Effect of Compression Ratio on Performance, Combustion and Emission Characteristics of a Diesel Engine Fueled with Rubber Seed Biodiesel–Diesel Blends

Chinmoy Jit Sarma, Bhaskor J. Bora, Dilip K. Bora, and Bhaskar J. Medhi

Nomenclature

BSEC	Brake-specific energy consumption
BTE	Brake thermal efficiency
CO	Carbon monoxide
CO_2	Carbon dioxide
CR	Compression ratio
EGT	Exhaust gas temperature
HC	Hydrocarbon
IC	Internal combustion
NHRR	Net heat release rate
NOx	Nitrogen oxides
PCP	Peak cylinder pressure
RBD	Rubber seed biodiesel
VCR	Variable compression ratio

C. J. Sarma · B. J. Bora (✉) · B. J. Medhi
Assam Energy Institute, Sivasagar, Center of Rajiv Gandhi Institute of Petroleum Technology, Sivasagar, Assam 785697, India
e-mail: bjbora@rgipt.ac.in

Energy Institute, Bengaluru, Center of Rajiv Gandhi Institute of Petroleum Technology, Bengaluru, Karnataka 561003, India

D. K. Bora
Department of Mechanical Engineering, Assam Engineering College, Jalukbari, Guwahati, Assam 781013, India

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1 Introduction

Internal combustion (IC) engines can be considered as one of the panaceas for power production. IC engines have got wide industrial applications and in transportation sector. Biodiesel can be utilized as an alternate fuel in any diesel engine without making any engine design change and is also eco-friendly [1]. India experimented the first biodiesel run flight from Delhi to Dehradun on 27th of August 2018 [2].

Biomass can be considered as solar energy stockpiled in the form of organic matter like plants or animal remnants having a net positive worth as a chemical reserve [3]. Biodiesel is produced from oils or fats through chemical conversion process, and it resembles diesel in terms of fuel properties. Biodiesel is identified as a potential candidate to substitute petroleum diesel, and therefore, it is drawing worldwide attention in research and development. One of the benefits of using biodiesel is that it does away with the intolerable odor and black smoke of diesel fuel. Biodiesel promotes burning of the hydrocarbons in a blend as it contains about 11% oxygen. Biodiesel run diesel engines emit less carbon monoxide (CO) and thus reduce air pollution and hence are less harmful in comparison to conventional diesel fuel. Spillage of biodiesel results in less environmental sabotage as it is biodegradable in equivalence to conventional diesel.

Keeping in mind the fact of depletion of petroleum reserves and surge in environmental pollution, biofuels can substitute to diesel as is renewable and environmentally friendly. Among different types of biofuels available, rubber seed biodiesel seems to offer a tremendous potential. India produces about 5000 tons of rubber seed oil per annum [4]. The chemical and physical characteristics of rubber seed biodiesel resemble to that of diesel fuel.

Vegetable oils have comparable intensity of energy use, cetane number, and latent heat of vaporization with that of diesel. They emit less hazardous gases and are environmentally benign. But, due to their high viscosity, fuel pulverization is inadequate which results in partial burning. The thickness of the biofuels can be curtailed by mixing it with diesel. The thickness of biofuels can be curtailed by directly mixing with diesel, preheating, and transesterification. Senthil et al. [5] curtailed the thickness of rubber seed oil by mixing it with diesel in various percentages, tested its thickness at different temperatures and run a diesel engine with it. The resultant brake thermal efficiencies (BTEs) were 28.64, 27.74, 26.82, and 26.2% for B25, B50, B75, and B100 and that obtained for diesel mode at full load is 29.92%. Due to slow burning of vegetable oils, exhaust gas temperature (EGT) exhibited is greater with all mixtures of rubber seed oil (RSO) at 100% load in correlation to diesel oil. For RSO and its blend, carbon monoxide (CO) and hydro carbon (HC) emissions are maximum at full load, and for B25 biodiesel blend, CO, NO, and HC emissions are optimal. Geo et al. [6] evaluated the performance of RSO, rubber seed oil methyl ester (RSOME) run diesel engine run with diesel as a primary fuel, and hydrogen as an added fuel at 25, 50, 75, and 100% load conditions. The pre-blend burning rate increases due to addition of hydrogen which raises the BTE. At 100% load, the BTE of RSO and RSOME raises from 26.56 to 28.12% and 27.89

to 29.26% with hydrogen addition. HC and CO emission decreases for all loads because of addition of hydrogen; however, NOx emission raises due to the rise in burning temperature because of the high pre-blend burning. Geo et al. [7] studied the performance of rubber seed oil with diethyl ether (DEE) addition run diesel engine at various injection rates. Due to addition of DEE in RSO, the BTE of the engine raises, and maximum BTE obtained is 28.5% at 200 g/h injection rate of DEE. HC and CO emission decreases due to addition of DEE; however, NO_x emission raises due to raise in pre-blend heat release rate. Patil et al. [8] evaluated the performance of RSME diesel blend run diesel engine with fractional addition of butanol. BTE, exhaust gas temperature, carbon dioxide (CO_2), and NO_x emission rises with rise in engine load. Krishna et al. [9] evaluated the performance and emission characteristics of rubber seed biodiesel with diethyl ether (DEE) addition run semi-adiabatic diesel engine (SADE) with EGR (exhaust gas recirculation). Low values of BTE with raise in brake-specific energy consumption (BSEC), EGT and NOx emissions were obtained when the blend A15B85 (additive DEE 15% + rubber seed biodiesel 85%) is run in an ordinary diesel engine (ODE). When the blend A15B85 is run in a SADE, BTE increased, & BSEC, EGT, cylinder pressure values decreased with advancement in start of injection (SOI) timing; however, NOx emission continues to rise due to raise in pre-blend heat release rate. Xuan et al. [10] evaluated the performance, combustion, and emission parameters by adding 10% dimethylfuran (DMF) with petrol in spark-ignition engine or with diesel in compression ignition engine and found that the results obtained were better than pure petrol or diesel. Swarup et al. [11] evaluated the emission parameters of producer gas produced from waste babul wood pieces-blended Jatropa biodiesel in single as well as dual fuel mode diesel engines at gas flow rate of 21.69 kg/h. CO_2, CO, and hydrocarbon emission level rises with rise in load in dual fuel mode, however, NOx and smoke emission level drops with rise in engine load. Swarup et al. [12] evaluated the emission parameters of Jatropa oil methyl ester-blended biodiesel in a diesel engine. CO, HC, and NO emission level for the blend was lesser than that of conventional diesel, whereas smoke darkness was higher for the biodiesel blend because of high thickness, low volatility, and low calorific value of the blend.

The exhaustive literature highlights that no literatures have been reported on the effect of the operating parameter such as compression ratio on the performance and emission characteristic of a rubber seed biodiesel run diesel engine. This forms the basis of the present study.

2 Materials and Methods

A 3.5 kW, single cylinder, four stroke, water cooled, direct injection, stroke length 110 mm, bore 87.5 mm, 661 cc variable compression ratio (VCR) diesel engine (Compression ratio ranging from 12 to 18) operating at 1500 rpm and having injection timing variation option from 0° to 27° BTDC has been considered as test setup as

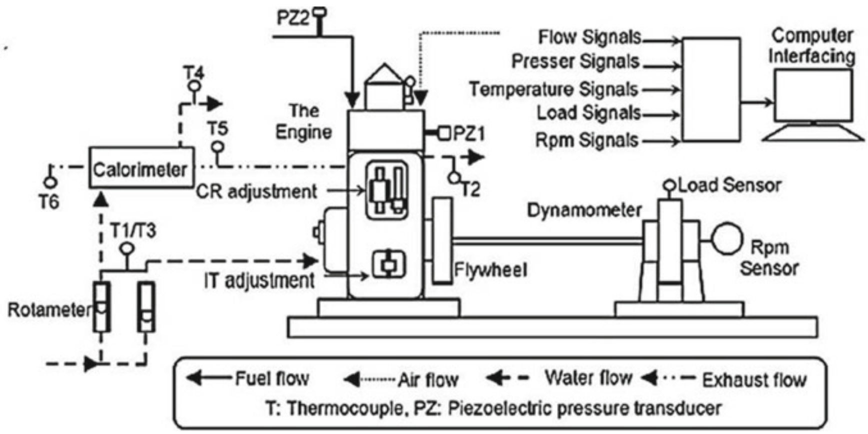


Fig. 1 Schematic diagram of the VCR engine setup

shown in Fig. 1. The description of the test setup is already discussed in the previous study [13].

Rubber seed biodiesel (RBD) is considered for the study as it is non-edible oil. The emission investigation is performed by a flue gas analyzer made of Testo. The flue gas analyzer specifications are given in Table 2. The working of the gas analyzer is discussed in the previous work [13]. The characteristic properties like density, calorific value, cetane number, flash point, and fire point of RBD are 875 kg/m^3, 39.73 MJ/kg, 52.6, 420, and 440 K, respectively, while that for conventional diesel are 840 kg/m^3, 42 MJ/kg, 45–55, 346, and 355 K. The performance, combustion, and emission parameters are evaluated for three different compression ratios (CRs) of 17, 17.5, and 18 at standard injection timing of 23° BTDC for 100% RBD by varying the engine load from 20 to 100%, and the outcomes have been matched with the outcomes attained for 100% diesel at standard CR of 17.5 for the same loads (Tables 1, 2, 3 and 4).

The relative errors of independent variables as well as the uncertainty linked with various performance parameters are given in Tables 5 and 6.

Table 1 Engine specifications

Engine	Make Kirloskar, single cylinder, 4 stroke, water cooled, stroke 110 mm, bore 87.5 mm, 661 cc
	Diesel mode: 3.5 KW@ 1500 rpm, CR range 12-18. Injection variation:0–27^0 BTDC

Table 2 Gas analyzer specifications

Sensors	Sensor type/range/repeatability/resolution
CO	Electrochemical /0–10000 ppm/' ± 5% of reading for < 200 to 2000 ppm, ± 10% of reading up to > 2000 ppm, ± 10 ppm for 0 to 199 ppm/ ± 1 ppm
CO_2	INFRARED /0–20% v/v/ ± 1%/ ± 0.1% v/v
NO	Electrochemical/0–4000 ppm/' ± 5% of reading up to < 2000 ppm, ± 10% of reading up to > 2000 ppm/ ± 1 ppm
HC	Electrochemical/methane: 100 to 40,000 ppm, propane: 100 to 21,000 ppm, butane: 100 to 18,000 ppm/ ± 2%/10 ppm

Table 3 Fuel properties

Properties	Diesel	RBD
Chemical composition	C12H26	C18.05 H34.7 O_2*
Density (kg/m3) at 298 K and 1 atm	840	875
Lower calorific value (MJ/kg)	42	39.73
Cetane number	45–55	52.6
Flash point (K)	346	420
Fire point (K)	355	440

Table 4 Experimental matrix

Mode	Fuel used	CR	IT	Loading condition
Diesel	100%	17.5	23°	20% (BP = 0.7 kW),
	Diesel			40% (BP = 1.4 kW),
Biodiesel	100% RBD	18	BTDC	60% (BP = 2.1 kW),
		17.5		80% (BP = 3.8 kW),
		17		100% (BP = 3.52 kW)

Table 5 Relative errors of independent variables

Independent variable	Relative error (%)
Engine speed	0.5
Engine load	0.5
Liquid fuel flow rate	1
LHV of liquid fuel	1
CO, CO_2, NO_X, and HC emissions	3

Table 6 Uncertainty linked to various performance parameters

Parameters	Uncertainty (%)
BTE	1.5
BSFC	1.5

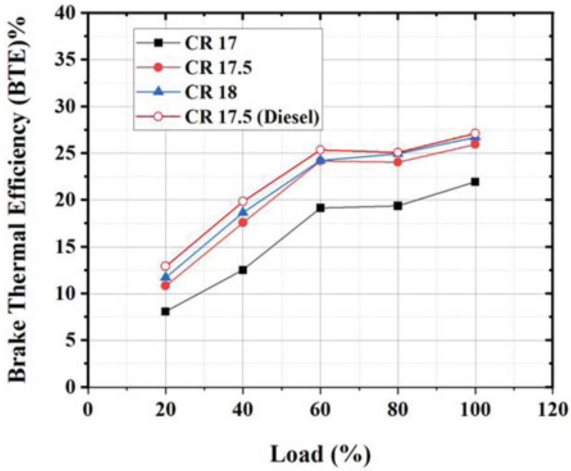


Fig. 2 BTE at different load for CR 17, 17.5,18

3 Results and Discussion

The current study has evaluated the performance, combustion, and emission characteristics of a rubber seed biodiesel run diesel engine at CR of 17, 17.5, and 18, respectively.

3.1 Performance Analysis

From Fig. 2, it is evident that for RBD brake thermal efficiency (BTE) increases for CR 17, 17.5, 18 as load increases from 20 to 100%. Whereas for diesel at standard CR of 17.5, BTE increases with increase in load from 20 to 60%, from 60 to 80% load increase BTE decreases, and again, BTE increases from 80 to 100% load increase. At 100% load, the BTEs are found to be to be 26.71, 25.97, and 21.93% for CRs of 18, 17.5, and 17, respectively, for biodiesel mode in contrast to 27.11% under diesel mode. From Fig. 3, it is evident that for RBD exhaust gas temperature (EGT) increases for CR 17, 17.5, 18 as load increases from 20 to 100%. Whereas for diesel at standard CR of 17.5, EGT increases with increase in load from 20 to 80% and from 80 to 100% load increase EGT decreases.

3.2 Combustion Analysis

From Fig. 6, it is evident that when the engine is running with RBD, less net heat is released than in diesel mode because of low heating value of RBD than diesel. The

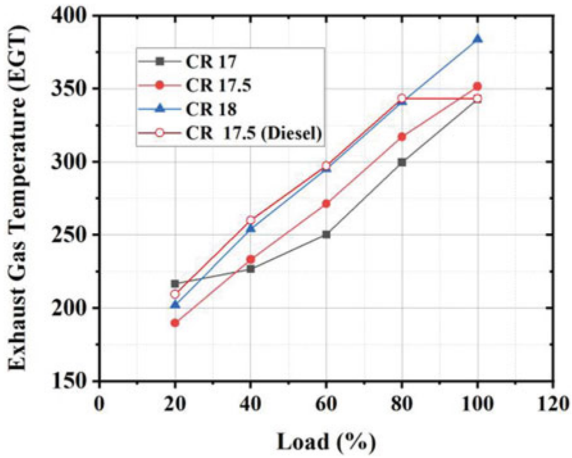


Fig. 3 EGT at different load for CR 17, 17.5, 18

net heat release rate (NHRR) at 100% load for RBD at CR of 17, 17.5, and 18 is 25.26, 41.95, and 47.6 J/deg.CA and that for diesel is 51.43 J/deg.CA at CR of 17.5. It can thus be concluded that as CR is raised NHRR also raises. From Fig. 4, it is evident that when the engine is running with RBD, peak cylinder pressure (PCP) is less than when the engine is running with diesel for all the CRs. It is also evident form Fig. 5 that the PCP approaches toward TDC with rise in CR when the engine is running with RBD. When the engine is running with RBD, as CR raises PCP also raises. The PCP rises with the rise of CR in RBD mode. It has been found that when the engine is running with RBD, PCP falls by 24.64, 22.67, and 20.44% for CRs of 17, 17.5, and 18. Similar findings on the variation of BTE, EGT NHRR, and PCP with the change of compression ratio have been reported by previous study [13] (Fig. 6).

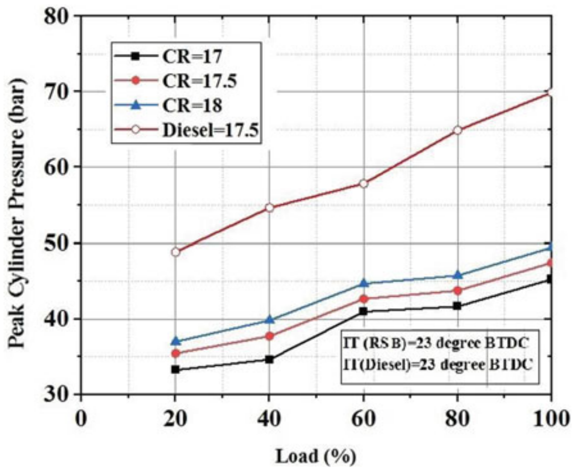


Fig. 4 Peak cylinder pressure at various loads for different CR

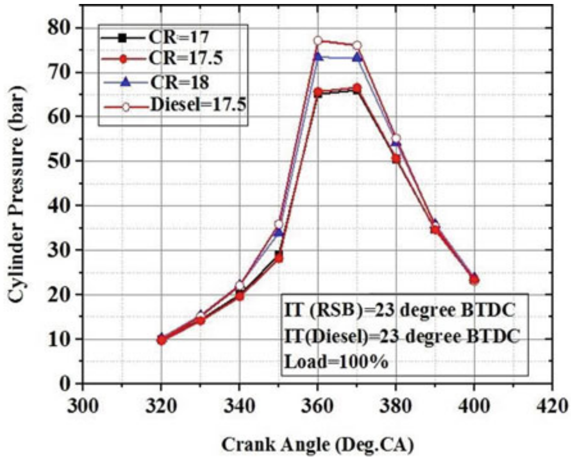


Fig. 5 Cylinder Pressure at different crank angles for CR 17, 17.5, 18

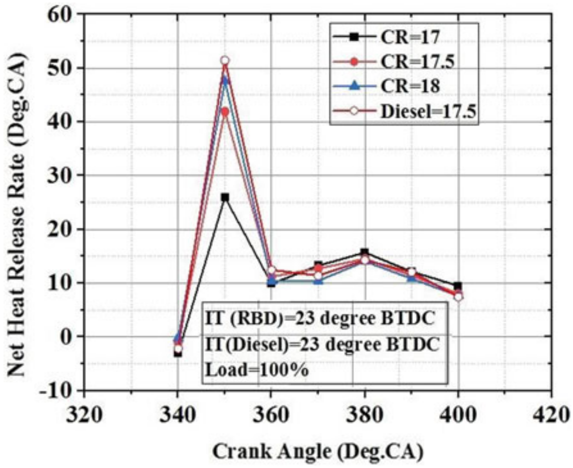


Fig. 6 Neat heat release rate at different crank angles for CR 17, 17.5, 18

3.3 Emission Analysis

In Fig. 7, it is evident that for RBD at CR 17.5, CO emission decreases when load increases from 20 to 80%, and when the load is further increased from 80 to 100%, CO emission increases. Whereas, for diesel, CO emission exponentially increases as load increases from 20 to 100%, but its values are much lower than RBD. HC emission for both RBD and diesel decreases with increase in load from 20 to 80% and from 80 to 100% load increase HC emission increases. The nitrogen oxides (NO_x) emission for RBD increases with increase in load from 20 to 60%, from 60 to 100% load increase NO_x emission remains constant. Whereas, for diesel, NO_x emission slightly decreases as load increases from 20 to 40% and beyond that NO_x emission exponentially increases as load increases from 40 to 100%. CO_2 emission remains almost constant and low as load is raised for both RBD and diesel. From Fig. 8, this is evident for RBD at CR 18, CO emission increases when load increases from 20 to 80%, and when the load is further increased from 80 to 100%, CO emission decreases. Whereas, for diesel, CO emission exponentially increases as load increases from 20 to 100%. HC emission for both RBD and diesel decreases with raise in engine load from 20 to 80%, and from 80 to 100% load increase, HC emission increases. For both RBD and diesel, NO_x emission first rises with increase in load from 20 to 40%; NO_x emission level falls with increase in load from 40 to 80%, and NO_x emission again rises with rise in load from 80 to 100%. CO_2 emission remains almost constant, and low as load is raised for both RBD and diesel. From Fig. 9, this is evident for RBD at CR 17, CO emission levels are higher than diesel mode from 20 to 60% load increase, and beyond 60% load increase, CO emission levels are much lower than diesel. HC emission for RBD as well as for diesel drops with rise in engine load from 20 to 80% and beyond 80% load increase HC level slightly surges up; however, the HC emissions for RBD are slightly higher than diesel at all loads. NO_x emissions for RBD rise with rise in engine load from 20 to 60%, and beyond 60% load increase, NO_x emission remains constant, whereas for diesel NO_x emission level drops with rise in engine load up to 40%, and beyond 40% load increase, NO_x emission level rises. However, NO_x emission level for RBD at all loads is higher than diesel. CO_2 emission remains almost constant & low when load is raised for RBD & diesel. Similar trend on the variation of CO, NO_x, and HC emission with the change of compression ratio has been reported by previous study [13].

In summary, BTE for RBD mode raises with rise in engine load for CR 17, 17.5, and 18, respectively. BTE for diesel mode raises with rise in engine load from 20 to 60%; further, increase in engine load from 60 to 80% shows a fall in BTE; again, further increase in engine load 80–100% shows rise in BTE. At 100% load, the BTEs are found to be to be 26.71, 25.97, and 21.93% for CRs of 18, 17.5, and 17 under biodiesel mode in contrast to 27.11% under diesel mode.

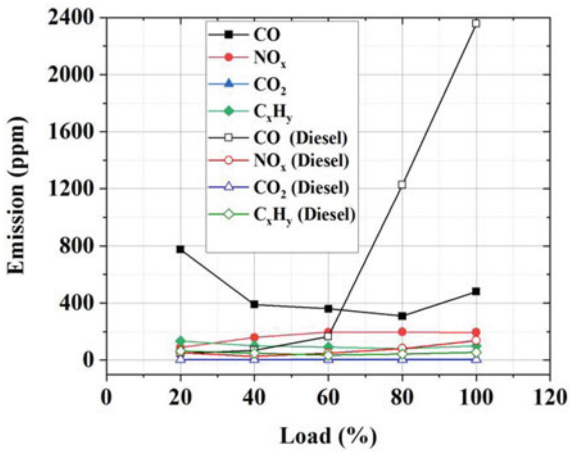


Fig. 7 Emission at different load for CR 17.5

Fig. 8 Emission at different load for CR 18

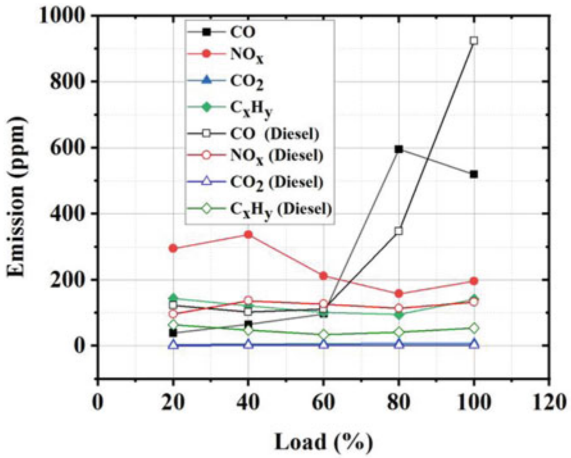
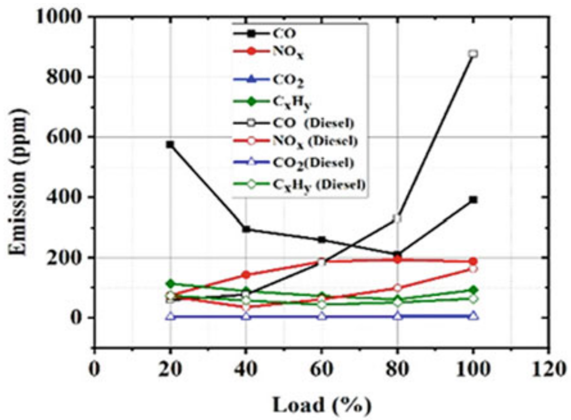


Fig. 9 Emission at different load for CR 17



For RBD, exhaust gas temperature (EGT) increases for CR 17, 17.5, and 18, respectively, as load increases from 20 to 100%. Whereas, for diesel at standard CR of 17.5, EGT increases with increase in load from 20 to 60%, from 60 to 80% load increase EGT decreases, and again, EGT increases with 80–100% load increase. When the engine is running with RBD, less net heat is released than in diesel mode because of low heating value of RBD than diesel. NHRR at full load for RBD at CR of 17, 17.5, and 18, respectively, is 25.26, 41.95, and 47.6 J/deg.CA and that for diesel is 51.43 J/deg.CA at CR of 17.5. It can thus be interpreted that as CR is raised NHRR also raises for RBD mode.

It is evident that when the engine is running with RBD, PCP is less than when the engine is running with diesel for all the CRs. It is also evident that the PCP approaches toward TDC with rise in CR when the engine is running with RBD. When the engine is running with RBD, as CR raises, PCP also raises. The PCP rises with the rise of

CR for RBD mode. It has been found that when the engine is running with RBD, PCP falls by 24.64%, 22.67%, and 20.44% for CRs of 17, 17.5, and 18, respectively.

For RBD at CR of 17 and 17.5, with raise in engine load from 20 to 80%, CO emission rate drops, and when the load is further raised from 80 to 100%, CO emission rate increases. For RBD at CR of 17 and17.5, HC emission increases with increase in load from 20 to 60%; from 60 to 80% load increase, HC emission decreases, & again, HC emission increases from 80 to 100% load increase. For RBD at CR of 17, NOx emission rate raises with raise in engine load from 20 to 80%; from 80 to 100% load increase, NOx emission rate decreases. For RBD at CR of 17.5, NOx emission rate raises with raise in engine load from 20 to 60%; from 60 to 100% load increase, NOx emission remains constant.

4 Conclusions

The present study investigates the effect of compression ratio on the performance, combustion, and emission characteristic of a rubber seed biodiesel run diesel engine. Rubber seed biodiesel can be utilized in a diesel engine as an alternative fuel as the results in laboratory is interesting. The efficiency rises with the use of high compression ratio 18:1 for rubber seed biodiesel. At CR 18, CO emission slightly increases when load increases from 20 to 80%, but when the load is further increased from 80 to 100%, CO emission decreases. Emission rate of HC marginally rises with raise in engine load. With raise in engine load from 20 to 40%, NOx emission rate increases; with further rise in engine load from 40 to 80%, NOx emission rate actually drops, therefore using this fuel at high load capacity (say ~80%) seems beneficial.

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