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Effects of CNG flow rate on combustion, performance and emissions characteristics of biodiesel fuelled diesel engine

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Abstract : In this paper, an experimental investigation was carried out to understand the effect of CNG flow rate and jatropha biodiesel as pilot fuel under dual fuel mode on combustion, performance and emissions characteristics of an unmodified DI diesel engine. The CNG was inducted at various mass flow rates (0.2, 0.4, 0.6, 0.83 kg/h) with the incoming air through intake manifold. The pilot fuel (diesel or jatropha biodiesel) supply was regulated to maintain the desired engine power while keeping the CNG flow rate fixed. The combustion parameters (peak cylinder pressure, heat release rate, ignition delay and combustion duration), performance (brake thermal efficiency, brake specific fuel consumption and exhaust gas temperature) and emissions characteristics (NO_x, HC, CO_2, CO and smoke opacity) were analyzed for dual fuel mode CNG-biodiesel and compared with conventional diesel fuel. The performance and emissions characteristics results depicts that jatropha biodiesel as pilot fuel exhibits better fuel characterization as compared to conventional diesel fuel particularly at higher engine loads. In spite of above benefits, the higher NO_x emissions were reported with higher CNG flow rate under CNG-biodiesel operated diesel engine. However, jatropha biodiesel and CNG dual fuel combination with 0.2 kg/h flow rate of CNG is beneficial for improving combustion performance and emissions characteristics.

Keywords : Biodiesel, CNG, smoke, dual fuel, diesel.

1. Introduction

Limited fossil fuel reserves and rising environmental degradation problems has attracted interest towards findings viable alternative clean fuels for diesel engines. Diesel engine is widely used in transportation, agricultural farm machinery, and various industrial applications. However, the toxic emissions emitted from diesel engine are a major source of poor urban ambient air quality. The oxides of nitrogen, smoke and particulate matter emitted from diesel engines poses serious health hazards. Engineers and researchers worldwide are finding alternative fuel options and other clean combustion technologies to rid of these problems [1-3].

CNG and biofuels (alcohols or biodiesel) is the subject of intensive research worldwide because of their clean combustion characteristics. Gaseous fuel is an attractive option for utilization in diesel engines under dual fuel mode. Dual fuel engines, utilizes two fuels (gas and liquid) simultaneously. Due to higher self-ignition temperature of primary gas fuel, pilot fuel (high cetane number) is required to initiate combustion [4-7]. In this mode, the gaseous fuels like hydrogen, CNG, biogas, producer gas can inducted along with air in intake manifold and liquid pilot fuel (diesel or biodiesel) is injected in similar manner as in diesel engine and acts as an ignition source for combustion. The dual fuel engines can replace upto 80% of fossil fuel energy.

CNG due to its high octane rating, cheap availability, and good combustion characteristics is using as an alternative fuel for internal combustion engines. CNG whose, main constituent is methane, are readily mixes with air to from homogenous air-fuel mixture and burn over wide range of flammability limits [8]. It cuts down greenhouse gas, PM, NO_x, smoke opacity several fold.

The performance, combustion and exhaust emissions characteristics of dual fuel compression ignition engines using diesel fuel and natural gas have been reported by several researchers [9]. Also combustion characteristics of dual fuel engine were examined in details numerically and experimentally to explore the effects of various parameters such as intake pressure and temperature [10,11]. Natural gas as a main fuel in a dual fuel engine ignited by biodiesel showed that injection pressure has significant effect on combustion characteristics as well as injection timing [12].

Some researches on biodiesel as a pilot fuel in dual fuel engine has been reported in literature [13]. Since The high centane number of biodiesel reduces its ignition delay and hence its combustion advances leading to smaller rich zones and as result lower HC and CO emissions. Moreover, higher oxygen content in biodiesel improves the oxidation of the mixture and leads to less HC and CO emissions [14,15].

Biodiesel can be produced through transesterification process from variety of feedstocks like vegetable oils, animal fats, and even waste cooking oil. The use of biodiesel as a pilot fuel and other alternative fuels as main fuel (such as alcohols) was recommended by previous works [16,17]. The addition of methanol to biodiesel dual fuel engine leads to an increase in fuel ignition delay and as a result the peak cylinder pressure decreases [18]. The lower amount of CO and NO_x emissions was the other effect of this methanol blending. Using hydrated ethanol in RCCI diesel engine improves thermal efficiency of the engine by up to 55% along with extremely low NO_x, CO and soot emissions [19].

From the open literature, it was found that, none of the research study has been done on the effects of various CNG mass flow rate on CNG-biodiesel combination under dual fuel mode. However, limited research studies have been done on the utilization of CNG-biodiesel under dual fuel mode in conventional diesel engines. The main aim of this study is to experimentally investigate the effects of CNG flow rate on jatropha biodiesel fuelled engine and its influence on combustion, performance and emissions characteristics. All the tests were performed at a constant speed of 1500 rpm under different engine loads for conventional diesel and dual fuel mode. A comparative evaluation was made with various tested fuels on the basis of combustion, performance and emissions characteristics.

2. Materials and method

2.1. Raw Materials

Diesel fuel was purchased from local retail outlet of petrol pump. The chemicals required for transesterification process (Potassium hydroxide, Methanol, Ethanol) were procured from Merck Chemicals. Jatropha oil was procured from local oil supplier. The transesterification process was carried out in the biodiesel reactor as shown in the Fig. 1. CNG was purchased from local vendor of Indraprastha Gas Limited, New Delhi. The CNG composition is given in Table 1.

2.2. Preparation of jatropha methyl ester (JOME)

The transesterification reaction were carried out in a 10 litre three-neck stainless steel reactor equipped with temperature indicator, reflux condenser and variac for temperature controlled oil bath. The process was performed with 1% w/w of catalyst amount, 6:1 oil/methanol molar ratio, 65 ^{0}C for 120 minutes. First of all, jatropha oil was preheated at 70 ^{0}C to remove the traces of moisture in the oil. The desired quantity of catalyst and methanol mixture was prepared by shaking on magnetic stirrer and then poured into reactor along with preheated oil for 2 hours. Then, it allows settling in separating funnel for overnight so that glycerol was separated at the bottom. After settling of glycerol, the remaining upper layer of methyl ester was washed with distilled water 3-4 times to remove catalyst and excess methanol. Then, it was heated at 110 ^{0}C to removes the traces of moisture. Finally, the jatropha methyl ester was kept for cooling and then stored in bottle. After transesterification, the colour of jatropha oil changed from deep brown to reddish yellow. The kinematic viscosity of jatropha methyl ester was found to increases with addition of jatropha oil methyl ester in diesel – biodiesel fuel blend. A similar increment was found also in Relative density. However, the calorific value of the biodiesel (JOME) was found to be 38.450 MJ/kg, which is less than the calorific value of the diesel (43.560 MJ/kg). With 20% of biodiesel in the diesel, the calorific value of the blend decreased simultaneously. The flash point, fire point, cloud point and pour point of diesel biodiesel fuel blends were found increases with the addition of 20% of biodiesel in the diesel. Biodiesel produce must meet the specifications (ASTM D-6751) in order to use it as a fuel component for transportation fuel. This specification requires elaborate testing and these tests can be compared with diesel fuel. The physico-chemical properties of the Biodiesel produced were tested in Laboratory of Engines and Unconventional Fuels, Centre for Energy Studies, IIT Delhi which is mentioned in Table 2.

Fig. 1. Biodiesel Reactor and separating funnels.

Table 1 Properties of Test Fuels.

Properties/Fuels	Diesel	JOME B20	JOME B100	CNG
Relative Density@15 ^{0}C	0.8445	0.8526	0.8892	0.79
Viscosity@40 ^{0}C, cst	2.6803	3.1024	4.7867	
Lower Heating value, kJ/kg	43560	42540	38450	50000
Flash Point (^{0}C)	65	86	170	
Fire Point (^{0}C)	71	91	176	
Cloud Point (^{0}C)	-1	11	22	
Pour Point (^{0}C)	-6	-3	12	

Compressed Natural Gas was purchased from the local retailer outlet of IGL (Indraprastha Gas Limited), New Delhi with the composition given in **Table 2**.

Table 2 Composition of CNG.

S.No.	Constituent	Fraction (%)
1	Methane	96.113
2	Ethane	2.571
3	Propane	0.359
4	I-butane	0.05
5	N-butane	0.09
6	I-pentane	0.01
7	Nitrogen	0.598
8	Carbon dioxide	0.149
9	Hexane	0.06

(Source: Gas Authority of India Ltd.)

2.3. Experimental setup

In the present work a normal diesel engine was converted into dual fuel operation without major modifications. An experimental test rig was developed with necessary instrumentation for studying the engine performance, emission and combustion characteristics. The whole test was conducted for the standard injection pressure and injection timings. The engine typically used for this study was a single cylinder DI commercial diesel engine. It is an air cooled, naturally aspirated constant speed compression ignition engine commercially used in emergency power back up genset whose major specifications are shown in Table 3. The engine was coupled to a 5 kVA electric generator through which load was applied by increasing the field voltage shown in Fig. 2.

The engine was tested at 20, 40, 60, 80 and 100 percent brake load conditions. The engine has the capability to run either on pure diesel or dual fuel mode. Fig. 2 shows the control panel equipped with instruments such as speed indicator, Digital voltmeter, Digital ammeter, Digital Temperature Indicator, inclined U tube manometer, Liquid fuel measuring Burette.

A piezoelectric pressure transducer, Kistler make, model 701A was used for measuring the cylinder gas pressure and magnetic pickup, Electro make, model 3010 AMa was used to measure crank angle. The 100 pressure cycle data were recorded and stored in host computer for further combustion analyses.

The air flow is measured by using an air box with orifice fitted to it. The pressure drop across the orifice was noted on an inclined manometer filled with liquid of specific gravity of 0.714. The scale on the manometer was given in terms of equivalent water column in mm.

The temperature was measured by Chromel-Alumel K-type thermocouple installed in various parts of the engine as shown in Fig. 2. The temperature to be measured was intake mixture, exhaust gas, lubricating oil and fin (cylinder wall). The measured values of temperature in (deg ^{0}C) were displayed on a digital temperature indicator mounted on the engine control panel.

In the present investigations two liquid pilot fuels are used, diesel and B20 blend of jatropha methyl ester. The B20 blend was obtained by mixing of 20% by volume of biodiesel and 80% by volume of petroleum diesel.

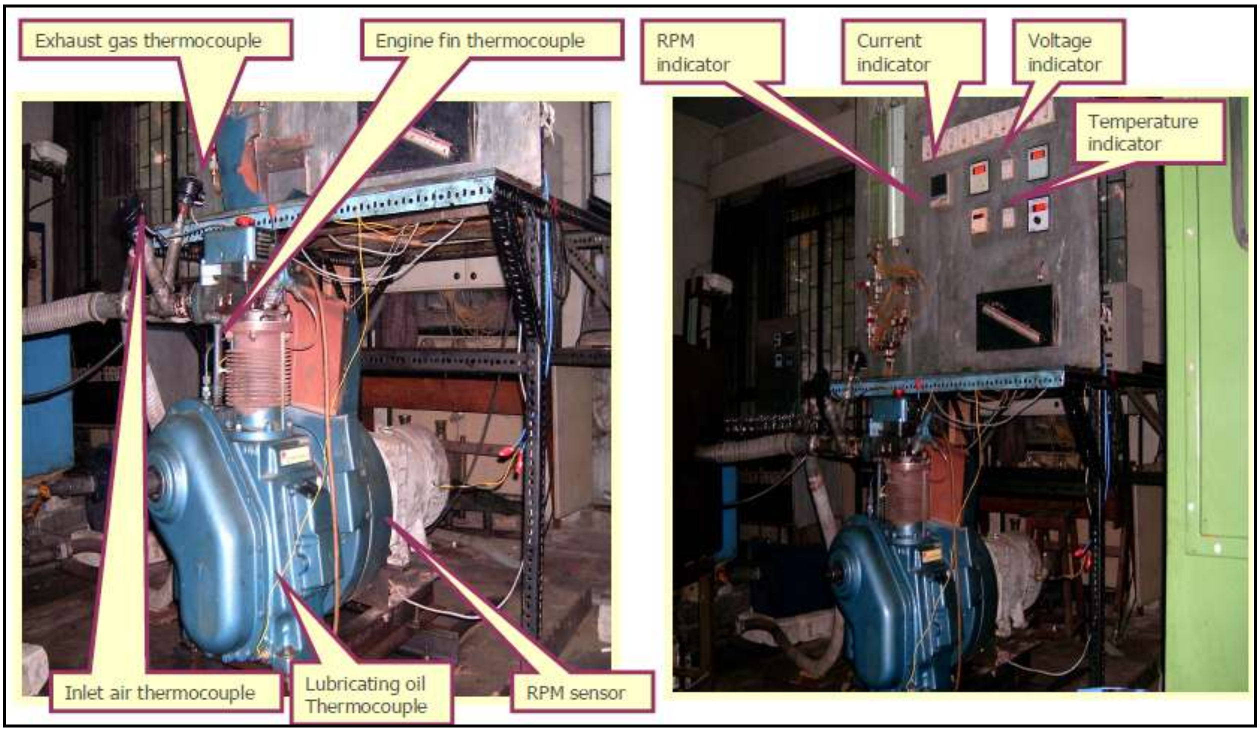

Fig. 2. Experimental setup.

Table 3 Engine Specifications.

Make and Model	**Kirloskar (DAF8)**
Bore X Stroke	95 X110 mm
Rated Power	5.9 kW (8 BHP)
Rated Speed	1500 rpm
Number of Cylinder	Single
Compression Ratio	17.5:1
Type of Cooling	Air Cooled
Lubrication Type	Forced Feed
Displacement Volume	779.704 cc
Nozzle opening Pressure	200 bar
Static Injection timing	26 ^{0}bTDC

The pilot liquid fuels were alternatively supplied to the engine injection pump from separate tanks, under gravity feed. Fuel consumption was measured by a calibrated glass burette by measuring the time required for the consumption of 50 ml of fuel.

The CNG from storage vessel first enters a flame trap which was fitted with a pressure gauge, rotameter, regulating valve and safety release valve. Then gas enters a surge tank, which was cylindrical in shape and sealed from all sides. Surge tank dampened the fluctuations of the supply pressure to the engine so as to maintain a constant flow rate. The rotameter was used to measure the flow rate of CNG in LPM. The gas flow was maintained at a slight pressure of 1 kg/cm^2 (gauge), supplied to the engine. The CNG flow rate was set at several constant levels.

Gas samples were drawn while the engine was operating steadily under a specified set of operating conditions. The analyzers were allowed to reach a thermal stability before use. 10-15 minutes were required to reach the stability condition. The exhaust surge tank was fitted to the engine exhaust manifold pipe and the pressure of exhaust gas was maintained at 70 mm water pressure before taking readings. This ensures continuous flow of exhaust gas because the exhaust gas flow is pulsating in nature due to cyclic variations of the engine and this causes error in readings. The probe was then inserted in the exhaust pipe to measure the values of exhaust emissions. For exhaust emission analysis AVL 4000 DiGas Analyzer was used. This analyzer gave emissions of gases namely CO, CO_2, HC, O2 and NO_x.

For measuring the smoke, AVL 437 smoke analyzer was used. This instrument gives reading in terms of smoke opacity. The uncertainty of some measured parameters is shown in Table 3.

2.3. Test Procedure

The engine was started at no load position for warming up with diesel fuel. Initially, experiments were conducted with diesel fuel to obtain baseline data at all engine loads. All the tests were performed at a constant speed of 1500 rpm from no load to 100% of engine brake power.

The CNG flow rate was kept constant at various levels and desired engine power was maintained by manually regulating the supply of pilot fuel (diesel or JOME). This procedure was repeated for all operating loads till desired engine power was attained.

Data was collected at various levels of CNG substitution under different loading conditions using JOME B20 as pilot fuels and analyzed critically. Dual fuel operation with JOME pilot fuel were compared on the basis of brake thermal efficiency, power output, brake specific energy consumption and exhaust emissions such as HC, CO, NO_x and smoke opacity.

3.1 Performance characteristics

3.2.1. Brake thermal efficiency

Brake thermal efficiency of diesel engine is defined as efficiency with which the chemical fuel energy is converted into useful work. Fig. 8 represents brake thermal efficiency variations with CNG energy share. At higher loads, induction of small amount of CNG improves brake thermal efficiency. This is mainly due to the enhanced combustion rates. Flame propagation through CNG-air mixture leads to high heat release rates and improved brake thermal efficiency. Beyond 0.2 kg/h of CNG mass flow rate, the brake thermal efficiency drops with increase in natural gas substitution. Higher CNG mass flow rate reduces the air available for combustion which also reduces thermal efficiency. At light loads, with higher CNG mass flow rate, the dual fuel operation shows poor performance as compared to conventional diesel. At light load conditions, the concentration of pilot fuel quantity is small to burn gaseous-air mixture completely and this leads to fall in thermal efficiency.

3.2.2. Brake specific energy consumption

Fig. 9 illustrates brake specific energy consumption variations with engine loads. Brake specific energy consumption is a more reliable parameter when comparing fuels of different calorific values. As shown in the Fig. 9, at low loads, the brake specific energy consumption for dual fuel operation increases with increase in CNG mass flow rate. This reveals a poor utilization of the gaseous fuel at the low to intermediate engine loads. This may be due to the lower combustion temperature and air fuel ratio inside the combustion chamber of the engine [27]. On the other hand, at higher loads, the improvement of gaseous fuel utilization leads to a relevant improvement in the brake specific energy consumption under dual fuel operation, which tends to be slight higher as compared to conventional diesel.

3.2.2. Exhaust gas temperature

Fig. 10 shows the exhaust gas temperature profile with engine loads. The exhaust gas temperature indicates the optimum use of heat energy of a fuel. The increase in exhaust gas temperature in the tailpipe reduces the conversion of heat energy of fuel into useful work. As seen in the Fig. 10, with increase in engine load increases the exhaust gas temperature for all tested fuels. This tendency is due to increase in total fuel input energy with increase in engine loading. It was observed that a conventional diesel engine shows higher exhaust gas temperature than dual fuel engine at entire engine loads. With increase in CNG mass flow rate, the exhaust gas temperature decreases, keeping engine load constant. The decrease in exhaust gas temperature may be due to prolonged ignition delay, the combustion phase shifted certain degree towards expansion stroke thereby reducing combustion pressure and temperature and these factors keeps lower exhaust gas temperature in tailpipe [28].

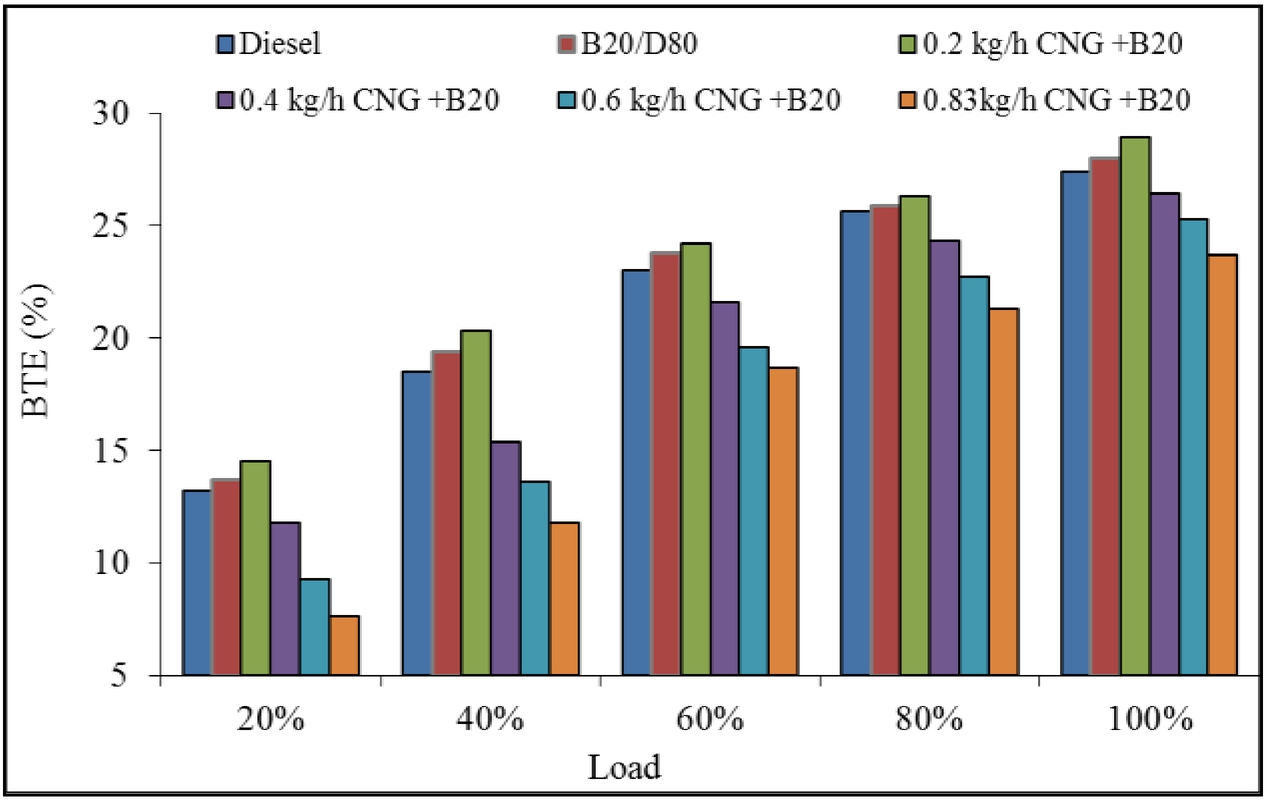

Fig. 8. Variation of BTE with engine loads.

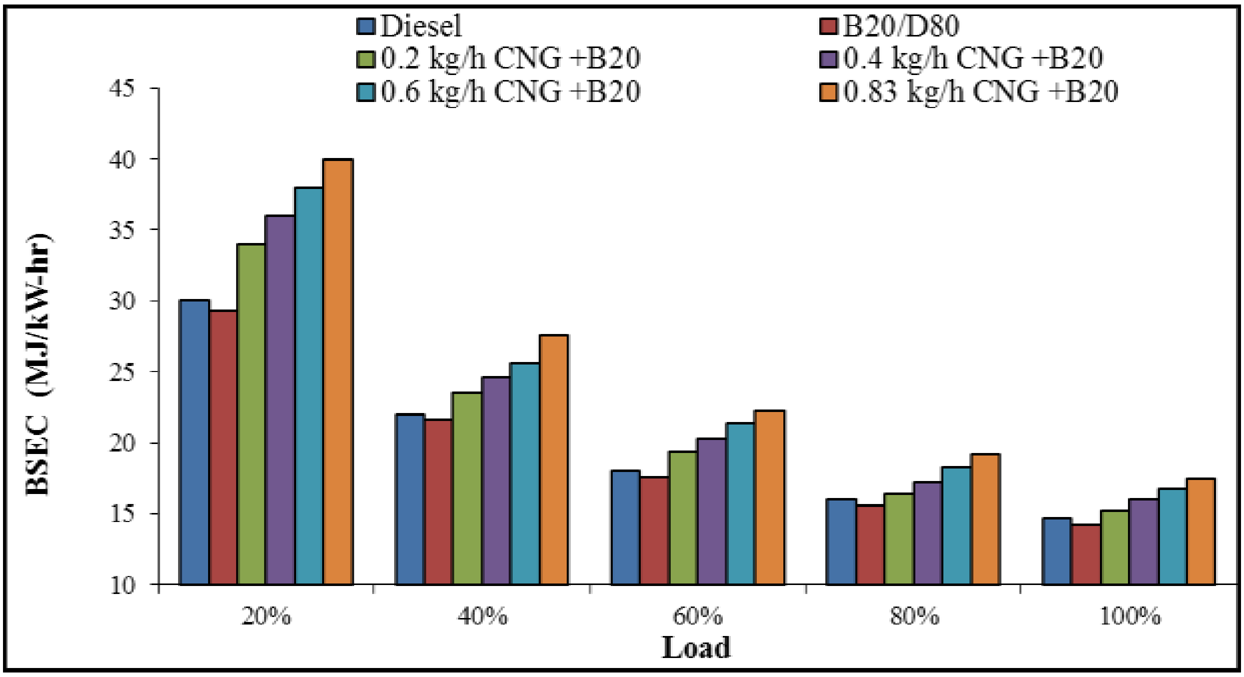

Fig. 9. Variation of BSEC with engine loads.

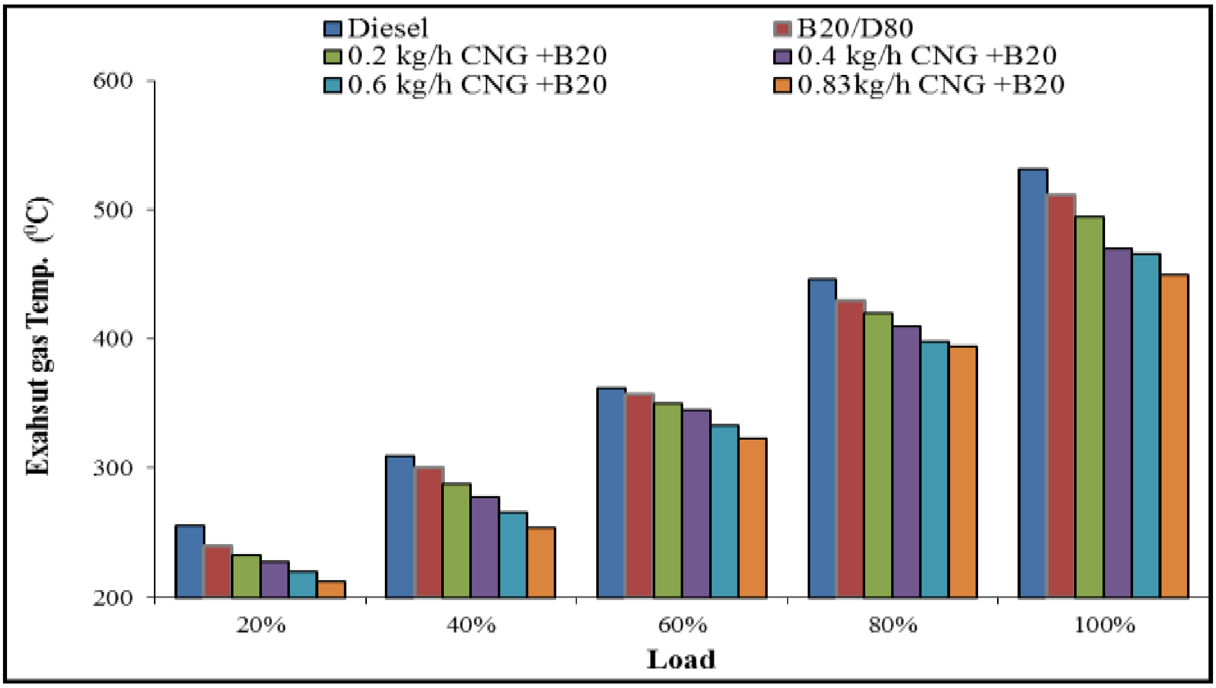

Fig. 10. Variation of exhaust gas temperature with engine loads.

3.3. Emissions characteristics

3.3.1. Unburned hydrocarbons

Unburned hydrocarbons are the unburned quantity of fuel emitted from exhaust tailpipe. The unburned hydrocarbon emissions variation with engine loads is shown in Fig. 11. It is clear, that unburned hydrocarbon emissions are considerably higher under dual fuel mode than diesel or JOME B20 at all loads. With increase in CNG flow mass, HC emissions further increases, keeping engine load constant. At light load conditions the pilot fuel quantity is small to burn the overall fuel-air mixture completely, results in higher emissions of hydrocarbon. Under dual fuel operation, the filling of the crevice volumes with unburned mixture of air and gaseous fuel during compression and combustion while the cylinder pressure continuous to rise, is an important source dominating the formation of HC emissions [29]. Valve overlap between intake and exhaust to facilitate scavenging is also a major cause of source of hydrocarbon emissions under dual fuelling as some part of the fuel left unburned in exhaust tailpipe [30]. As load increases, higher combustion gas flame temperature and rich fuel-air mixture improves combustion process and promotes better oxidation of fuel in the engine cylinder. At higher loads, with increase in CNG flow mass, the HC emissions were slightly higher than normal single fuel operation. JOME biodiesel blend exhibits lower HC emissions over entire engine loads range. This may be due to shorter ignition delay, high cetane number and oxygen availability which tends to promotes better combustion characteristics in rich fuel zone [31].

3.3.2. Oxides of Nitrogen

The three factors which promote NO_x emissions are combustion temperature, oxygen concentration and residence time inside combustion chamber. Fig. 12 shows the variation of NO_x emissions with engine loads. It was observed that NO_x emissions decreases, with increase in CNG flow mass, keeping engine load constant. At lower loads, with increase in CNG substitution there was sharp decrease in NO_x formation. It was mainly due to the reduction of gas temperature by high specific heat capacity of premixed charge and finally reduction in oxygen concentration for combustion [32]. This may also be due to lower oxygen availability due to increase in gaseous flow supply and lower combustion temperature. Both the factors lower the NO_x emissions under dual fuel as compared to normal diesel or B20 fuelled diesel engine. At higher engine loads (80% and 100%), with increase in CNG flow mass, results in higher NO_x emissions than baseline diesel or B20 jatropha biodiesel. This may be attributed due to the improvement in combustion characteristics of CNG and richer fuel-air mixture results in rapid combustion thereby increases combustion gas flame temperature and subsequently higher NO_x level in exhaust tailpipe. B20 jatropha biodiesel exhibits higher NO_x level than baseline diesel fuel at entire engine loading conditions. This can be explained by the fact that biodiesel contains oxygen content and high cetane number, which results better oxidation of fuel promotes higher NO_x emissions.

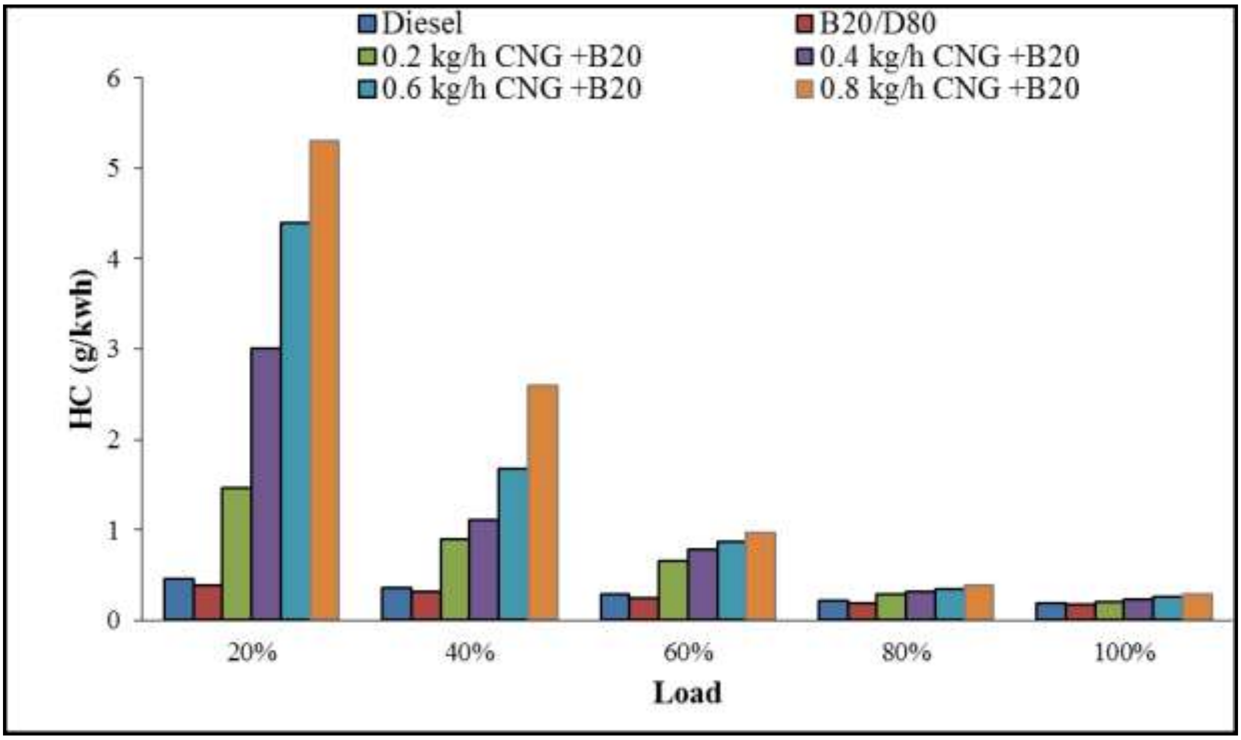

Fig. 11. Variation of HC emissions with engine loads.

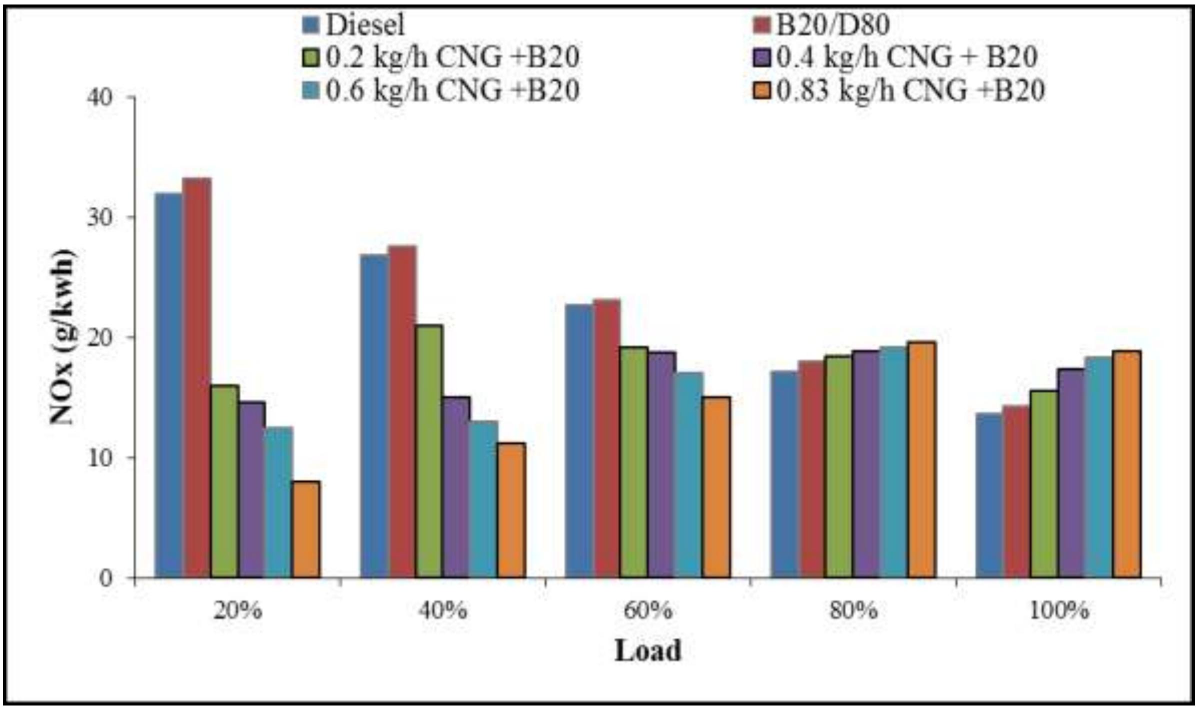

Fig. 12. Variation of NO_x emissions with engine loads.

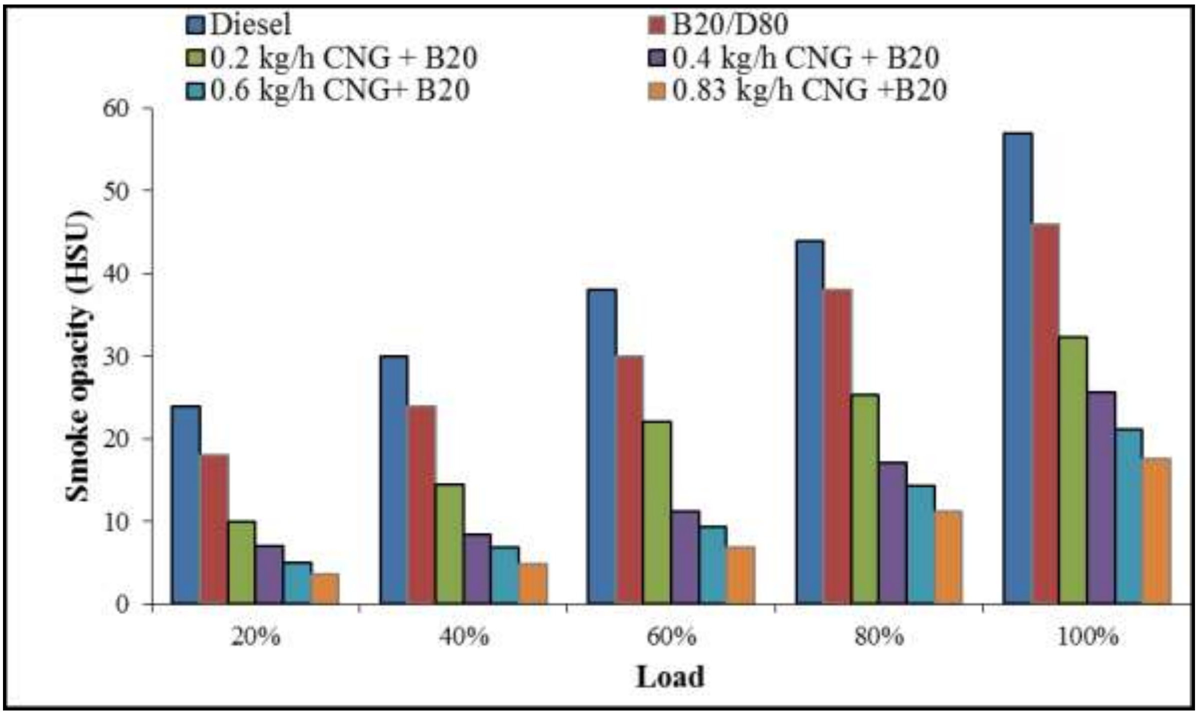

Fig. 13. Variation of smoke opacity emissions with engine loads.

3.3.3. Smoke opacity

Fig. 13 represents variations of smoke emission with engine loads for all tested fuels. It was observed that smoke opacity emissions increases with increase in engine loads. However, the smoke emissions under dual fuel with various CNG flow rates, the smoke opacity decreases, keeping engine load constant. The formation of smoke is mainly associated with pilot fuel i.e. diesel or B20 as CNG is a non-soot forming fuel. With an increase in CNG share, smoke opacity decreases and the reduction as compared to normal diesel or JOME B20 fueled operation is sharper. The main reason is that natural gas, whose methane is the main constituent, being a lower paraffin family, has very small tendency to produce soot [33].Taking these factors into account it seems that for a dual fuel operation, high CNG supply is an efficient method to reduce the smoke emission. Practically, gaseous fuel does not produce smoke, while it contributes to the oxidation of the one formed from the combustion of the liquid fuel. JOME biodiesel blend emits less smoke as compared to normal diesel fuel. This may be due to good combustion characteristics, higher cetane number and absence of aromatics in fuel characterization.

3.3.4. Carbon monoxide

Carbon monoxide represents poor and incomplete combustion of fuel due to limited availability of oxygen concentration and lower gas flame temperature. Fig. 14 shows the variation of CO emissions with engine loads.

As shown in Fig. 14, dual fuel engine shows higher level of CO emissions than conventional diesel or B20 operation at low to intermediate loads. This was attributed due to the poor and incomplete combustion arising from low pilot ignition source, very lean mixture and higher auto-ignition temperature of CNG makes slower flame propagation results in higher CO emissions [34]. As observed with increasing CNG flow mass, CO emissions increases, keeping engine load constant. However, at higher loads, due to improvement in combustion and higher gas flame temperature the CO emissions under dual fuelled engine are lower than normal diesel fuel.

However, JOME B20 produces lower CO emissions as compared to diesel due to oxygen concentration in biodiesel which oxides the fuel into CO_2 formation.

3.3.4. Carbon dioxide

Fig. 15 shows the CO_2 emissions variation with engine loads. CO_2 can be used as an indication of complete combustion efficiency. It is a main source of global warming and a product of complete combustion. CNG, whose main constituent is methane, has lowest carbon to hydrogen ratio amongst hydrocarbons, having low tendency to produce CO_2 than conventional diesel fuel [17]. It was observed that using dual fuelling with CNG-JOME combustion produce lower CO_2 emissions than conventional diesel mode. It is clear from the Fig. 15 that with increase in CNG mass flow rate, CO_2 emissions decreases, keeping engine load constant. So, dual fuel combustion is an effective technique for reducing greenhouse gas like carbon dioxide emissions. B20 fuelled engine shows slightly lower carbon dioxide levels at higher loads as compared to normal diesel fuel. This may be due to the oxygen content in biodiesel and better combustion characteristics.

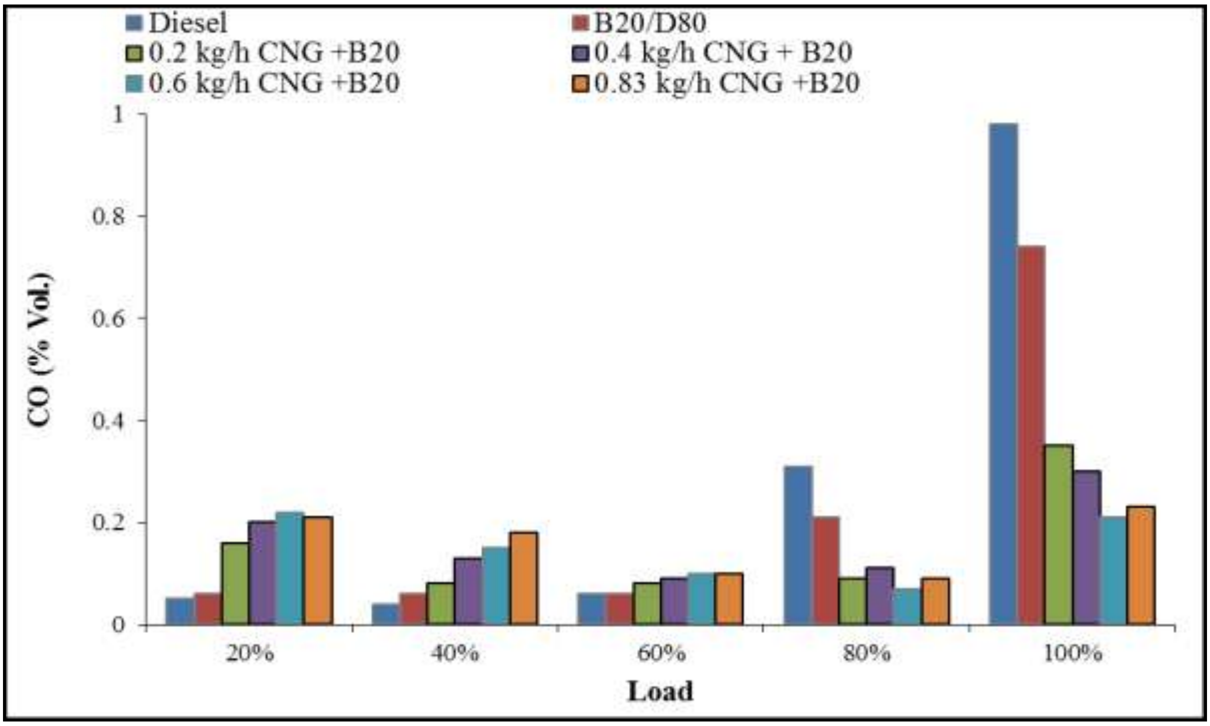

Fig. 14. Variation of CO emissions with engine loads.

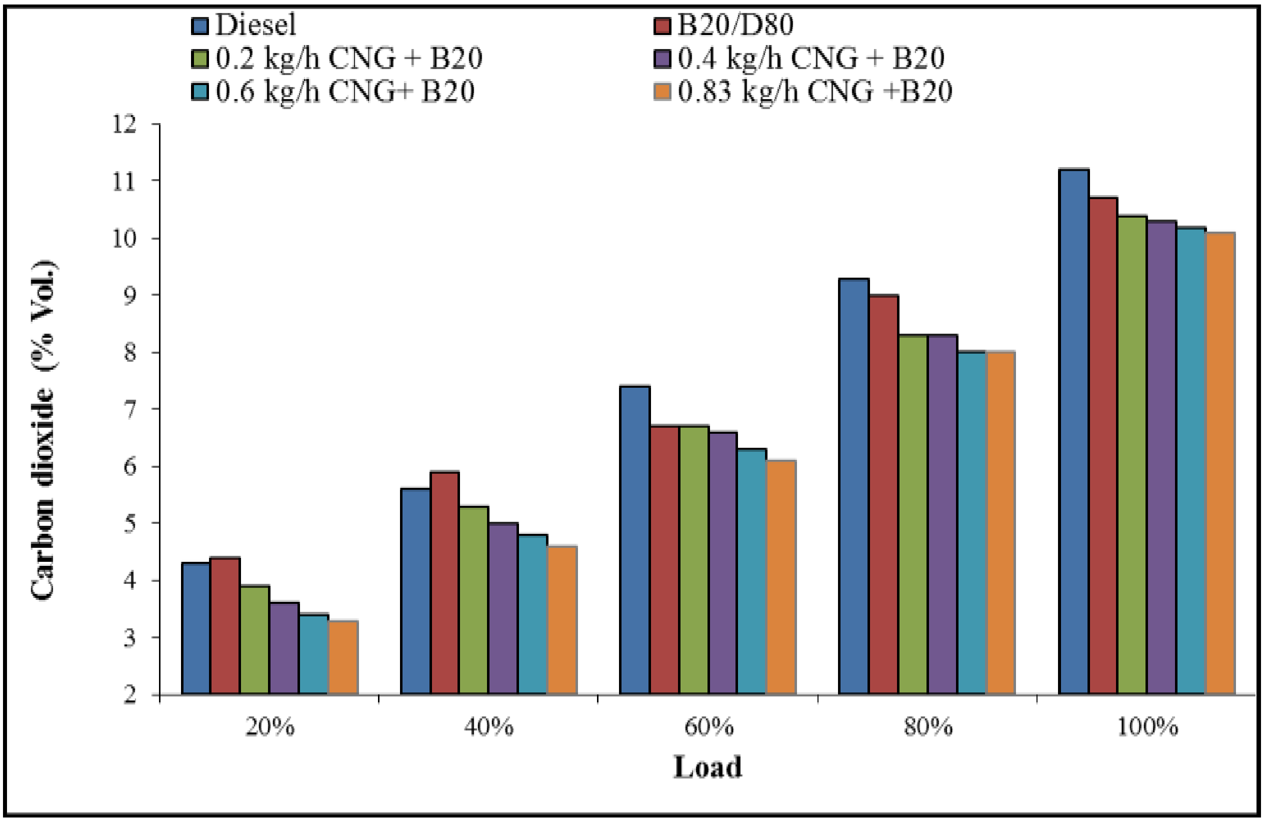

Fig. 15. Variation of CO_2 emissions with engine loads.

4. Conclusion

In this experimental work, the effect of CNG flow rate with jatropha biodiesel under dual fuel mode were investigated on the basis of combustion, performance and emissions characteristics. The study shows that with 0.2 kg/h CNG flow rate, BTE increases, at all loads. It is due to improvement in combustion due to small CNG enrichment which makes more homogenous air fuel mixture. However, beyond 0.2 kg/h CNG flow rate, BTE falls rapidly at all engine loads. BSEC increases, with increasing CNG flow rate, at lower loads. It reveals the poor gaseous fuel utilization due to low combustion temperature. At higher loads, BSEC curve is slightly higher than conventional diesel or B20 fuelled operation. Exhaust gas temperature increases with load but with increasing CNG flow rate, it decreases, keeping load constant. HC and CO emissions were higher at lower loads with increasing CNG flow supply. Smoke reduces at all engine loads with increasing CNG flow rate. NO_x were lower with increasing CNG supply at lower loads but at higher loads, it was higher. This is due to rapid combustion and higher gas flame temperature at higher loads. CO_2 remains lower with increasing CNG supply, at all engine loads. The overall results indicate that employing CNG-biodiesel dual fuel combustion is a beneficial method in improving engine combustion performance and reducing emissions characteristics.

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