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TECHNICAL PAPER

Performance and emission characteristics of diesel and vegetable oil blends in a direct-injection VCR engine

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Abstract The speedy diminution of conventional fuel and vacillation of diesel price in the global market demand an urgent need for widespread research, so that some viable alternative is obtained and sustainable energy demand with less ecological impact is met. In the present exploration, *Jatropha* curcas oil is used as substitute fuel to examine the emission and combustion characteristics for optimizing the compression ratio of a direct-injection, single-cylinder, four-stroke VCR diesel engine running with mineral diesel and vegetable oil blends at different compression ratios of 16, 17 and 18 and varying the load from idle to a rated load of 3.5 kW. The impact of compression ratio on fuel consumption, combustion pressures and exhaust gas emissions has been investigated and presented. The optimum compression ratio which gives best performance was identified. The result shows that the thermal efficiency, exhaust gas temperature and emission parameters such as NO_X, HC and CO at optimum compression ratio 18 with blends containing up to 30 % (by volume) jatropha oil is satisfactory to run an unmodified diesel engine.

Keywords Blending · Viscosity · Concentration · Performance · Emission analysis

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Abbreviations

VCR	Variable compression ratio
BSFC	Brake specific fuel consumption
EGT	Exhaust gas temperature
NO_X	Oxides of nitrogen
CO_2	Carbon dioxide
CO	Carbon monoxide
CR	Compression ratio
HC	Hydrocarbon
ICE	Internal combustion engine
B10	10 % Jatropha oil and 90 % diesel oil in blends
B30	30 % Jatropha oil and 70 % diesel oil in blends
B50	50 % Jatropha oil and 50 % diesel oil in blends
B80	80 % Jatropha oil and 20 % diesel oil in blends
B100	100 % Jatropha oil

1 Introduction

Vegetable oils are harmless to the environment and help to considerably lessen emission of sulfur oxides, carbon monoxide, smoke, particulate matter and noise in diesel engine operations [1]. Over the last few decades, numerous researchers have established that among the multisources of energy as fuel in a diesel engine, a number of adverse physical properties, predominantly their viscosity, restricted the direct use of vegetable oils as fuel in diesel engines, causing deprived fuel atomization, unfinished combustion and carbon deposition on the injector and valve seats and ensuing in severe engine fouling [2–4]. The problems arising through the use of neat vegetable oils in diesel engine operation can be solved by the amalgamation of vegetable oils with diesel fuel, which facilitates avoiding damage to engine elements for short-term operation of diesel engine and producing lower thermal efficiency, lower NOx and higher CO and HC

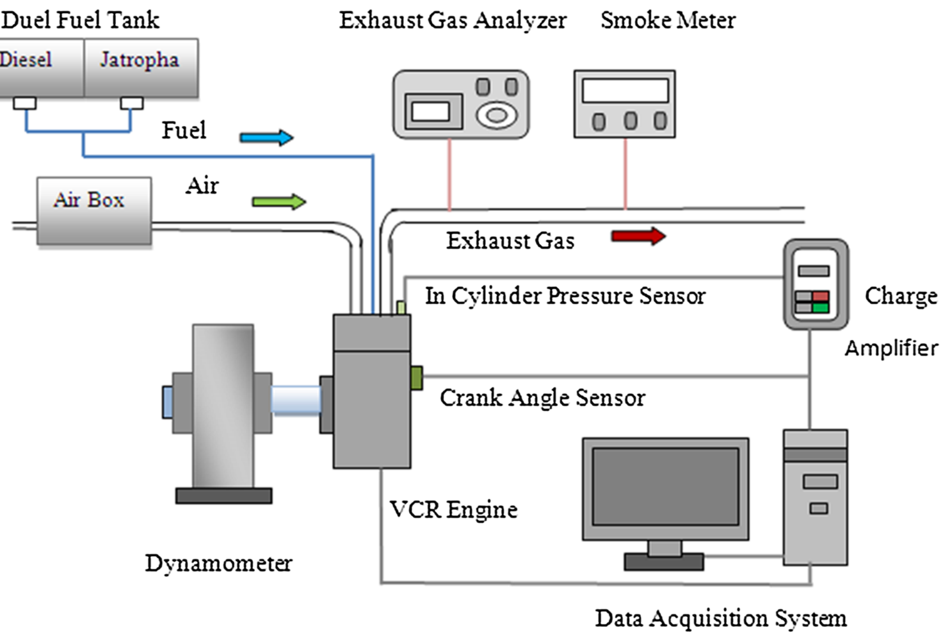

Fig. 1 Schematic diagram of the experimental setup

emissions [5–7]. Forson et al. [8] stated that jatropha oil and its blends with diesel give a similar performance and emission characteristics to diesel for lesser blend concentration in an ICE operation. Pramanik [9] reported that jatropha oil and its blend with diesel in an ICE shows a similar kind of results. In this study, the elevated viscosity of *Jatropha curcas* oil is reduced by blending with diesel, and an explanation is given about the engine performance and emission characteristics without any considerable hardware modifications to the VCR engine.

Table 1 Scientific specifications of the test engine

Parameter	Specification
General details	Single-cylinder, four-stroke compression ignition engine, constant speed, vertical, direct injection
Bore	87.5 mm
Stroke	110 mm
Capacity	661 cm^3
Compression ratio	17.5:1
Rated power	3.5 kW
Rated speed	1500 rpm
Dynamometer	Eddy current
Cooling system	Water cooling
Injection timing	23° bTDC
Injection pressure	200 bar

2 Materials and methods

2.1 Experimental and test procedure

Figure 1 describes the detailed illustration of the investigational arrangement and Table 1 depicts the scientific specifications of the engine.

The engine used for the present investigation is a four-stroke, water-chilled, single-cylinder, VCR (variable compression ratio), direct inoculation, upright diesel engine. Online performance assessment of the diesel engine is done by using the Labview-based Engine Recital Investigation software package "EnginesoftLV". The engine speed of 1500 rpm is kept constant during engine operation. The oil sump is filled with lubricating oil prior to carrying out the experiments. The eddy current dynamometer is coupled to the engine with a control system. Specifically planned tilting cylinder block arrangement facilitates the transformation of the CR of the engine with continuous running and without altering the combustion chamber geometry of the engine. The setup has stand-alone panel box consisting of air box, two fuel tanks for duel fuel test, manometer, fuel measuring unit, transmitters for air and fuel flow measurements, process indicator and engine indicator. With the help of the piezoelectric pressure transducer fixed on the engine cylinder and crank angle encoder fixed on the flywheel, the cylinder pressure is predetermined with respect to crank angle. A gas analyzer (AVL Di Gas 444) is used to determine the exhaust gas discharges (CO, CO_2, HC, NO_X) from the engine, and the smoke meter (AVL 437) is employed to deliberate the smoke opacity in the engine exhaust. To ensure the accuracy of the measured values, the gas analyzer is calibrated before each measurement using reference gases and the smoke meter is also allowed to adjust its zero point before each measurement. The engine is first run on standard diesel for investigating the engine performance at all load conditions and different CRs 16, 17 and 18. Then parallel experiments are carried out with neat jatropha oil and 10, 30, 50 and 80 % jatropha oil blends which are prepared on a volume basis over the same range of loads and CRs. For all situations, by preserving the injection pressure of 203 bars and 23° CA BTDC injection timing at a rated speed of 1500 rev/min, the emission assessments and the other assessments are traced thrice and a mean of these is used for comparison. The performance of the engine at changed loads and situations are estimated in terms of BSFC, brake thermal efficiency and emissions of carbon monoxide, carbon dioxide, unburnt hydrocarbon and oxides of nitrogen with exhaust gas opacity and temperature.

Table 2 Properties of mineral diesel and jatropha oil

Property	Mineral diesel	Jatropha oil
Density (kg/m^3)	840.8	917.5
API gravity	37.223	23.1025
Kinematic viscosity at 40 °C (cSt)	2.635	36.58
Pour point (°C)	−6	4.48
Cloud point (°C)	3.48	9.47
Flash point (°C)	72	230
Fire point (°C)	104	275
Conradson carbon residue (%, w/w)	0.1	0.8
Ash content (%, w/w)	0.01	0.03
Calorific value (MJ/kg)	44.764	38.5855
Carbon (%, w/w)	80.288	75.873
Nitrogen (%, w/w)	1.684	0
Hydrogen (%, w/w)	12.368	10.617
Oxygen (%, w/w)	1.178	11.062
Sulfur (%, w/w)	0.252	0

Table 3 List of instruments and the range, accuracy and percentage uncertainties

Instruments	Range	Accuracy	Percentage uncertainties
Gas analyzer	NO_X 0–5000 ppm	±10 ppm	±0.1
	HC 0–2000 ppm	± 15 ppm	±0.15
	CO 0–10 %	± 0.02 %	±0.15
	CO_2 0–20 %	± 0.03 %	±0.15
Smoke meter	BSN 0–10	±0.2	±0.12
EGT indicator	0–900 °C	±0.1 °C	±0.13
Load indicator	0–100 kg	±0.1 kg	±0.15
Pressure pickup	0–110 bar	±0.1 bar	±0.1
Crank angle encoder		±0.1°	±0.1

3 Result and discussions

The elevated viscosity of unadulterated vegetable oils as fuels for diesel engines are the main difficulties and this is overcome by amalgamating it with mineral diesel. Tables 2 and 3 present the important physical, chemical and other properties of diesel and *Jatropha curcas* oil. The performance and emission features of *Jatropha curcas* oil and its different blends with diesel fuel operation are observed and compared with baseline diesel and are presented in Figs. 2, 3, 4, 5, 6, 7 and 8.

3.1 Performance analysis

3.1.1 Brake thermal efficiency

Figure 2 presents the disparity of brake thermal efficiency at a variety of engine loads with changed compression ratios. Brake thermal efficiency with jatropha oil and its blends is established to be less than that of pure diesel operation from no load to full load conditions and this disparity is higher at full load condition. For same blends, the performance of the engine is improved considerably with the increase in CR. It can be noticed from Fig. 2a that at CR 16, brake thermal efficiency with jatropha oil and its blends are lesser than that of diesel fuel by 1.25, 3.844, 4.83, 6.88 and 8.837 % with 10, 30, 50, 80 and 100 % jatropha oil blends at 50 % engine loading, and by 1.68, 3.75, 5.34, 6.34 and 8.78 % with 10, 30, 50, 80 and 100 % jatropha oil blends at 87 % engine loading. Figure 2c shows that at CR 18, the brake thermal efficiency with jatropha oil and its blends is lesser than that of diesel fuel by 1.51, 3.37, 4.55, 6.71 and 9.65 % with 10, 30, 50, 80 and 100 % jatropha oil blends at 50 % engine load, and by 1.41, 3.253, 4.73, 5.99 and 8.01 % with 10, 30, 50, 80 and 100 % Jatropha oil blends at 87 % engine load. The brake thermal efficiency of the test engine is low at low engine loads, but significantly high at higher engine loads, because at low loads the amount of fuel requirement is less, which will produce lower in-cylinder pressure. Whereas the increase in the amount of injected fuel leads to increase in load, the in-cylinder pressure and heat release is increased [10]. But at high load, the engine efficiency decreases because of paucity of oxygen with respect to the huge amount of supplied fuel (constant rpm engine at high load) and leads to incomplete combustion.

3.1.2 Brake specific fuel consumption

BSFC means the rate of fuel utilization per unit output. Figure 3 illustrates the consumption of fuel in kg/kWhr with respect to the brake output of the engine. Observations for BSFC at CR 16, 17 and 18 with diesel, jatropha oil and its blends are recorded and represented graphically for analysis. From Fig. 3a, at CR 16, BSFC is found to be higher by 2.58, 4.82, 7.21, 8.28 and 10.21 % with 10, 30, 50, 80 and 100 % jatropha oil blends at 50 % engine load, and by 2.25, 4.52, 5.49, 7.54 and 9.56 % with 10, 30, 50, 80 and 100 % jatropha oil blends at 87 % engine load compared to that of diesel fuel.

Figure 3c illustrates that at CR 18, BSFC with jatropha oil and its blends are greater than that of diesel fuel by 2.54, 5.28, 7.54, 9.87 and 11.03 % with 10, 30, 50, 80 and 100 % jatropha oil blends at 50 % engine load, and by 2.12, 4.32, 6.52, 7.66 and 9.78 % with 10, 30, 50, 80 and 100 % Jatropha oil blends at 87 % engine load. BSFC is higher for tidy diesel fuel operation and increases slowly with increase in jatropha oil substitution in blends. These may be caused by the lofty viscosity and meager volatility of vegetable oils. Figure 3 also demonstrates that BSFC decreases with the increase in engine CR.

3.1.3 *Exhaust gas temperature*

Figure 4 illustrates the effect jatropha oil blends with respect to VCR at different engine load conditions on exhaust gas temperature. Figure 4 explains that with the increase in load and CR, the EGT increases for all the tested fuels. An indication is given by the exhaust gas temperature about the combustion separately, which depends on the blends used in the test and the amount of heat going waste with the exhaust gas [11]. Figure 4b demonstrates that at 65 % engine load, the exhaust gas temperature with blends is lesser than that of diesel by 3.2, 5.4, 8.52, 10.24 and 11.41 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 16, and by 3.01, 5.12, 7.24, 9.57 and 11.27 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 18. From Fig. 4c, at 93 % engine load, the exhaust gas temperature is found to be less by 2.84, 4.82, 6.43, 8.52 and 10.71 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 16, whereas at CR 18, it is found to be less by 2.43, 4.56, 7.21, 10.07 and 11.2 % with 10, 30, 50, 80 and 100 % jatropha oil blends compared to that of diesel fuel. It is clear that the exhaust gas temperature is higher for pure diesel and gradually decreases with increase of jatropha oil concentration in the blends because of the lower calorific value of jatropha oil. Hence, the peak temperature of the cylinder decreases.

3.2 Emission analysis

3.2.1 *NO_X emission*

Figure 5 represents the effect of changing CR and jatropha oil blends with diesel on NO_X emission formed inside the engine cylinder at different engine load conditions. Figure 5 illustrates that the NO_X level increases with increase

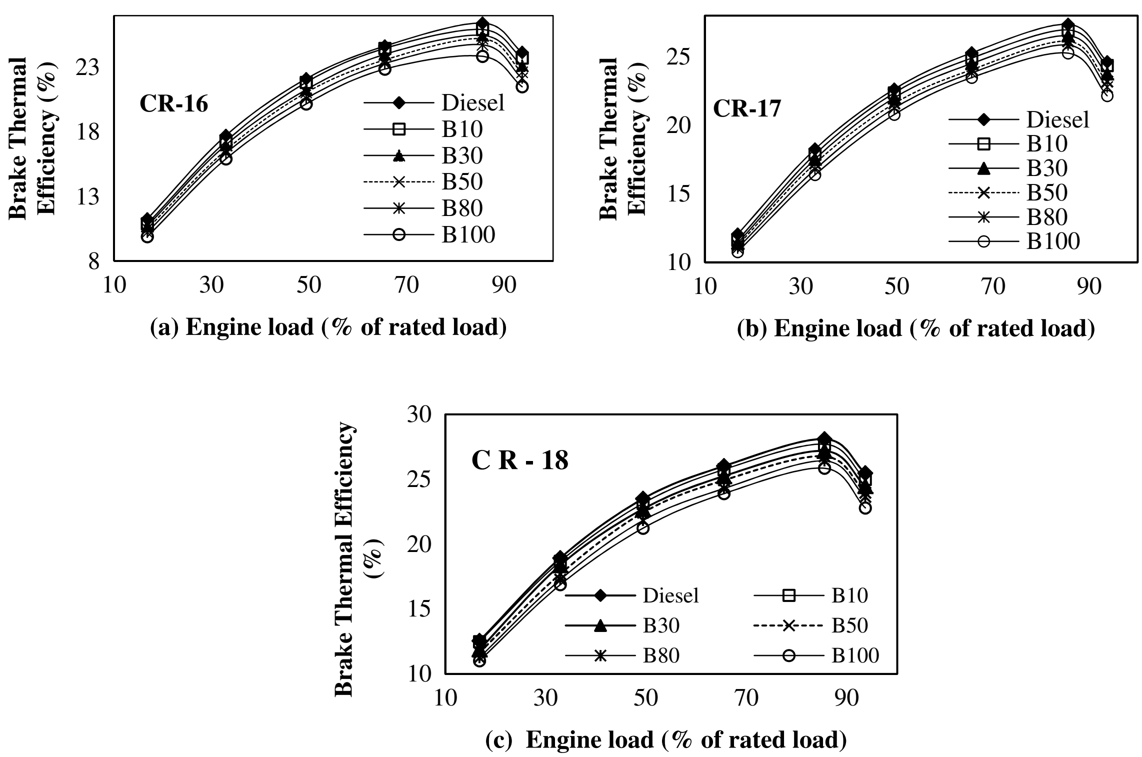

Fig. 2 Brake thermal efficiency with respect to engine load for diesel and different jatropha oil blends at CR = 16, 17 and 18

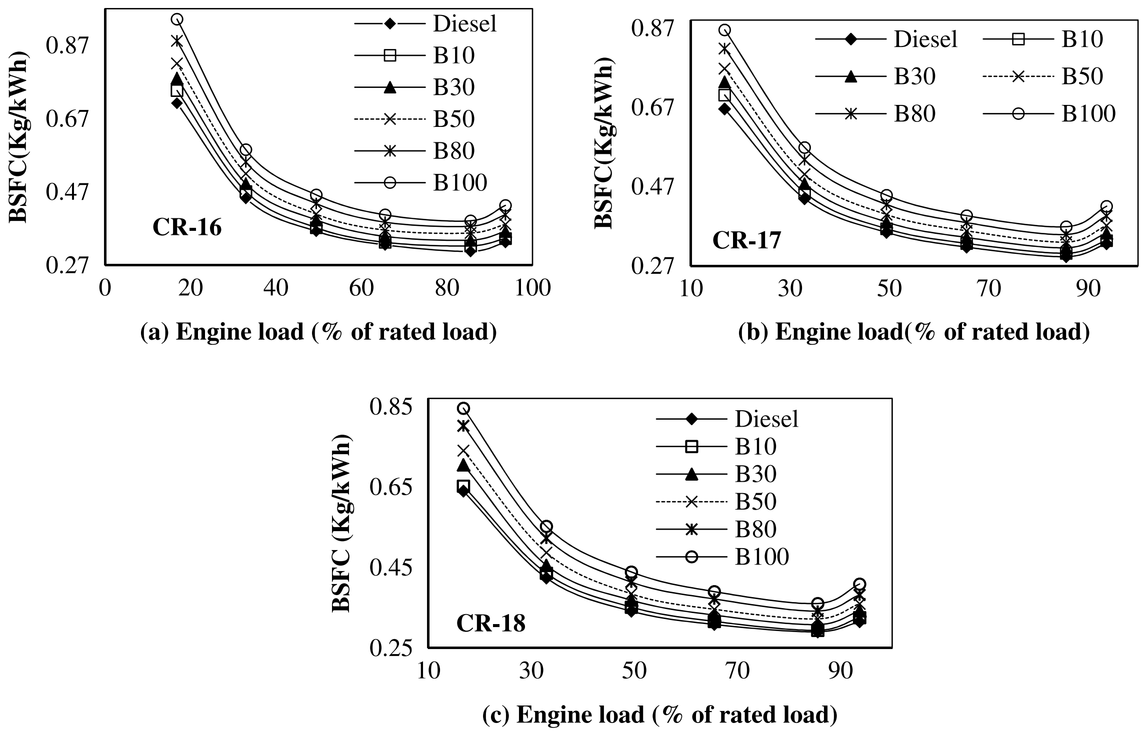

Fig. 3 Brake specific fuel consumption with engine load for diesel and different jatropha oil blends at CR = 16, 17 and 18

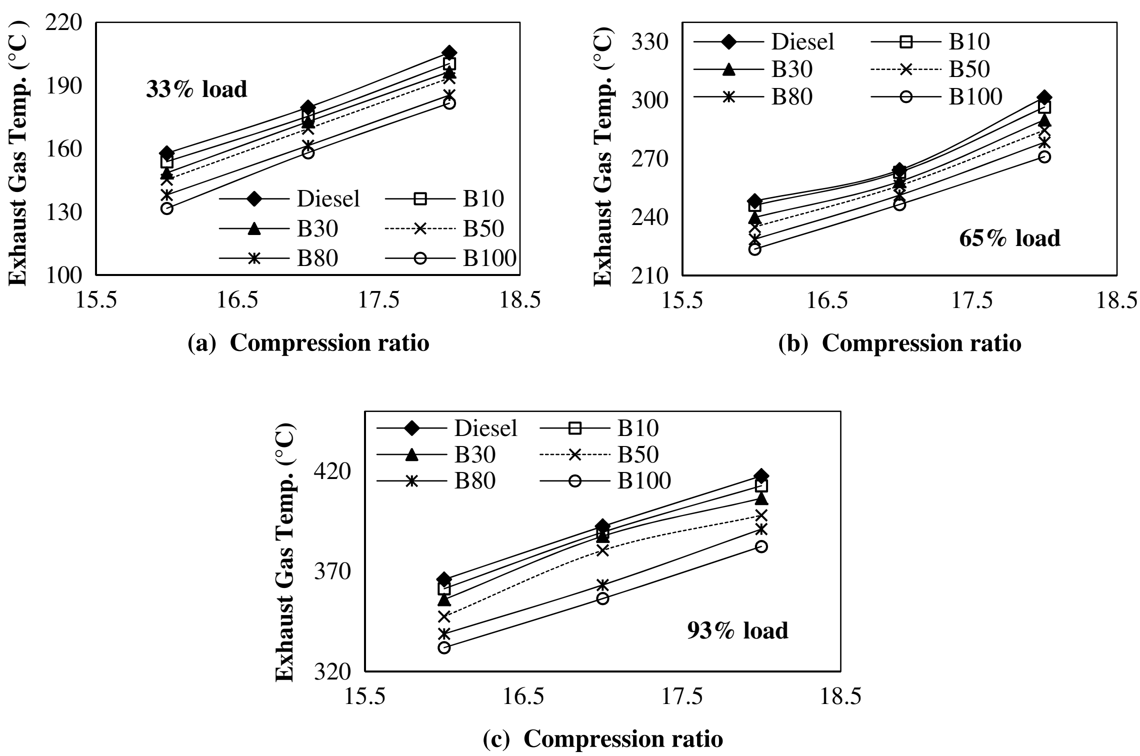

Fig. 4 Effects of compression ratios on exhaust gas temperature for diesel and different jatropha oil blends at 33, 65 and 93 % engine load

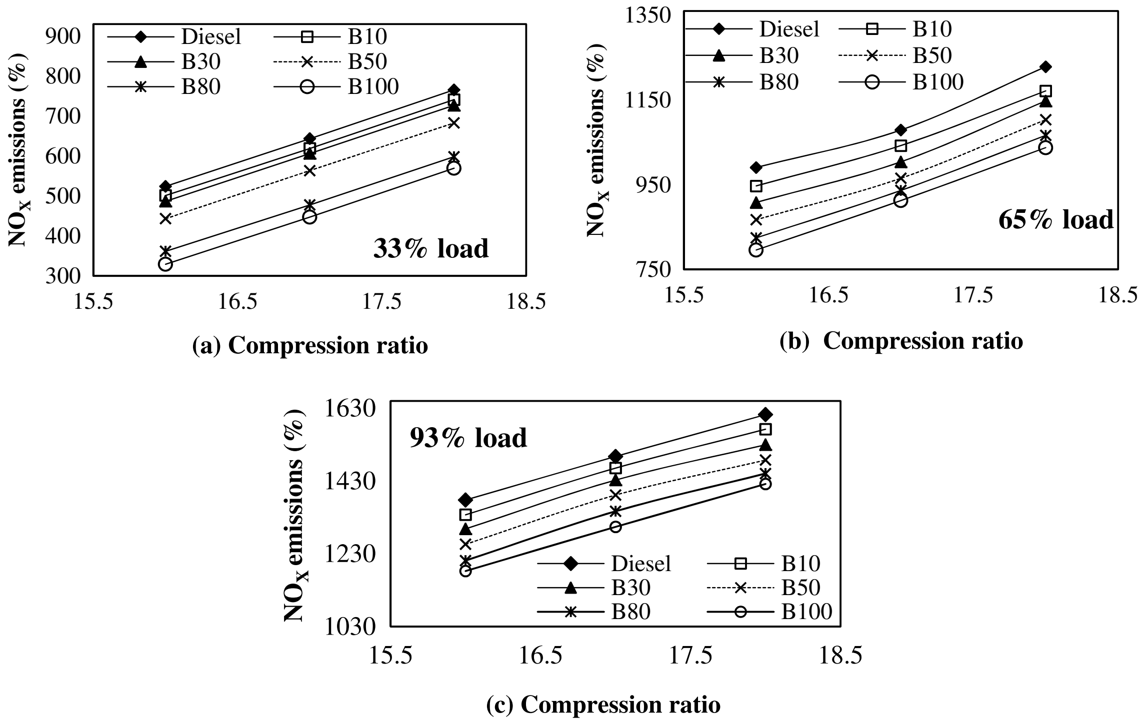

Fig. 5 Variations of NOx emission with respect to VCR for diesel and different jatropha oil blends at 33, 65 and 93 % engine load

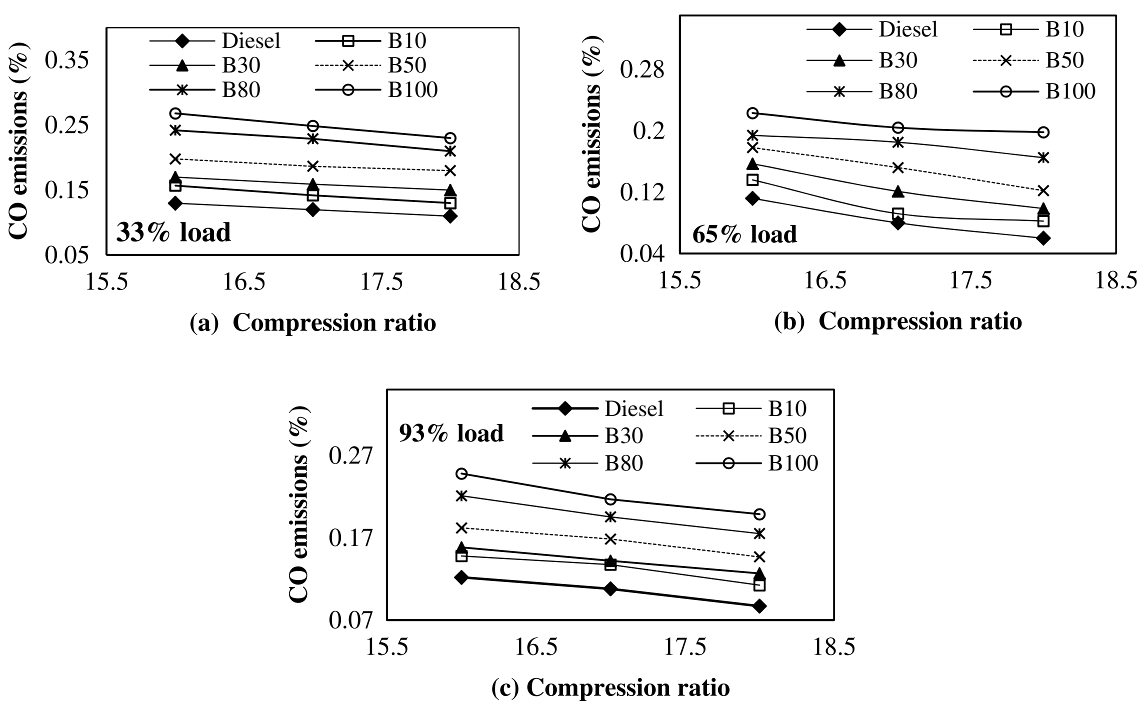

Fig. 6 CO emission with variable CR for diesel and different jatropha oil blends at 33, 65 and 93 % engine load

in engine loads and CR for both diesel and blended fuel operations and also decreases with the increase in jatropha oil percentage in the blends. Figure 5b explains that at 65 % engine load, NO_X emission is reduced by 3.6, 6.1, 9.56, 11.22 and 13.47 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 16, and by 2.8, 5.63, 8.83, 12.11 and

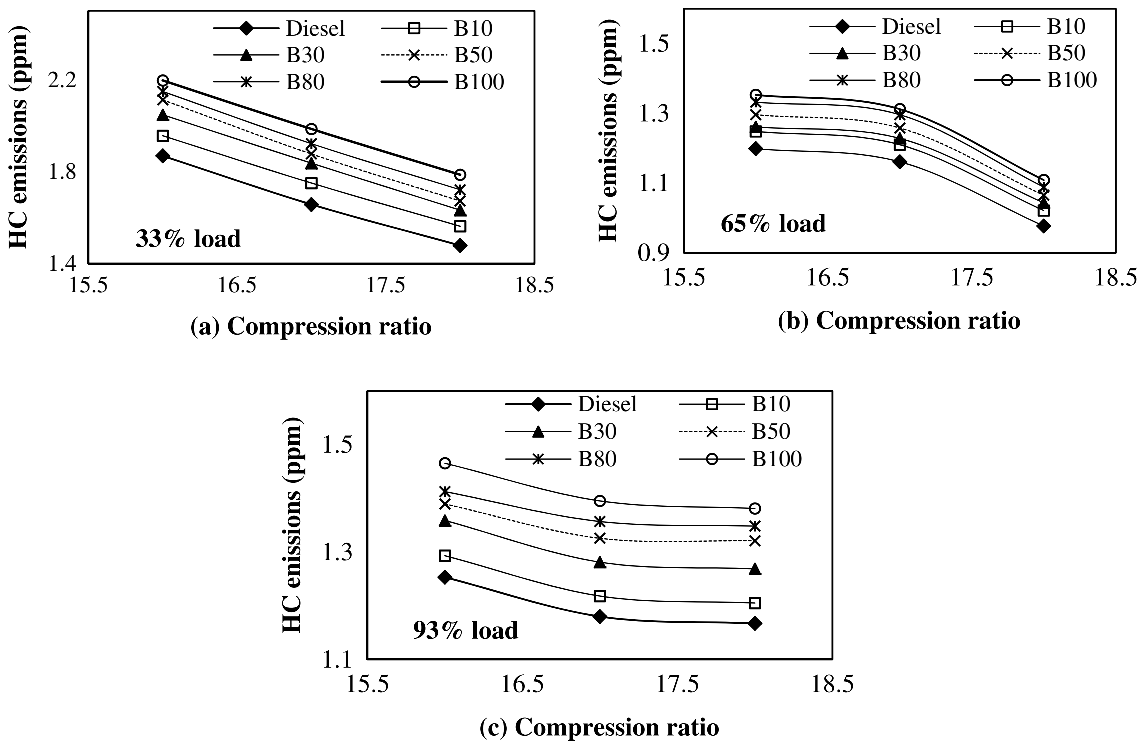

Fig. 7 Variations of HC emission vs VCR for diesel and different jatropha oil blends at 33, 65 and 93 % engine load

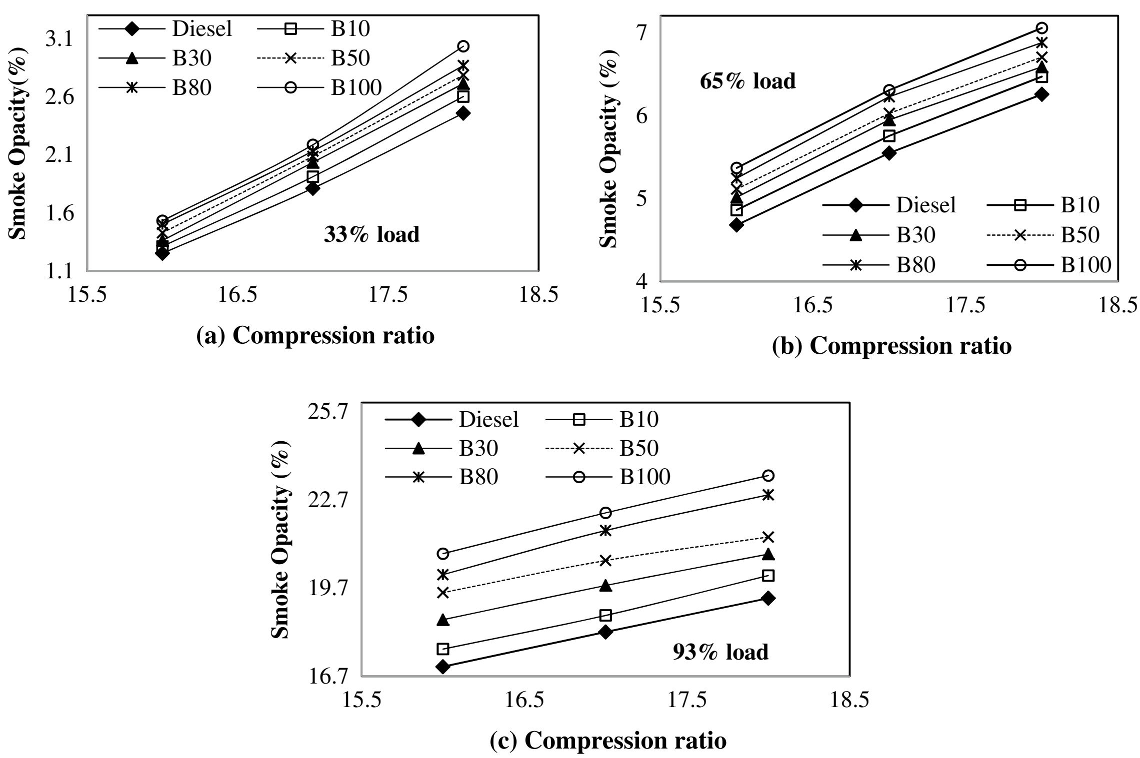

Fig. 8 Effects of compression ratio on smoke opacity for diesel and different jatropha oil blends at 33, 65 and 93 % engine load

13.4 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 18 compared to that of diesel fuel. Figure 5c shows that at 93 % engine load, NO_X emission is decreased by 2.78, 5.76, 8.13, 10.12 and 11.83 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 17, but at CR 18 it is found to be less by 2.11, 6.27, 8.66, 11.33 and 12.4 % with 10, 30, 50, 80 and 100 % jatropha oil blends compared to that of diesel fuel. NO_X emission decreases with the increase in jatropha oil percentage in the blends due to the lower calorific value of jatropha oil, which reduces the peak temperature and pressure of the engine cylinder. The augmentation of CR increases the compression temperature of air, while minimizing the ignition delay of the fuel causing improved combustion characteristics of the blends and resulting in higher NO_X production in the exhaust. NO_X production in the combustion chamber of a CI engine generally depends on the higher combustion temperature, excess oxygen and combustion duration [8].

3.2.2 *CO emissions*

Figure 6 presents the variation of carbon monoxide emission with respect to VCR of the diesel engine using diesel, jatropha oil and its blends at different engine loads. As shown, CO emission decreases with the increase in load; however, it is increased in high engine loads. Since at low engine loads in-cylinder pressure is low, the combustion products cannot be exhausted from the cylinder completely. So, during the next cycle this residual gas (without oxygen) dilutes the fresh air and causes incomplete combustion resulting in higher CO emission. On the other hand at high engine load, more fuel is injected into the cylinder (constant RPM engine) and causes incomplete combustion due to the deficiency of the oxygen resulting in higher CO emission. It increases with increase in jatropha oil concentration in the blends compared to that of diesel, because the higher viscosity and poor volatility of jatropha oil results in poor atomization and combustion characteristics [12]. Figure 6b illustrates that at 65 % engine load, CO emission is increased by 5.93, 10.15, 14.87, 18.73 and 20.21 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 16, and by 5.25, 7.6, 11.59, 17.1 and 20.4 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 18 compared to that of diesel fuel.

Figure 6c explains that at 93 % engine load, CO emission is increased by 5.23, 10.31, 14.1, 17.3 and 19.23 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 16, and by 5.16, 9.87, 14.05, 17.85 and 19.57 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 18 compared to that of diesel fuel. CO is an intermediate product in the combustion of hydrocarbons. It is formed mainly due to incomplete combustion, which is exacerbated by lack of oxidants, temperature and residence time. Unfinished burning of any hydrocarbon fuel is accountable for the creation of CO [11]. Whereas the increase in CR leads to decrease in delay period, it results in lower CO emission.

3.2.3 *HC emission*

Figure 7 depicts the variation of unburned HC emission for diesel, jatropha oil and its blends at different engine loads with respect to VCR. HC concentration in the exhaust of the diesel engine decreases with load applied for both diesel and blended fuel forms. It is higher for blended fuel than pure diesel operation and further increases with increase in jatropha oil concentration at all load conditions of the engine due to poor atomization of blends because of its high density and viscosity [5], which causes incomplete combustion of fuel and promotes HC emission. The ignition delay period can be reduced by increasing the compression ratio and so, the combustion duration is increased. Apart from that, the closer contact between the molecules of fuel and oxygen reduces the time of reaction due to the higher compression ratio. Figure 7b explains that at 65 % engine load, HC emission with blended fuels is higher than that of diesel fuel by 3.1, 5.32, 7.85, 9.05 and 10.84 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 16, and by 3.85, 4.7, 6.93, 8.27 and 10.35 % with 10, 30, 50, 80 and 100 % Jatropha oil blends at CR 18. Figure 7c demonstrates that at 93 % engine load, HC emission with blended fuels is higher than that of diesel fuel by 3.51, 5.2, 7.82, 9.32 and 11.87 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 16, and by 2.52, 4.2, 7.14, 8.61 and 9.23 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 18.

3.2.4 *Smoke emission*

The variations of smoke opacity as a function of engine load are given in Fig. 8 at VCR for both diesel fuel and blended fuel operations. From Fig. 8, it is obvious that smoke opacity increases with increase in jatropha oil concentration in the blends and CR of the engine. Figure 8b explains that at 65 % engine load, smoke opacity is increased by 2.57, 3.18, 4.35, 5.87 and 6.5 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 16, whereas it is increased by 3.36, 5.82, 7.08, 9.4 and 11.23 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 18 d compared to that of diesel fuel. From Fig. 8c, at 93 % engine load, smoke opacity is found to be higher by 3.82, 5.56, 7.92, 8.38 and 10.3 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 16, and by 4.1, 5.32, 7.78, 9.34 and 11.32 % with 10, 30, 50, 80 and 100 % jatropha oil blends at CR 18 compared to that of diesel fuel. It is also noted that smoke decreases at medium loads, but increases at high loads. At high load, smoke opacity increases because of paucity of oxygen with respect to the huge amount of supplied fuel leading to incomplete combustion. Smoke is produced in the rich mixture zone in the combustion chamber due to elevated viscosity, resulting in a larger fuel droplet size [11]. It is more for blended fuel compared to that of pure diesel operation. Also, it is clear that smoke opacity increases with the increase in jatropha oil concentration at all conditions. This is due to poor atomization and combustion characteristics of jatropha oil and its blends [8].

4 Conclusions

In the present study, the VCR engine is fueled with jatropha oil blends as alternative fuels and conclusions of the study are given below:

- Brake thermal efficiency with jatropha oil and its blends is found to be less than that of pure diesel operation from no load to full load conditions, and this disparity is higher at full load condition. For the same blend, the performance of the engine is improved considerably with the increase in CR.
- With the increase in brake power and CR, the EGT increases for all the tested fuels.
- The NO_X level increases with increase in engine loads and CR for both diesel and blended fuel operations.
- There is a smaller amount of CO emission at low engine loads, but increases significantly at high engine loads and with increase in jatropha oil concentration in the blends compared to that of diesel and also decreases with increase in CR.
- Thermal efficiency, exhaust gas temperature and emission parameters such as NO_X and CO at CR 18 with blends containing up to 30 % (by volume) jatropha oil is comparable to that of the diesel fuel.
- So, blends containing up to 30 % (by volume) jatropha oil at CR 18 can be used as an alternative fuel without any engine modification.

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