarkable fuel for spark ignition engine, and also become a beckoning fuel for compression ignition engine researchers. The fossil fuel that is the breath fuel for the compression ignition engines is getting depreciated as a common knowledge [1] and leaving exhaust engines as the traits a human health and atmosphere. To the grounds, the researchers around the world are in chase of a duck soap solution for the problem.

Hydrogen is an appealing IC Engine fuel for such researchers, due to its advantages such as renewable, non-toxic, non-odorant and also results in complete combustion. Hydrogen is considered to meet energy, environment and sustainable development needs [2,3]. It has many potential uses, is safe to manufacture and is environment friendly [4]. According to Yadav et al. hydrogen combustion will produce no greenhouse gases, no ozone layer depletion chemicals and little or no acid rain ingredients and pollution.

2. Hydrogen for CI engines

According to studies conducted by the Ma et al. [5] hydrogen can be used as sole fuel for S.I. engine. However signified drop in brake power of the engine was observed due to low compression ratio. Increase in compression ratio would result in knocking.

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When hydrogen needs to be used for C.I. engines, it is to be noted that the self-ignition temperature of the hydrogen is 576°C, and is not possible to achieve the temperature during normal compression stroke even at higher compression ratios. Researchers at Cornell University failed to achieve compression ignition of H_2 at compression ratio of 29, this concluded some external sources are required to ignite H_2 [6]. In-case of diesel engine co-fuelling of diesel with LPG [11,12], methane [8,10], natural gas [7] and hydrogen–methane combination were studied. Most research in dual fuel engine has concentrated on defining the extent of dual fuelling and its effect on emissions and performance [9] hydrogen addition to methane has been reported to be effective to promote combustion at homogeneous lean operation.

3. Experimental procedure

Series of experimental cycles were conducted with varying injection-operating pressures and iterations were done with varying percentage of hydrogen substitutions and the results were compared with pure diesel.

The exhaust gas analyser used is MN-05 multi gas analyser (5 gas version) is based on infrared spectroscopy technology with signal inputs from an electrochemical cell. Non-dispersive infrared measurement technique used for the measurement of CO, CO_2, and HC gases. Each individual gas absorbs infrared radiation that can be used to calculate the concentration of sample gas. Analyser uses an electrochemical cell to measure oxygen concentration. It consists of two electrodes separated by an electrically conducted liquid or cell. The cell is mounted behind a poly tetra fluro ethene membrane through which oxygen can diffuse. The device therefore measures oxygen partial pressure. If a polarizing voltage is applied between the electrodes the resultant current is proportional to the oxygen partial pressure.

The engine used in the present study is a Kirloskar AV-1, single cylinder direct injection, water-cooled diesel engine with the specifications given in Table 1. While a schematic view of the experimental setup is shown in Fig. 1. Diesel injected with a 3 holes injector each with nozzle diameter of 0.15 mm. The engine is coupled to an Eddy current dynamometer. Engine exhaust emission was measured. At each cycle, the engine was operated at varying IOPs and the emissions were noted. The experiment was carried out by keeping the compression ratio constant i.e.16.5:1 (for nomenclature see Table 2).

Table 1
Table of specifications.

Type	Four-stroke, single cylinder, compression ignition engine, with variable compression.
Make	Kirloskar AV-1
Rated power	3.7 kW, 1500 rpm
Bore and stroke	80 mm × 110 mm
Compression ratio	16.5:1
Cylinder capacity	553 cc
Dynamometer	Eddy current dynamometer
Orifice diameter	20 mm
Fuel	Diesel and hydrogen
Calorimeter	Exhaust gas calorimeter
Cooling	Water cooled engine
Starting	Hand cranking and auto start

Table 2
Nomenclature.

NO_x	Oxides of nitrogen
CO	Carbon monoxide
BTE	Brake thermal efficiency
UHC	Unburnt hydrocarbon
PPM	Parts per million
IOP	Injection operating pressure
% H_2	Percentage of hydrogen
ROPR	Rate of pressure release
ROHR	Rate of heat release
CA	Crank angle
HI	Heat input
CI	Compression ignition
IC	Internal combustion
LHV	Lower heating value
m_{H_2}	Mass of hydrogen
m_D	Mass of diesel

4. Results and discussions

Significant results were obtained at full load conditions at various injection operating pressures i.e. 200, 220 and 240 bar and various percentage substitution of hydrogen (for results see Table 3).

4.1. Brake thermal efficiency

Brake thermal efficiency is the measure of performance of the engine calculated as the ratio of brake power generated to the heat input. Brake thermal efficiency was calculated for various injection operating pressures from 200 to 240 bar at full load condition with different percentages of hydrogen substitutions. Pure diesel has shown 27.9% BTE at 220 bar which was 5.2% more than that of at 200 bar and decreased by 2.8% at 240 bar, as shown below in Fig. 2. The addition of H_2 directly increases the BTE, because of the properties of H_2 such as wide flammability limits, minimum ignition energy, higher flame velocity and high calorific value. At 10% and 20% of hydrogen substitution the brake thermal efficiencies were 4% and 3.2% more than that of 200 bar respectively, and again a decrease by 2.5% and 1.7% at 240 bar. The brake thermal efficiencies were higher at 220 bar with 10% and 20% of hydrogen substitution than that of 200 bar respectively because of fine droplets formed due to proper atomization of the pilot fuel and more spray penetration. This enhances uniformity in mixing of H_2 with air that leads to complete combustion. Further increase in the IOP i.e. 240 bar decreases the ignition delay period which in turn decreases homogenous mixing possibility leading to incomplete combustion and hence less brake thermal efficiency.

Table 3
Result analysis of performance characteristics and emission on different hydrogen substitutions compared to pure diesel.

Parameters	200 bar		220 bar		240 bar		Remarks
	10% Hydrogen	20% Hydrogen	10% Hydrogen	20% Hydrogen	10% Hydrogen	20% Hydrogen	
BTE	2.6↑	6↑	1.4↑	3.9↑	1.7↑	5↑	Increases
NO_x	72↑	92↑	24.9↑	45.6↑	28.5↑	65.7↑	Increases
UHC	15.6↓	25.2↓	2.1↓	7↓	22.1↓	30.5↓	Decreases
CO	6.8↓	31↓	15.3↓	48.7↓	12.6↓	45.4↓	Decreases

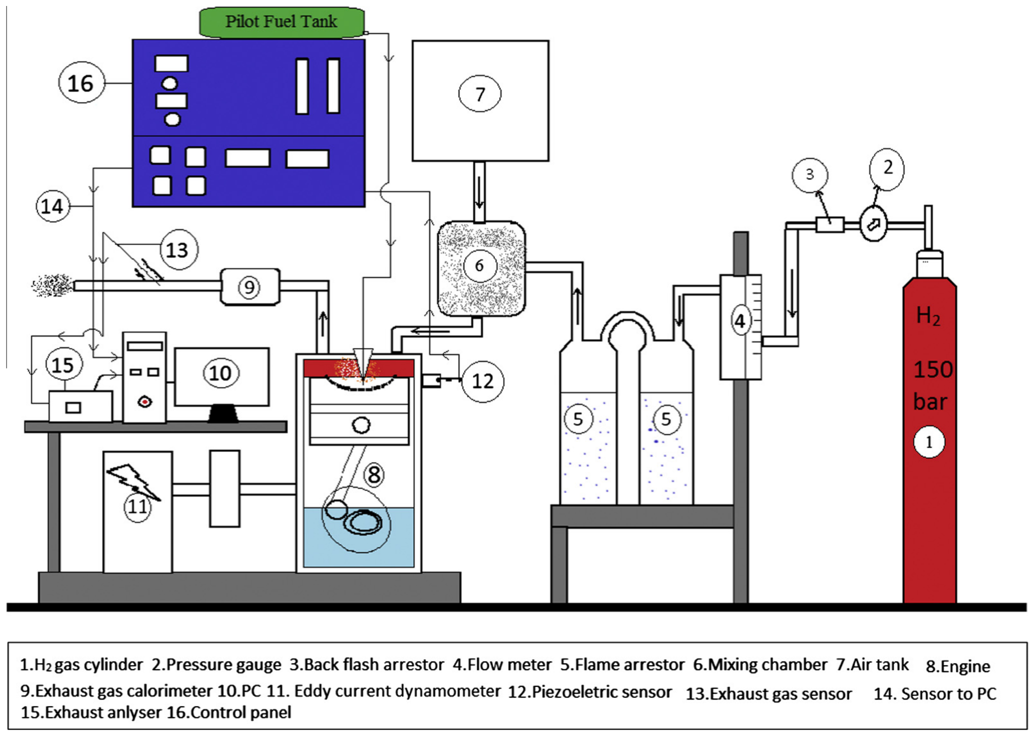

Fig. 1. Schematic view of experimental setup.

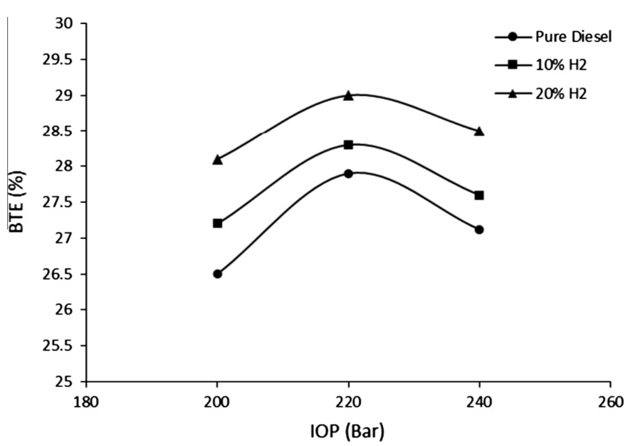

Fig. 2. Effect of injection operating pressure on brake thermal efficiency.

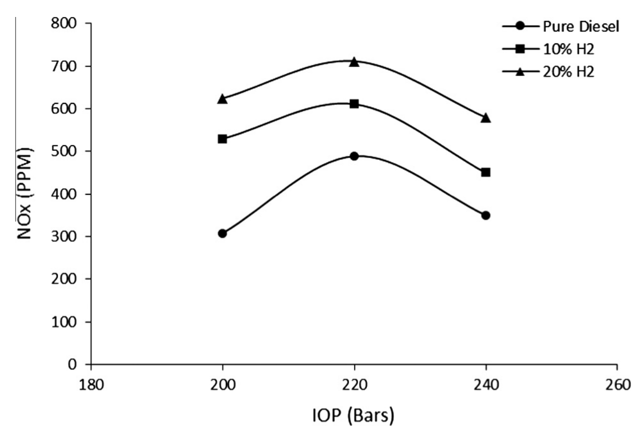

Fig. 3. Effect of injection operating pressure on NO_x emissions.

5. Emissions

5.1. NO_x emission

NO_x (oxides of nitrogen) are formed inside the combustion chamber due to presence of excess of oxygen and high combustion temperature that favour for oxidation reaction. Fig. 3 shows the variation of NO_x emissions at various IOPs for various substitution of hydrogen. The effect of injection operating pressures can be seen on NO_x and it was found that at 220 bar and at all percentages of hydrogen NO_x levels were increased. There was increase of NO_x by 37%, 13.2% and 12% at 220 bar compared to that at 200 bar for all percentage of hydrogen substitutions i.e. 0%, 10% and 20% respectively. Reduction of NO_x by 28.4%, 26.3% and 18.5% was observed at 240 bar compared to that at 220 bar for 0%, 10% and 20% of hydrogen substitution respectively.

5.2. UHC emissions

UHCs are organic compounds that are formed due to incomplete combustion of hydrocarbon based fuels. The unburnt hydrocarbon emission is shown in Fig. 4 at full load for various IOPs i.e. 200 to 240 bar at different percentages of hydrogen substitutions. The decreasing trend of UHC was observed at all injection operating pressures with increasing % of H_2 substitution when compared to pure diesel because of its wide flammability limit and high calorific value. At 220 bar, because of proper atomization and mixing, maximum % of carbon content burnt and the possibility of formation of UHC is greatly minimized. For 10% H_2 and 20% H_2 substitution at 220 bar minimum content of UHC was observed and at 240 bar there was a mild increment in UHC content, because of the shorter delay period and rapid combustion.

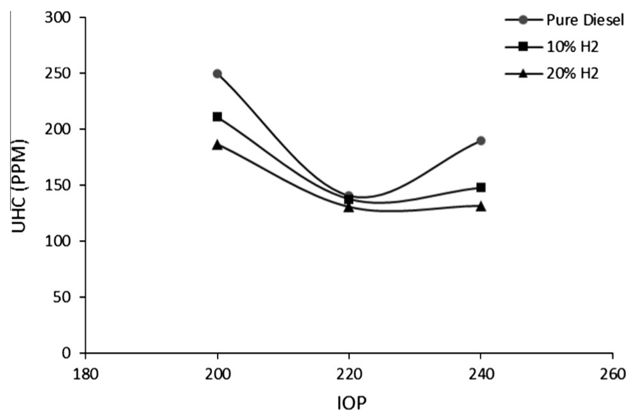

Fig. 4. Effect of injection operating pressure on unburnt hydrocarbons.

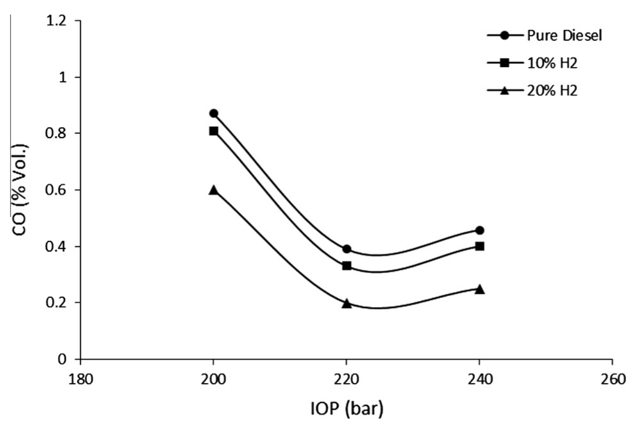

Fig. 5. Effect of injection operating pressure on carbon monoxide emissions.

5.3. CO emissions

Carbon monoxide is a colourless poisonous gas. Small amount of CO concentrations when inhaled slows down physical and mental activities. Carbon monoxide is found only in engine exhaust. It is a product of incomplete combustion due to insufficient amount of air in the air fuel mixture or insufficient time in the cycle for completion of combustion. Fig. 5 describes the behaviour of CO emissions at different IOPs and at different substitutions of H_2. However in the duel fuel mode as the % H_2 is increased, uniform mixing is achieved with the air which causes to minimize the formation of CO at 200 and 220 bar. At 240 bar the formation of CO increases because of lack of mixing of fuel with air and insufficient time for combustion.

6. Combustion reaction

For complete combustion of hydrocarbon fuel the sufficient quantity of oxidization is needed. If oxidizer quantity is more than stoichiometry then the mixture is said to be lean, if it is less than the stoichiometry oxidizer, then the mixture is said to be rich. For complete combustion the air–fuel ratio is determined by writing simple atomic balances. Assuming 100 mol of air contain 21 mol of O_2 and 79 mol of N_2. 1 mol of O_2 + (79/21 = 3.76) mole of N_2 i.e. 1 + 3.76 = 4.76 mol of air is required for complete combustion where N_2 being inert gas which does not take part in the reaction.

$$C_xH_y + H_Y + x[x + (y/4) + (Y/4)](O_2 + 3.76N_2)$$
$$\rightarrow [(Y/2) + (y/2)]H_2O + xCO_2 + [x + (y/4) + (Y/4)]3.76N_2$$

In both reactions, the total masses of the reactant and product have remained same, which is the confirmation of the principle of conservation of mass. In this chemical reaction, the number of moles remains constant. Combustion of fuel species takes place in the presence of oxygen (air), CO_2 and N_2. But nitrogen being inert does not take part in the reaction.

7. Combustion parameters

From the various IOPs it has been found that maximum efficiency and minimum emissions at 220 bar. So combustion parameters are studied only on 220 bar.

7.1. Cylinder pressure vs. crank angle

Fig. 6 shows the cylinder pressure vs. crank angle at full load and at various substitutions of hydrogen at 220 bar. As the substitution of hydrogen percentage in dual fuel mode is increased the rate of pressure rise per crank angle is simultaneously increased because the pilot fuel ignites nearly 2–3 degrees advance than that of the normal diesel fuel. The highest peak pressure was observed for 20% H_2 substitution due to high flammability of hydrogen, rapid combustion, smaller drop size distribution, large jet penetration of the fuel spray makes proper air–fuel mixture and large amount of fuel burnt in the premixed combustion stage.

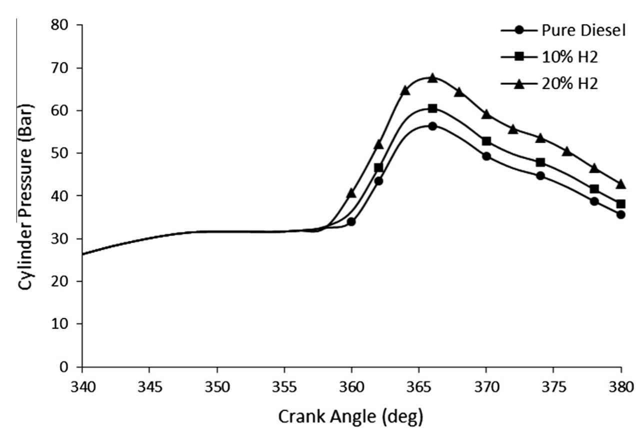

Fig. 6. Cylinder pressure vs. crank angle.

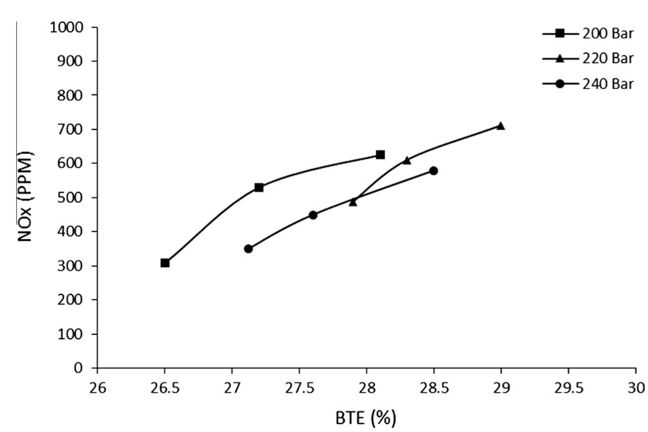

Fig. 7. Effect of brake thermal efficiency on NO_x.

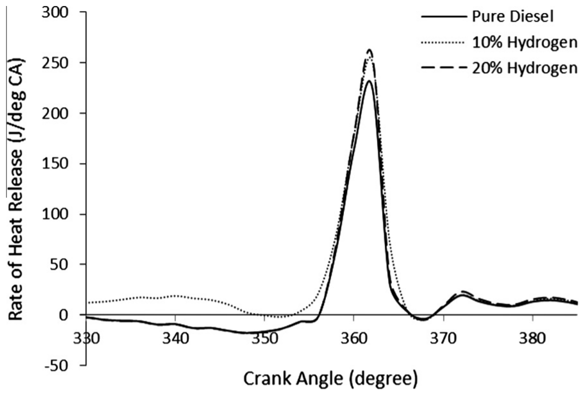

Fig. 8. Rate of heat release at different hydrogen substitutions.

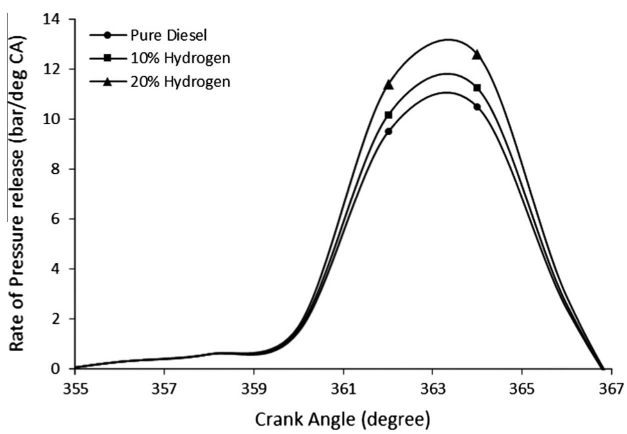

Fig. 9. Rate of pressure release at different hydrogen substitutions.

7.2. BTE and NO_x diagram

Fig. 7 shows the effect of brake thermal efficiency (BTE) and NO_x values on experimental investigation of hydrogen substitution on various IOPs. It is observed that on substitution of 10% hydrogen at 220 bar, the BTE was calculated as 28.3% and on increasing hydrogen substitution by 20% at same pressure, BTE was calculated as 29%. It is also observed that for 2.4% increase in BTE, the penalty of NO_x emissions increases from 611 to 712 ppm i.e. by 16.53%.

8. ROHR & ROPR

8.1. Rate of heat release (ROHR)

Fig. 8 shows the rate of heat release per degree of crank angle at full load for different substitutions of hydrogen. In this operation, the peak heat release rate was found at 360° crank angle and at 20% substitution of hydrogen. The peak heat release rate for dual mode at 20% hydrogen substitution was 258.3 J/deg CA and 226.8 J/deg CA for pure diesel operation. The peak heat release is more in case of dual mode at 220 bar IOP this is due to fine atomization of fuel for fluent combustion.

8.2. Rate of pressure release (ROPR)

Fig. 9 shows the rate of pressure release per degree of crank angle at 100% load for different substitutions of hydrogen. In this operation, the peak pressure rise was found at 364° crank angle for 20% substitution of hydrogen. The peak pressure rise for dual mode at 20% hydrogen substitution was 12.6 bar/deg CA and 10.5 bar/deg CA for pure diesel operation. The peak pressure rise is more in case of dual mode at 220 bar IOP.

8.3. Heat Input

It is defined as the product of mass of fuel (kg/h) to its lower heating value (kJ/kg).

$$\text{Hydrogen Heat input} = m_{H_2} \times (\text{LHV})$$

$$\text{Diesel Heat input} = m_D \times (\text{LHV})_{\text{diesel}}$$

$$\text{Total heat input} = m_{H_2} \times (\text{LHV})_{H_2} + m_D \times (\text{LHV})_{\text{diesel}}$$

$$\%H_2 \text{ heat input} = \frac{m_{H_2} \times (\text{LHV})_{H_2}}{\text{Total heat input}} \times 100$$

Fig. 10, pie diagram shows the heat input of hydrogen and diesel at various injection operating pressures at full load conditions. It is observed that the percentage of heat input of hydrogen is maximum at 220 bar IOP i.e. 21%.

9. Conclusions

The current paper presented the results of H_2 substitution by mass to the pilot fuel with varying different Injection operating pressures at full load conditions. Results summarized the effects on performance, emission and combustion characteristics.

BTE increases with increase in percentage of H_2 substitution (by mass) compared with pure diesel. BTE increases with increase in injection operating pressure up to 220 bar, further BTE decreases with increase in IOP. So at 220 bar H_2 substitutions gives the maximum value of BTE.

It was noticed that as the hydrogen percentage increases NO_x level also increases at all injection operating pressures. However the formation of NO_x increases from 200 to 220 bar for all substitution, further increasing of IOP, NO_x level gradually decreases. The decreasing trend of UHC was observed at all injection operating pressures with increase in percentage of H_2 substitution when

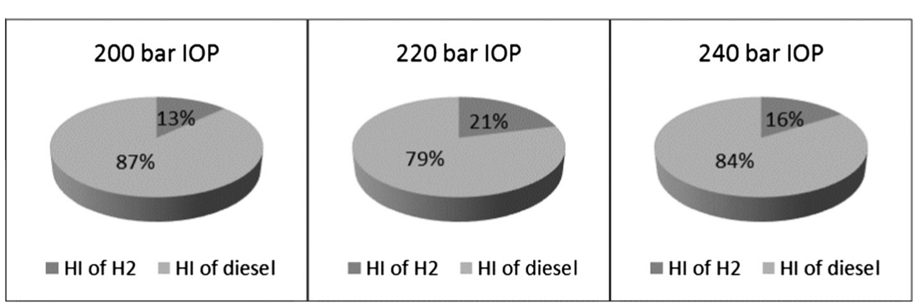

Fig. 10. Heat input of H_2 and diesel at various IOPs.

compared to pure diesel. For 10% H_2 and 20% H_2 substitution at 220 bar minimum content of UHC was observed and at 240 bar there was a mild increment in UHC content because of the shorter delay period and rapid combustion. In the dual fuel mode as the percentage of H_2 increased, uniform mixing is achieved with the air that causes minimization in the formation of CO at 200 bar and 220 bar. At 240 bar, the formation of CO increases because of lack of mixing of fuel with air and insufficient time for combustion.

The rate of pressure rise inside the cylinder per degree of crank angle was maximum at 20% of H_2 substitution followed by 10% of H_2 and then for pure diesel. The cylinder pressure obtained in H_2-diesel dual fuel mode is higher than that obtained with pure diesel. The highest peak pressure was observed for 20% H_2 at 220 bar.

At 220 bar IOP with increase in hydrogen substitution there was an increase in BTE by 2.4% but the penalty of NO_x emissions also increased by 14.1%.

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