

An experimental investigation to study the effect of fuel additives and exhaust gas recirculation on combustion and emissions of diesel–biodiesel blends

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Abstract Cetane improver, Di-Tertiary Butyl Peroxide (DTBP), is used as a fuel additive to diesel–biodiesel blends to investigate the effect of exhaust gas recirculation (EGR) on diesel engines. Experiments were conducted on a single-cylinder, four-stroke and direct injection diesel engine with the said fuels using EGR to investigate the effect of fuel additive and EGR. The results reveal that the ignition of biodiesel blends is advanced by a few degrees crank angle (CA) and consequently peak pressure is pre-poned by 2–3° and also the combustion is finished earlier than that of diesel. With increase in the percentage of both biodiesel and DTBP, carbon monoxide (CO) and hydro carbon (HC) emissions were reduced considerably. CO emission reduction of 17–19 % and HC emission reduction of 23–25 % were observed with biodiesel with fuel additive when compared to that of diesel. With the combined effect of EGR and DTBP, NO_x emissions were reduced by 33–35 % when compared to pure diesel without EGR. Smoke increase of 9 % was observed with EGR when compared to conventional diesel engine.

Keywords Biodiesel blends · Combustion characteristics · DTBP · EGR · Emissions

1 Introduction

Faster depletion and increased emission of fossil fuels are the motivating factors for the development of alternative energy sources. Biodiesel is gaining momentum as an alternative to petroleum diesel, since the properties of the biodiesel are close to that of diesel. Biodiesel entails some advantages over diesel as the former has in-built oxygen, which helps in reducing the emissions like CO, HC and Particulates [1–3]. However, higher viscosity of biodiesel affects some processes such as atomization, vaporization and fuel–air mixing [4]. Furthermore, increased NO_x on the other hand is another disadvantage associated with biodiesel usage [5].

Addition of certain fuel additives to biodiesel is imperative for effective atomization and fuel–air mixing, since the properties of biodiesel affect the engine performance, combustion and emissions [6]. Fuel injection timing is an important parameter that influences the combustion and exhaust emissions of the diesel engines. If the fuel injection timing is advanced, the initial temperature and pressure of the air will decrease, which in turn increases the ignition delay (ID) period. The increase in ID period results in increased premixed burning phase and hence increases cylinder gas temperature thereby increasing NO_x emissions. ID period can be reduced by the addition of fuel additives [7].

So many fuel additives such as oxygenates, bio-additives and cetane number improvers have been used. Cetane number is actually a measure of a fuel's ignition quality. Ignition delay periods of higher cetane fuels are shorter

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than that of lower cetane fuels in a particular diesel engine [8]. Reduced ignition delay resulting from the addition of cetane improver can reduce the NO_x emissions by lowering the combustion temperatures [9]. And also, cetane number improver in combination with oxygenates improves the engine performance in addition to the reduction in emissions [10]. Two types of cetane improvers are widely used: (1) 2-Ethyl Hexyl Nitrate (EHN) (chemical formula: $\text{C}_8\text{H}_{17}\text{NO}_3$) and (2) Di Tertiary Butyl Peroxide (DTBP) (chemical formula: $\text{C}_8\text{H}_{18}\text{O}_2$). DTBP is known to reduce emissions such as CO, HC and NO_x in diesel engines [11].

However, these additives can reduce the NO_x emissions marginally. EGR is an effective way of reducing NO_x . EGR is recirculation of a part of the exhaust gases into the intake manifold, which helps in reducing the NO_x with the charge dilution effect [12]. Significant reductions in NO_x emission were observed with the increased EGR rates [13, 14]. However, this reduction is accompanied by deterioration in engine performance with an increase in other emissions such as CO, HC and particulates. Exhaust after-treatment techniques, such as diesel oxidation catalysts and soot traps can be coupled with EGR to reduce its negative effects [15]. In the present work, the combined use of EGR and DTBP is considered for improving the combustion and emissions when diesel–biodiesel blends are used as fuels.

2 Materials and methods

In the present experimental investigations, biodiesel derived from fish oil by transesterification is used for blending with diesel in varying proportions. Transesterification of fish oil is carried out to prepare biodiesel. Figure 1 shows the setup used for preparation of biodiesel by transesterification.



Fig. 1 Transesterification set-up for biodiesel production

Usually, biodiesel is prepared via two routes: one is acid-catalyzed transesterification and the other is alkali-catalyzed transesterification. In this study, the second method is used for the preparation of biodiesel. 50 g of the oil is poured into a container equipped with a mechanical stirrer and placed in a water bath. Then, a freshly prepared catalyst solution is introduced into the reactor. The solution is prepared in such a way that it consists of potassium hydroxide (KOH) by 0.5 wt % and raw oil dissolved in methanol at 1:6 ratio (methanol to raw oil ratio) to obtain highest yield based on literature [16]. The mixture is refluxed for 1 h with continuous stirring at 600 rpm at a temperature of 60 °C.

The mixture is allowed to cool down after the reaction is over, and then it is transferred into a separating funnel and left for some time so that two layers appear. The two layers formed are glycerol layer (lower layer) and the methyl ester layer (top layer). Glycerol layer is withdrawn and methyl ester layer is distilled under vacuum to recover excess methanol; then it is washed with distilled water twice. Finally, the solution is mixed with freshly activated sodium sulphate (Na_2SO_4) and filtered to be used later.

Fish biodiesel (FBD) is blended with diesel in different proportions such as 20, 30 and 40 % and cetane improver DTBP is added as 0.5 and 1 % by volume to the diesel–biodiesel blends. The calorific values of FBD obtained by varying different molar ratios (i.e., methanol to oil ratio),

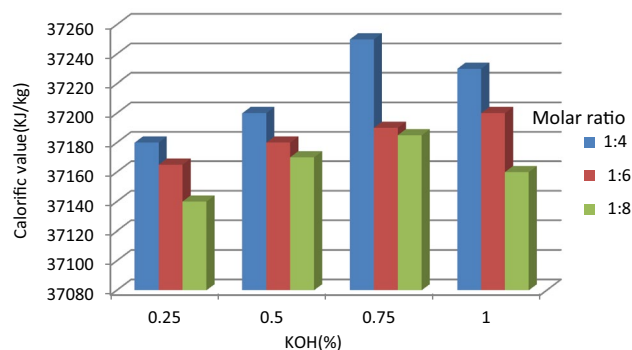


Fig. 2 Effect of molar ratio and KOH percentage on calorific value of biodiesel yield

Table 1 Properties of the diesel and FBD (B100)

Name of the fuel sample	Diesel	FBD (B100)
Characteristics		
Flash point (°C)	56	161
Fire point (°C)	60	172
Kinematic viscosity (mm^2/s)	3.15	10.15
Density (Kg/m^3)	830,896	
Lower calorific value (KJ/kg)	42,500	37,250
Dissolved oxygen (ppm)	0	8.2

Table 2 Properties of DTBP

Property	Value
Chemical formula	C ₈ H ₁₈ O ₂
Flash point, tag open cup, °C	18
Density (Kg/m ³)	800
Heat of combustion, KJ/kg	Not available
Melting point, °C	−40
Flammability	Flammable
Vapor pressure, at 20 °C	40 mmHg

namely 1:4, 1:6 and 1:8 and different concentrations of KOH such as 0.25, 0.5, 0.75 and 1 by weight percentage (wt %) are presented in Fig. 2. It can be seen from the figure that highest calorific value is obtained with 0.75 wt % KOH and 1:4 molar ratio, keeping other parameters such as reaction time (1 h) and temperature (60 °C) constant.

The physical and chemical properties of diesel and FBD (100 % biodiesel) such as viscosity and calorific value, etc. are presented in Table 1 and the properties of DTBP (provided by the supplier) are presented in Table 2. Usually, chemical cetane number improvers are the compounds which readily decompose and form free radicals, which in-turn promote the rate of initiation. This increased rate of chain initiation improves the ignition characteristics of diesel fuel. The commercial cetane number improvers are chemicals selected from alkyl nitrates, certain peroxides and tetraazoles. EHN and DTBP are the two popular cetane number improvers and also when compared to nitrate-based additives such as EHN, DTBP is more promising to reduce NO_x since it does not contain nitrogen. In small quantities, DTBP is as effective as other additives for increasing cetane number of diesel fuels [17].

Biodiesel is blended with diesel in different proportions such as 20, 30 and 40 percentages. Fuel additive, DTBP, is added as 0.5 and 1 % by volume to the said diesel–biodiesel blends and the solution is stirred continuously for 1 h so that blending is effective. Diesel–biodiesel blends with DTBP are designated as B20D0.5, B30D0.5, B40D0.5, B20D1, B30D1 and B40D1 (i.e., B20D0.5 implies biodiesel 20 % with 0.5 % DTBP and remaining is diesel by volume).

3 Experimentation

The engine used for the experimentation is shown schematically in Fig. 3, which is a single-cylinder four-stroke naturally aspirated direct injection diesel engine. Specifications of the test engine are shown in Table 3. An eddy current dynamometer 080CN is used for loading the engine. The engine is directly coupled to the eddy current

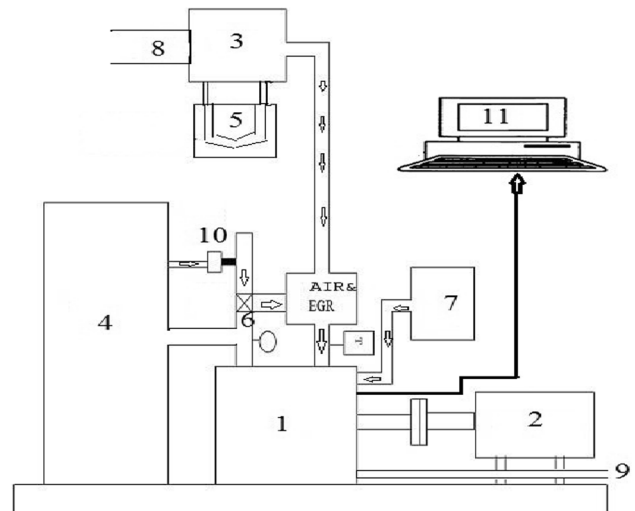


Fig. 3 Schematic diagram of the experimental set-up. 1 Test engine; 2 Dynamometer; 3 Air tank; 4 Exhaust gas drum; 5 U-tube manometer; 6 EGR valve; 7 Fuel Tank; 8 Orifice; 9 Exhaust gas analyzer; 10 Exhaust probe; 11 Computer

Table 3 Specifications of the test engine

Particulars	Specifications
Rated power	4.4 kW
Bore	87.5
Stroke length	110 mm
Swept volume	0.661 L
Compression ratio	17.5:1
Rated speed	1500 rpm
Injector operating pressure	210 bar
Connecting rod length	220 mm
Start of injection	24.9° bTDC

dynamometer; the engine and dynamometer are interfaced to a control panel which is connected to a computer. For measuring the pressure variation with the crank angle in the cylinder, the engine is equipped with an AVL GH12D miniature pressure transducer and AVL 617 indimeter software with a data acquisition system consisting of sensors, analog to digital card and software package for acquisition of the data of the engine parameters and processing.

An AVL five gas analyzer FGA512 is used for measuring the CO, HC and NO_x, and AVL smoke meter OMS103 is used for measuring the smoke opacity. The ranges of emission measuring instruments with their error are given in Table 4. For circulation of exhaust gases into the intake manifold, an EGR set up is provided which consists of an exhaust drum for storing the exhaust gases, a control valve to vary the EGR rate and a manometer for measuring the flow rate of EGR. The rate of EGR is varied manually with the help of a control valve.

Table 4 Ranges of emission measuring devices

Type of emission	Measurement range	Resolution
CO	0–10 % volume	0.01 % volume
NO _x	0–5000 ppm volume	1 ppm volume
HC	0–20,000 ppm volume	1 ppm volume
Smoke opacity	0–99.9 % volume	0.10 % volume

4 Results and discussion

4.1 Combustion analysis

Combustion characteristics results such as cylinder pressure and heat release rate variation with crank angle are presented in Figs. 4–7. Figure 4a–d shows the variation of cylinder pressure with crank angle for diesel and

diesel–biodiesel blends with 0.5 % DTBP at 0, 10, 20 and 30 % EGR rates, respectively, and Fig. 5a–d shows that of diesel and diesel–biodiesel blends with 1 % DTBP. It is observed that maximum cylinder pressure decreases slightly with increase in EGR. It is also seen from these graphs that the injection of biodiesel blends is advanced by a few degrees of crank angle (CA), and consequently peak pressure is preponed by 2–3° CA and also the combustion is finished earlier than that of diesel. Shahabuddin et al. [18] reported that biodiesel has 1–5° early start of combustion and 0.25–1.01° shorter ignition delay as compared to diesel. Bannikov [19] also reported similar results with regard to the start of combustion and ignition delay of biodiesel. Maximum cylinder pressure (P_{max}) of 73.48 bar at 6° aTDC (after Top Dead Center) has been recorded for diesel while P_{max} of 70.85, 68.02 and 67.32 bars at 8° aTDC was recorded for B20D0.5, B30D0.5 and B40D0.5

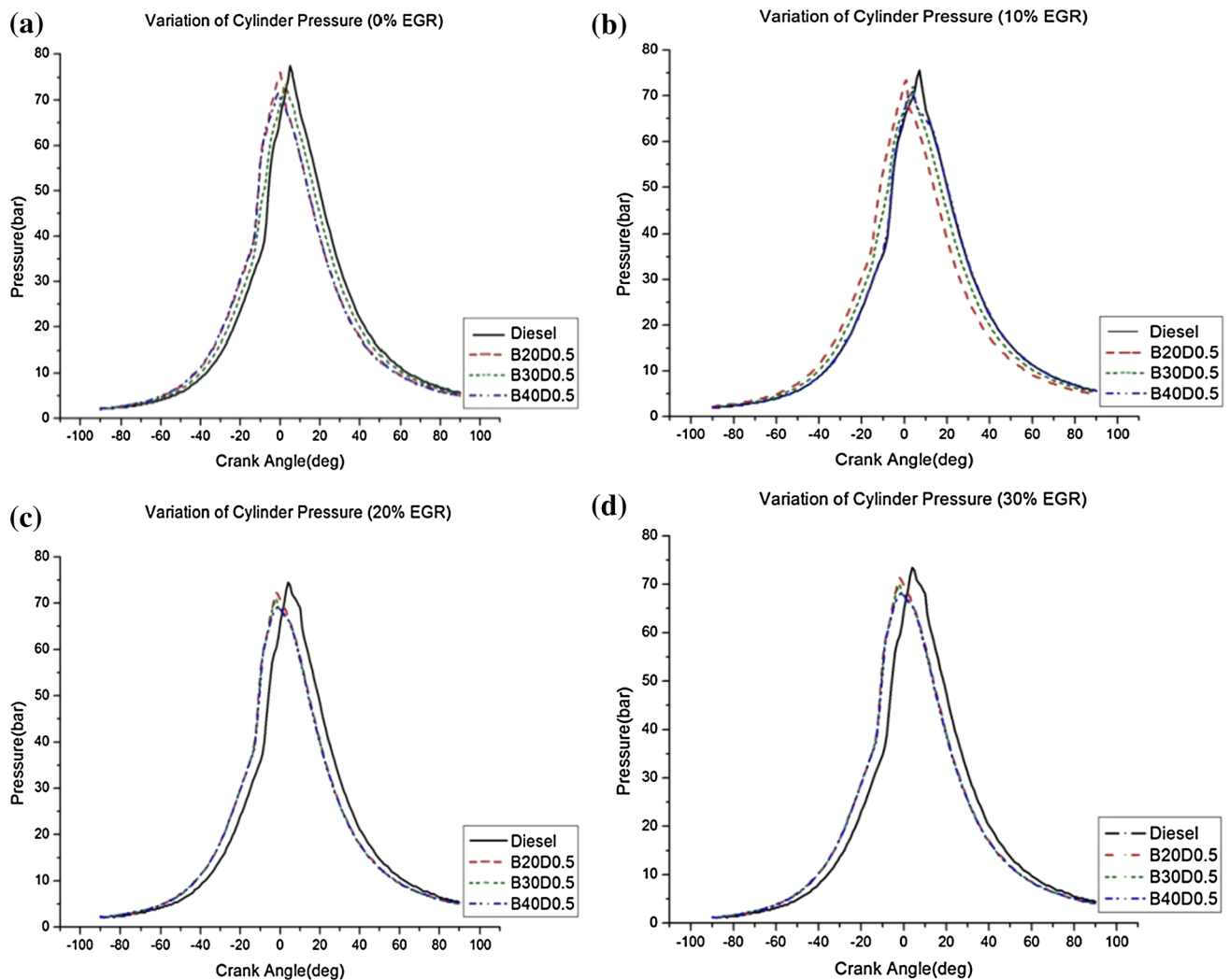


Fig. 4 Variation of cylinder pressure with crank angle at different EGR rates (0.5 % DTBP). **a** 0 % EGR, **b** 10 % EGR, **c** 20 % EGR, **d** 30 % EGR

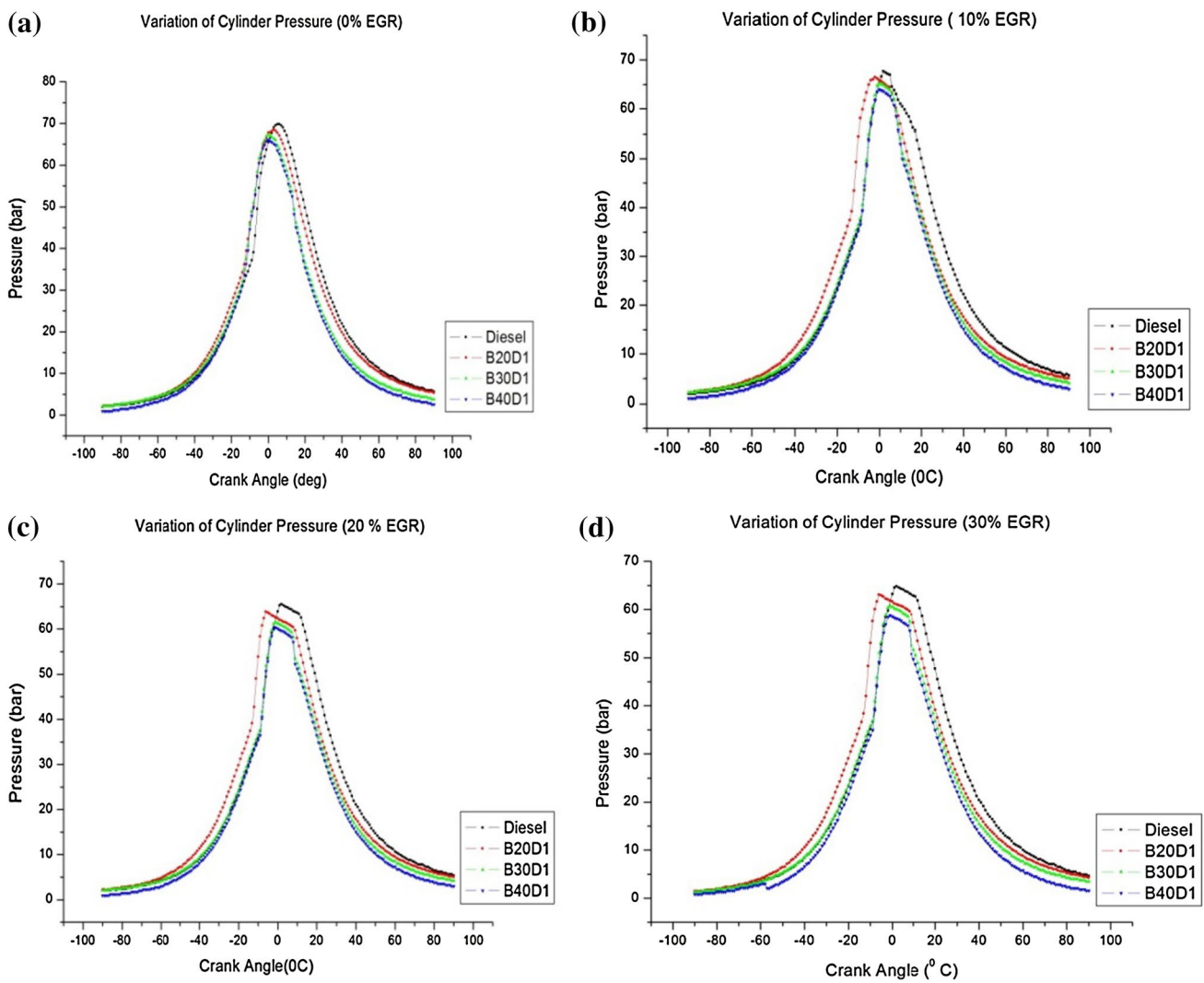


Fig. 5 Variation of cylinder pressure with crank angle at different EGR rates (1 % DTBP). **a** 0 % EGR, **b** 10 % EGR, **c** 20 % EGR, **d** 30 % EGR

blends respectively. The fuel characteristics like fatty acid composition and higher cetane number of biodiesel with the addition of cetane improver are the main reasons for early start and finish of combustion.

Figure 6a–d shows the variation of heat release rate with crank angle for diesel and diesel–biodiesel blends with 0.5 % DTBP at 0, 10, 20 and 30 % EGR rates, respectively, and Fig. 7a–d shows that of diesel and diesel–biodiesel blends with 1 % DTBP. Peak HRR of blends is slightly less than that of diesel and further, higher EGR rates decrease peak HRR of all the fuels including diesel. For example, at 0 % EGR, peak HRR of 82.83 kJ/m³-deg is recorded at 11° bTDC (before Top Dead Center) for diesel while 80.762, 77.392 and 76.834 kJ/m³ deg is recorded at the same CA for B20D0.5, B30D0.5 and B40D0.5 fuel blends, respectively. While at 30 % EGR, peak HRR of 76.78 kJ/m³-deg is recorded at 11° bTDC for diesel while 73.49, 71.29 and

69.10 kJ/m³ deg is recorded at the same CA for B20D0.5, B30D0.5 and B40D0.5, respectively. Compared with diesel, the crank angle of maximum pressure and heat release rate of biodiesel blends are preponed by a few degrees. Nevertheless, ignition delay of biodiesel blends is shorter than that of diesel, which is an indication of better ignition quality of the blends.

Maximum cylinder pressure (P_{max}) of 73.23 bar at 6° aTDC has been recorded for diesel while P_{max} of 69.45, 67.8 and 66.72 bars at 7° aTDC was recorded for B20D1, B30D1 and B40D1 blends respectively. Biodiesel blends finish the combustion earlier than diesel though the injection is advanced and, therefore, reduces the ignition delay. This trend is similar at all the EGR rates. Peak HRR of blends are slightly less than that of diesel. For example, peak HRR of 84.83 kJ/m³-deg was recorded at 11° bTDC for diesel, while 78.96, 77.02 and 76.04 kJ/m³-deg were

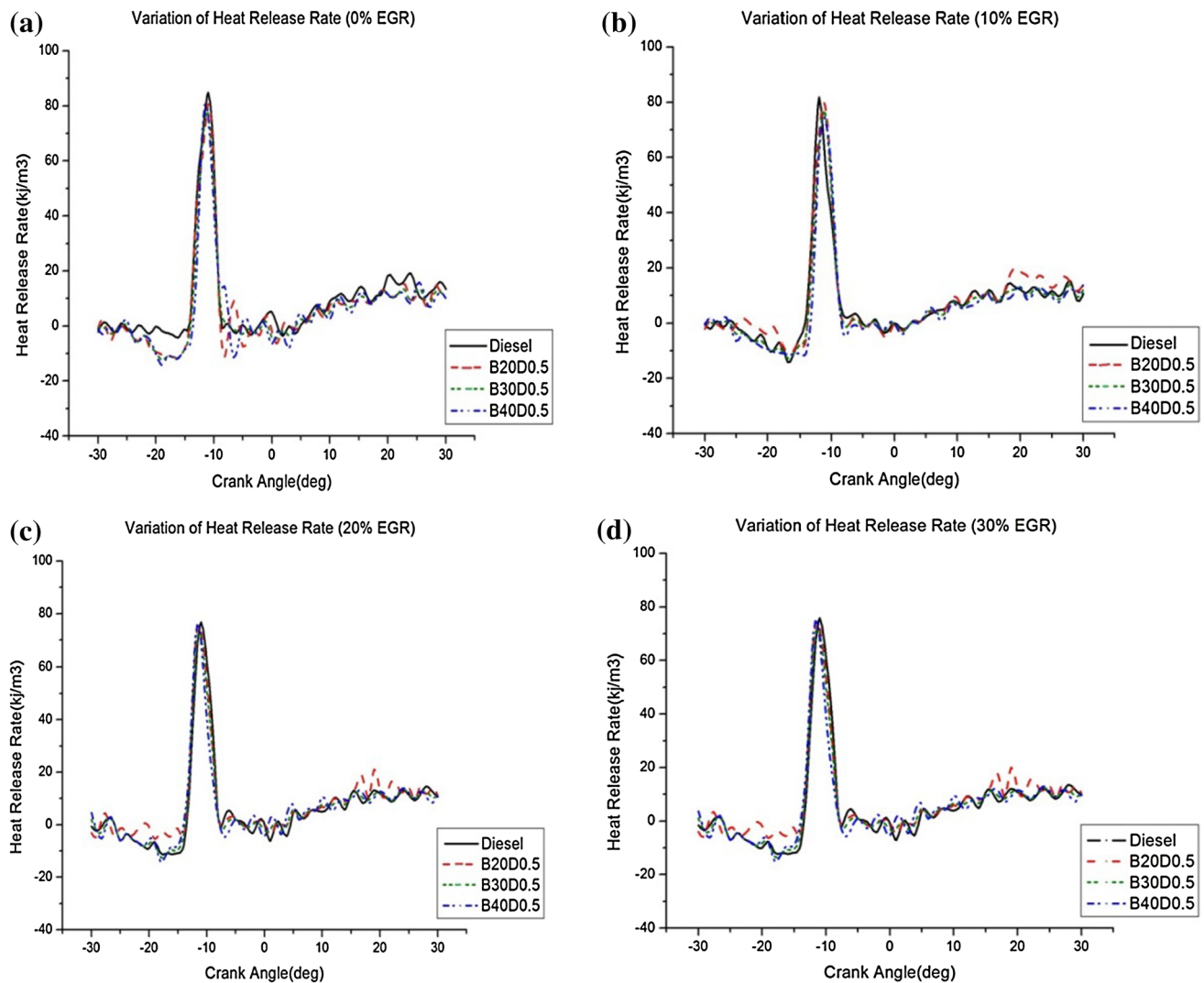


Fig. 6 Variation of heat release rate with crank angle at different EGR rates (0.5 % DTBP). **a** 0 % EGR, **b** 10 % EGR, **c** 20 % EGR, **d** 30 % EGR

recorded at the same CA for B20D1, B30D1 and B40D1, respectively.

4.2 Exhaust emission analysis

The experimental results of exhaust emissions such as CO, HC, NO_x and smoke opacity of different fuels such as diesel and different blends of diesel–biodiesel at different EGR rates are shown graphically in this section. Figure 8a, b shows the variation of CO emissions with EGR for 0.5 and 1 % DTBP, respectively. It is found from these figures that with increase in percentage of EGR, CO emission increases, for example, CO emission values of 0.05 and 0.063 % were observed for a biodiesel blend at 0 and 30 % EGR, respectively. However, this trend is reversed with increase in percentage of biodiesel. For example, at

a particular EGR, CO emission of 0.06 and 0.05 % was observed with diesel and biodiesel, respectively. It can be understood that the increase in oxygen content with increase in the percentage of biodiesel can compensate for the oxygen deficiency with higher EGR rates. Hanumantha Rao et al. [20] from their experimental investigations of jatropha biodiesel reported that biodiesel could reduce CO emissions by 14–18 % when compared to that of diesel fuel.

Figure 9a, b shows the variation of NO_x emissions with EGR for 0.5 and 1 % DTBP, respectively. Figures show that the combined effect of EGR and DTBP reduces NO_x emissions significantly. NO_x emission of 1624 ppm was recorded for pure diesel without EGR, while 1080 and 1065 ppm were recorded for B40D0.5 and B40D1, respectively at higher EGR (i.e., 30 % EGR). As reported

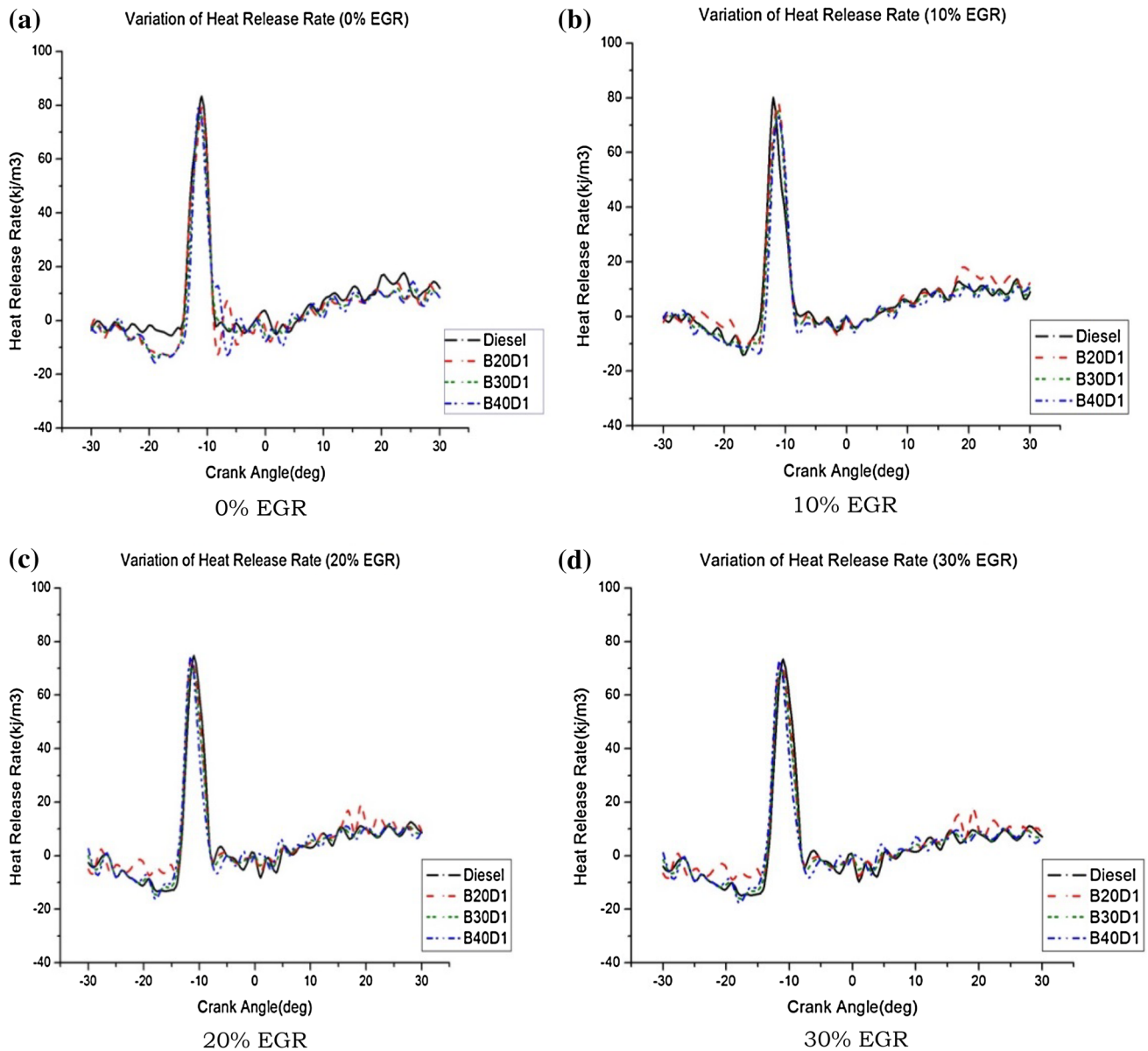


Fig. 7 Variation of heat release rate with crank angle at different EGR rates (1 % DTBP). **a** 0 % EGR, **b** 10 % EGR, **c** 20 % EGR, **d** 30 % EGR

by Mustafa Canakci et al. [21], the NO_x emissions of the biodiesel derived from animal fat-based yellow grease (YGME) and soybean oil (SME) are higher for all of the methyl esters than that of diesel fuel. The NO_x emissions of YGME and SME were increased by 13.1 and 11.6 %, respectively. The blend of 20 % sunflower methyl ester (SFME) and diesel (B20 SFME) at 15 % EGR rate reduced NO_x emissions by 25 % compared to diesel fuel [22]. The reason for reduction in NO_x with EGR is the reduction of combustion temperature as a result of the addition of exhaust gases to the intake air, which increases the amount of combustion accompanying gases which reduces the combustion temperature. Still higher EGR rates could

reduce NO_x emissions by a large amount, which, however, is accompanied by a reduction in BTE and increase in CO, HC and smoke emissions.

Figure 10a, b shows the variation of HC emissions with EGR for 0.5 and 1 % DTBP, respectively. Figures show that HC emissions increase with the increase in EGR rate. HC emission of 26 ppm was observed with diesel against 20 ppm with biodiesel blend at a particular EGR, which is 23 % less. The increase in oxygen content with increase in the percentage of biodiesel promotes the combustion and on the other hand, higher cetane number of biodiesel with addition of cetane improver reduces the burning delay, which could reduce HC emissions. A review of biodiesel fuel as

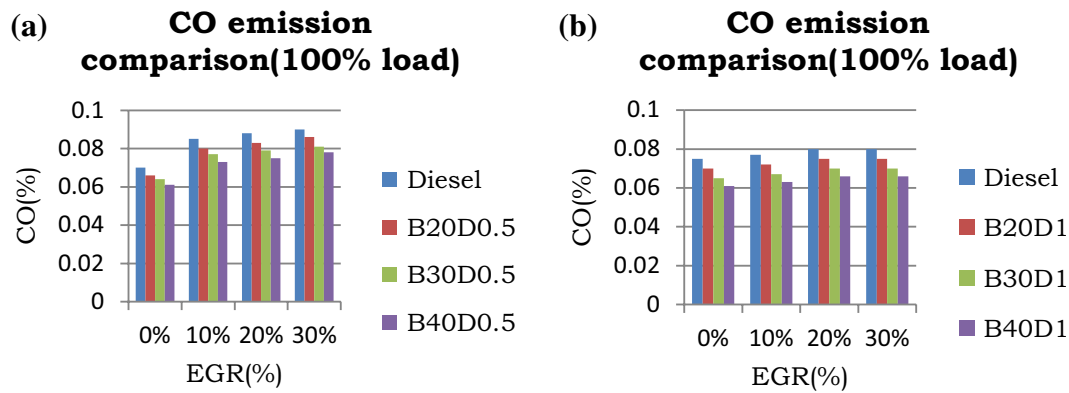


Fig. 8 Effect of exhaust gas recirculation on CO emissions. **a** 0.5 % DTBP, **b** 1 % DTBP

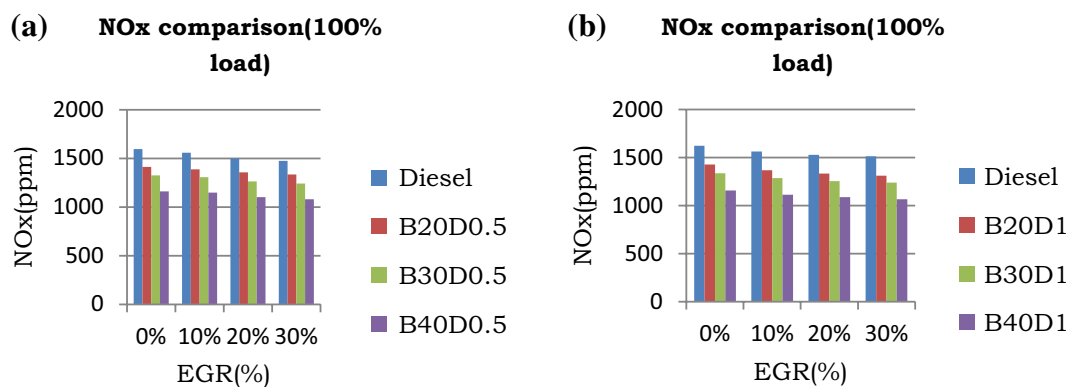


Fig. 9 Effect of exhaust gas recirculation on NO_x emissions. **a** 0.5 % DTBP, **b** 1 % DTBP

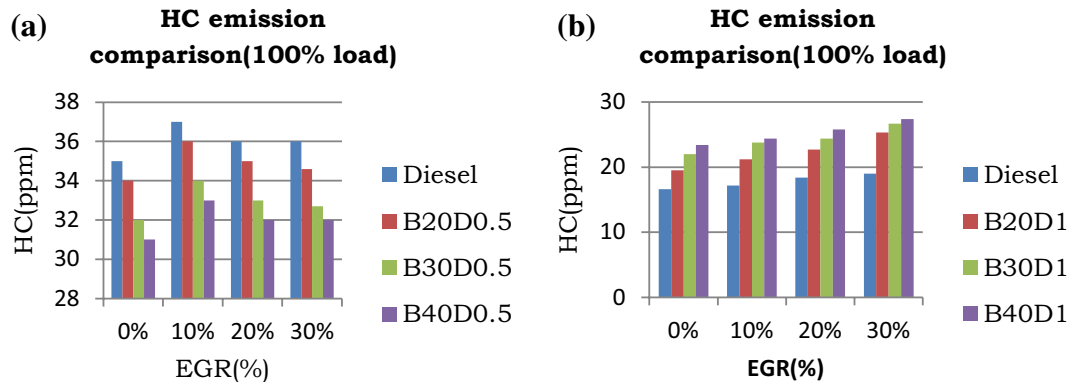


Fig. 10 Effect of exhaust gas recirculation on HC emissions. **a** 0.5 % DTBP, **b** 1 % DTBP

alternative to diesel by Gaurav Dwivedi et al. [23] reported that the use of biodiesel or its blends with diesel increases the NO_x emission and decreases the CO and HC emissions. HC emission reduction of 20 and 67 % were reported with B20 blend and pure biodiesel (B100), respectively.

However, with increase in the percentages of EGR, HC emissions are found increasing. HC emission of 20 ppm was observed at 0 % EGR against 21 ppm at 30 % EGR, which is 5 % more. Jafar Hussain et al. [14] reported, that EGR increases HC emissions by 20 % compared to conventional

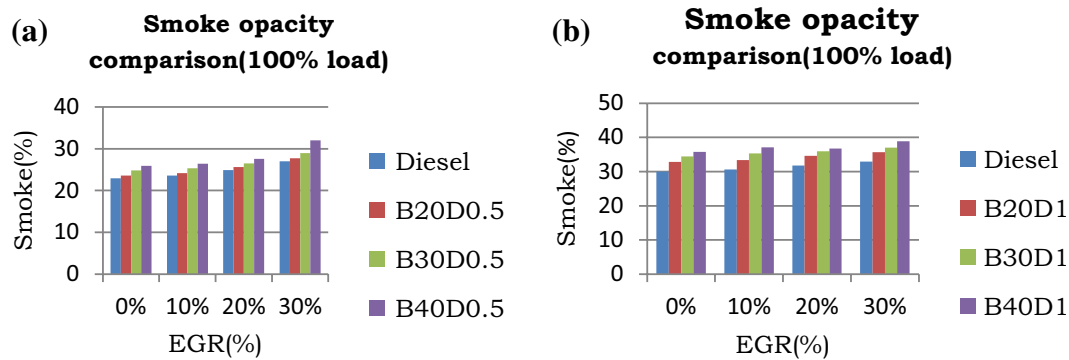


Fig. 11 Effect of exhaust gas recirculation on smoke opacity. **a** 0.5 % DTBP **b** 1 % DTBP

diesel engines. Figure 11a, b shows the variation of smoke opacity with EGR for 0.5 and 1 % DTBP, respectively. Figures show that the increase in smoke opacity is insignificant initially; however, it increases considerably with higher rates of EGR. It also increases with increase in the percentage of biodiesel. At a particular EGR, smoke with diesel is 30 % while with biodiesel it is 35.8 % which is 19 % more. Further, with increase in EGR rate also smoke increases. For a particular fuel, at 0 % EGR, smoke is 35.8 % while at 30 % EGR it is 38.9 %, which is 8.6 % more.

5 Conclusion

The conclusions derived from the experimental investigation of diesel engine fueled with diesel as a baseline fuel and diesel–biodiesel blends with the combined use of DTBP and the EGR are summarized as follows:

1. Both EGR and cetane number improver reduces the cylinder pressure and HRR slightly.
2. EGR increases the CO emissions; however, they are found decreasing with increase in the percentage of biodiesel and EHN at a fixed EGR.
3. The combined effect of EGR and cetane improver decreases NO_x emissions by about 40 % when compared with the diesel without EGR.
4. The HC emissions are found to increase slightly with increase in the percentage of EGR up to around 10 % and, however, this can be offset by the addition of EHN.
5. The smoke opacity increases with increase in EGR percentage and cetane number improver as well. Hence, it is concluded that an optimum diesel–biodiesel blend is found as B20 and when small volumes of DTBP like 0.5 % by volume is added to it, better efficiency and emissions are observed at 20 % EGR when compared to pure diesel operation.

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