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RESEARCH ARTICLE

Emission and performance analysis on the effect of exhaust gas recirculation in alcohol-biodiesel aspirated research diesel engine

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Abstract

In this study, the effect of blending pentanol to biodiesel derived from mahua oil on emissions and performance pattern of a diesel engine under exhaust gas recirculation (EGR) mode was examined and compared with diesel. The purpose of this study is to improve the feasibility of employing biofuels as a potential alternative in an unmodified diesel engine. Two pentanol-biodiesel blends denoted as MOBD90P10 and MOBD80P20 which matches to 10 and 20 vol% of pentanol in biodiesel, respectively, were used as fuel in research engine at 10 and 20% EGR rates. Pentanol is chosen as a higher alcohol owing to its improved in-built properties than the other first-generation alcohols such as ethanol or methanol. Experimental results show that the pentanol and biodiesel blends (MOBD90P10 and MOBD80P20) have slightly higher brake thermal efficiency (0.2–0.4%) and lower brake-specific fuel consumption (0.6 to 1.1%) than that of neat biodiesel (MOBD100) at all engine loads. Nitrogen oxide (NOx) emission and smoke emission are reduced by 3.3–3.9 and 5.1–6.4% for pentanol and biodiesel blends compared to neat biodiesel. Introduction of pentanol to biodiesel reduces the unburned hydrocarbon (2.1–3.6%) and carbon monoxide emissions (3.1–4.2%) considerably. In addition, at 20% EGR rate, smoke, NO_X emissions, and BTE drop by 7.8, 5.1, and 4.4% respectively. However, CO, HC emissions, and BSFC increased by 2.1, 2.8, and 3.8%, respectively, when compared to 0% EGR rate.

Keywords Pentanol · Biodiesel · Emissions · Exhaust gas recirculation · Diesel engine

Introduction

Diesel engines are employed in the transportation sector because of its lower fuel consumption, higher efficiency, and excellent durability. Human health and air quality get affected by the emissions from on-road engines (diesel). Many research works have attempted to sort out these issues by suitable reserves (Atmanli 2016; Dincer 2008). Combustion of biodiesel reduces the smoke and HC emissions but increases NO_x emissions. Biodiesel-fuelled diesel engine emits a higher concentration of NO_x emission (Barabas et al. 2010; Devarajan et al. 2017a). High-pressure direct injection (HPDI) seems to be one of the most efficient ways to tackle the stringent emission norms. But, in our study, we are not altering with the injection timing and the whole experiment is done under steady-state condition.

Many studies have proven that by doping alcohols (octanol/pentanol/butanol) to diesel improves its properties (Yilmaz et al. 2018; Yilmaz et al. 2017; Yilmaz and Atmanli 2017a, b; Atmanli 2016; Barabas et al. 2010; Devarajan et al. 2017a, b). Yilmaz et al. (2018) investigated the effect of alcohols (pentanol and propanol) in biodiesel/diesel/vegetable oil blends in four-cycle, four-cylinder diesel engine. The speed of the engine was maintained at 1800 rpm and by varying loads in step of 3 kW. An 11.9% reduction in NO_X emissions was achieved for pentanol/biodiesel/diesel/vegetable oil blends than propanol/biodiesel/diesel/vegetable oil blends at all loads. However, CO and smoke emissions increased with the addition of both alcohols to biodiesel/diesel/vegetable oil blends. Yilmaz et al. (2017) performed an experimental study on diesel and biodiesel

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(waste oil) with pentanol in a direct injection compression-ignition engine. The dosage level of pentanol in the diesel and biodiesel (waste oil) was about 10–20%. Since pentanol molecule donates oxygen for NO_X oxidation, a significant reduction in NO_X emissions was found for diesel/pentanol and biodiesel/pentanol blends. In addition, due to higher heat of vaporization of pentanol, considerable increase in heat loss between cylinder and gas was achieved which slightly increased HC and CO emissions for diesel/pentanol and biodiesel/pentanol blends than neat diesel and biodiesel. Results found a significant increase in brake thermal efficiency by adding 20% of pentanol to biodiesel. Further, BSFC increased for diesel/pentanol and biodiesel/pentanol blends than neat diesel and biodiesel owing to higher heating loss. They also concluded that by blending 20% of pentanol to biodiesel (waste oil), the creation of NO_X, HC, and CO emissions were lowered at part loads. Yilmaz and Atmanli (2017a, b) performed an experimental study on diesel with pentanol in a direct injection compression-ignition engine. The dosage level of pentanol in the diesel was about 5–35 vol%. Results found that the D95pen5 (95% diesel and 5% pentanol on a volume basis) showed a significant reduction in NO_X, CO, and EGT than neat diesel operation. However, brake thermal efficiency (BTE) and HC emissions increased by adding 5 vol% of pentanol to diesel. In addition, higher % increase of pentanol (10–35%) increased all the emissions of diesel engines at all loads. Most of the studies conducted earlier involving pentanol in diesel engine employed it in lower percentage as emulsifier/surfactant/solvents. More experimental information is essential for complete understanding of its impact on engine parameters as a neat biofuel. In addition, no study has been conducted on blending pentanol at various proportions to neat biodiesel to scrutinize its possessions on performance and emission.

EGR technology is highly effective in reducing the flame temperature and oxygen concentration of the working fluid inside the combustion chamber. In addition, it has been experimentally found that introducing EGR reduces the NO_x emissions of biodiesel (Zhu et al. 2011; Agarwal et al. 2011; Hussain et al. 2012; Bhaskar et al. 2013). However, there exists a gap in the literature on information related to the effect of EGR on engine pattern of biofuel (pentanol/neat biodiesel)-fuelled diesel engine. Hence, in the present study, the effect of EGR on performance and emission characteristics of two pentanol/biodiesel blends (10 and 20 vol%) under two EGR rates of 10 and 20% was investigated and compared with baseline diesel operation.

Materials and reagents

Fuel characteristics and blending

Mahua seeds consist of three layers namely endocarp, epicarp, and mesocarp. Mesocarp consists of natural resin which holds the source (oil). Moisture content in the seeds is dried. It is then milled for higher content of oil. Mahua oil contains 10% of cardol and 90% of anacardic acid. Pentanol is employed as higher alcohol. Pentanol is produced during the synthesis of the ester and offer potential advantages when blended with liquid fuels. Table 1 shows the properties of pentanol.

Transesterification

The methanolic solution comprised of 95 mL of methyl alcohol and 5 mL of sulfuric acid which was added at a molar ratio of 16:1 to the mahua oil. This sample was then heated (60 °C) at four different time durations (30, 45, 60, and 90 min) at the constant stirring rate by employing magnetic stirrer with a hot plate. Based on the result, it was found that heating the mixture at a temperature below 60 °C for 45 min was the optimum operating condition for acid-catalyzed esterification process (Yuvarajan and Venkata Ramanan 2016). Table 2 shows the properties of biodiesel-alcohol blends. From Table 2, it is inferred that all the properties of tested fuels meet the limits specified by Biodiesel standard ASTM D6751.

Engine setup

Water-cooled, 1500 rpm diesel engine was employed in this study. Table 3 illustrates the specification of the experimental setup. Table 4 illustrates the smoke meter and gas analyzer range and their accuracy. The external cooled EGR system is used in this work to achieve a lower intake charge temperature and to establish a lower cylinder temperature.

Result and discussion

Carbon monoxide (CO)

CO is formed due to deficient fuel combustion (Hasimoglu 2012; Karthikeyan and Prathima 2016). Deviation of CO for

Table 1 Properties of pentanol

Properties	Pentanol
Chemical formula	$C_5H_{11}OH$
CAS Number	71-41-0
Cetane number	20
Low heating value (MJ/kg)	32.1
Latent heat of vaporization (kJ/kg)	310
Kinematic viscosity at 40 °C (mm^2/s)	2.9
Density (kg/m^3)	815
Flash point (°C)	50
Self-ignition temperature (°C)	300
Oxygen (% by wt)	18.1

Table 2 Chemical properties of tested fuels

Properties	MOBD80P20	MOBD90P10	MOBD100	Diesel	Method	Allowable limits	
						Max	Min
Density at 15 °C (g/cm^3)	0.82	0.84	0.86	0.80	ASTM D4052	0.8	0.92
Kinematic viscosity at 40 °C (mm^2/s)	5.3	5.4	5.6	3	ASTM D445	1.9	6.0
Calorific value (kJ/kg)	38,554	39,188	40,141	42,500	ASTM D240	35,000	–
Cetane number	45	47	49	52	ASTM D976	42	–
Flash point (°C)	140	143	147	48	ASTM D93	93	–

fuels (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 1. CO emissions from diesel are higher than all the tested fuels. Oxygen contained in MOBD100, MOBD90P10, and MOBD80P20 lowers CO formation (Ibrahim 2016). CO emissions for MOBD90P10 and MOBD80P20 are lower than MOBD100 by 3.1 and 4.2%, respectively, at all loads. The reason for lower CO emissions for MOBD90P10 and MOBD80P20 is due to improved combustion rate (Ibrahim 2016). Hydroxyl group and *n*-pentanol oxygen atoms get bonded during the combustion and result in the lower formation of soot by slowing down the soot formation and increase the oxygen availability (Devarajan et al. 2016, 2017a).

Deviation of CO for fuels with EGR rates (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 2. The comparative rise in CO emission was observed for diesel, MOBD100, MOBD90P10, and MOBD80P20 at various fractions of EGR (10 and 20% flow rate). Oxygen content in the air reduces with EGR during the combustion and originates poor combustion. Higher CO emissions were observed as a result of lesser combustion temperature and oxygen content of fuels and deteriorated performance. Lower O_2 content in EGR forms rich and heterogeneous air-fuel mixture and engenders high CO emissions. CO emissions for diesel, MOBD100, MOBD90P10, and MOBD80P20 are 0.12, 0.10, 0.095, and 0.09% correspondingly at full load and 0% EGR conditions.

Table 3 Specification of experimental setup

Make	AVL 5402
Power	4.2 kW
Speed	1500 rpm
Diameter (D)	87.5 mm
Stroke (L)	110 mm
Compression ratio	18:1
Cone angle	110°
Injection type	Direct injection
Fuel injection pressure	200–1400 bar

Hydrocarbons (HC)

Deviation of HC for fuels (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 3. HC emission from biofuels (MOBD100, MOBD90P10, and MOBD80P20) is lower than diesel (Mahalingam et al. 2017; Li et al. 2015). HC emission reduces with the addition of pentanol at various proportions. Adding 10 and 20 vol% of pentanol to MOBD100 resulted in 2.1 and 3.6% reduction in HC emissions, respectively, at all loads when compared to neat MOBD100. Pentanol increases the combustion efficiency of fuel and promotes the combustion and reduces HC emission (Devarajan et al. 2016, 2017a).

Deviation of HC for fuels with EGR rate (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 4. The rise in HC emission was observed for diesel, MOBD100, MOBD90P10, and MOBD80P20 at various fractions of EGR (10 and 20% flow rate). Oxygen content in the air reduces with EGR during the combustion and originates poor combustion (Bhaskar et al. 2013). Higher HC emissions were observed as a result of lesser combustion temperature, charge dilution, and oxygen content of fuels and deteriorated performance (Hussain et al. 2012). Lower O_2 content in EGR forms rich and heterogeneous air-fuel mixture and engenders high HC emissions (Agarwal et al. 2011). Overall, HC emissions for diesel, MOBD100, MOBD90P10, and MOBD80P20 are in 89, 76, 71, and 69 ppm correspondingly at full load and 0% EGR condition.

Table 4 Smoke meter and gas analyzer range, accuracy, and uncertainties details

Measured quantity	Range	Accuracy	Uncertainties
CO	0–4000 ppm	0.015%	± 0.5 (%)
HC	0–19,999	± 10 ppm	± 0.1 (%)
NOx	0–4000 ppm	± 10 ppm	± 0.3 (%)
Smoke	AVL 437 smoke meter	0.005%	± 1.0 (%)

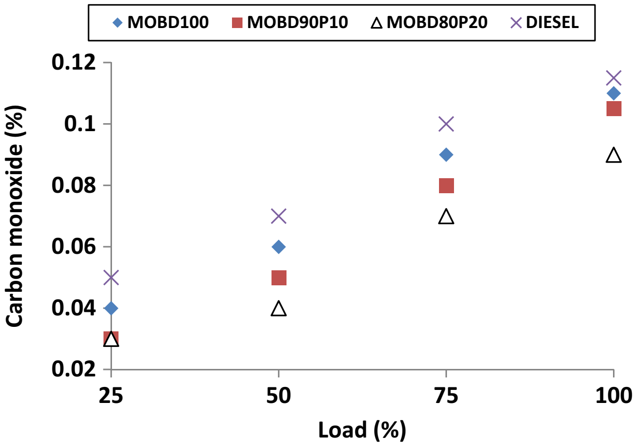

Fig. 1 Deviation of CO emissions for fuels

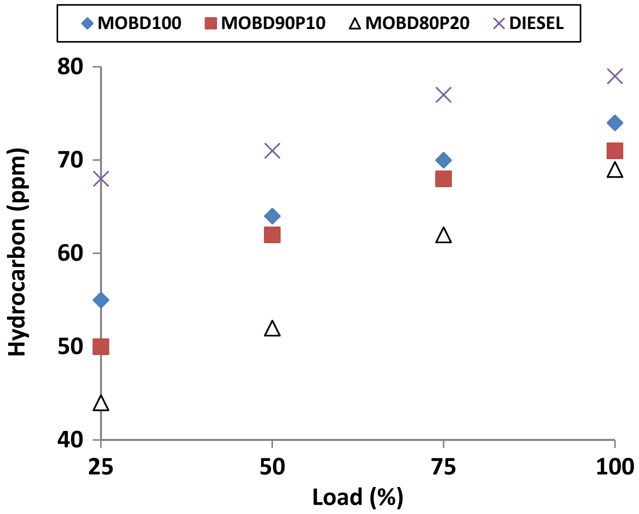

Fig. 3 Deviation of HC emissions for fuels

Oxides of nitrogen (NO_X)

The NOx emission formation inside the engine cylinder is because of the presence of excess oxygen content, the higher temperature of combustion, and residence time available for chemical reactions (Anderson et al. 2017; Devarajan et al. 2016). Under these circumstances, the diatomic nitrogen molecule present in the air is being converted into monoatomic nitrogen molecule and then reacts with excess oxygen molecule that resulted in NOx emissions. The mechanism of NOx formation in a diesel engine as described by Zeldovich mechanism from the presence of oxygen, nitrogen, and hydrogen free radicals is presented below (Nalgundwar et al. 2016).

$$N_2 + [O] \rightarrow NO + [N]$$
$$[N] + O_2 \rightarrow NO + [O]$$
$$[N] + [OH] \rightarrow NO + [H]$$

Deviation of NO_X for fuels (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 5. NO_X emission is higher for biofuels (MOBD100, MOBD90P10, and MOBD80P20) than from diesel at all loads. Adding 10 and 20 vol% of pentanol to MOBD100 resulted in 3.3 and 3.9% reduction in NO_X emissions, respectively, at all loads compared to neat MOBD100. Pentanol in biodiesel mixture lowers the cylinder temperature during combustion by making the air-fuel mixture leaner and reduces NO_X emission (Devarajan et al. 2016, 2017a; Joy et al. 2017).

Deviation of NO_X emissions for fuels with EGR rate (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 6. Comparative drop in NO_X emission was observed for diesel, MOBD100, MOBD90P10, and MOBD80P20 at various fractions of EGR (10 and 20% flow rate). Oxygen content in the air reduces with EGR during the combustion and lowers the temperature (Zhu et al. 2011). Lower NO_X emissions were observed as a result of lesser combustion temperature and oxygen content of fuels (Agarwal et al. 2011). Shorter availability of oxygen also causes the reduction in NO_X (Bhaskar et al. 2013). NO_X emissions at peak load and 0% EGR for diesel, MOBD100, MOBD90P10, and MOBD80P20 are 1035, 1365, 1310, and 1247 ppm correspondingly.

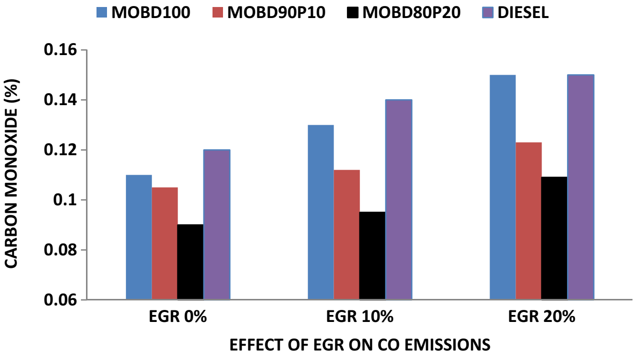

Fig. 2 Deviation of CO emissions for fuels with EGR

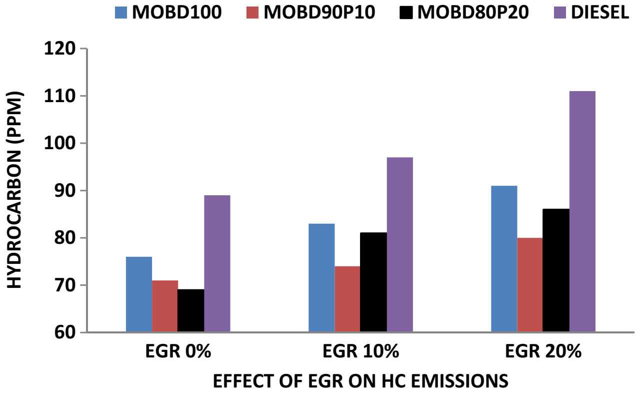

Fig. 4 Deviation of HC emissions for fuels with EGR

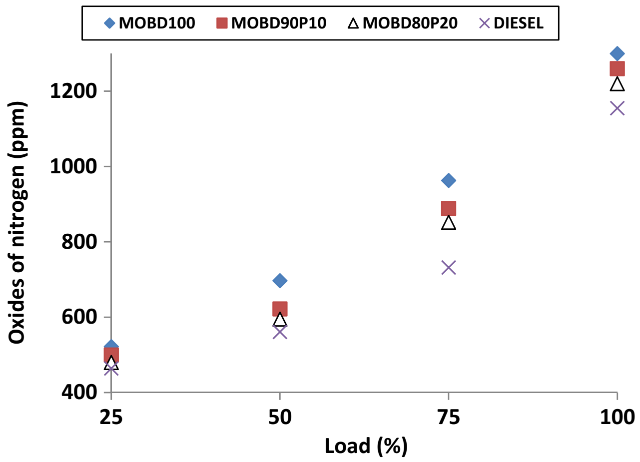

Fig. 5 Deviation of NO_X emissions for fuels

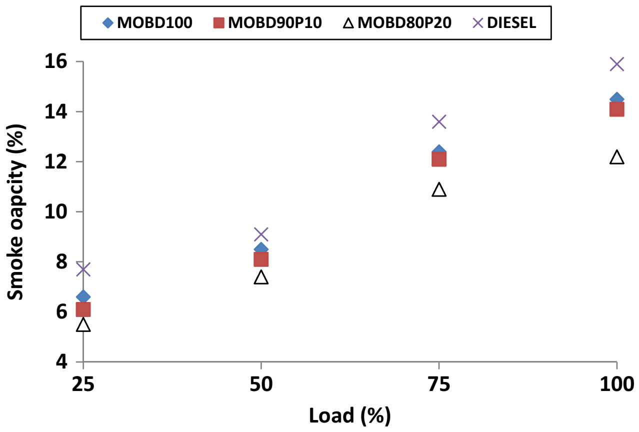

Fig. 7 Deviation of smoke for fuels

Smoke opacity

Deviation of smoke for fuels (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 7. Smoke emissions from biofuels are lesser than diesel (Yilmaz and Atmanli 2017a, b; Yuvarajan et al. 2016; Venkata Ramanan and Yuvarajan 2015b). Adding 10 and 20 vol% of pentanol to MOBD100 resulted in 5.1 and 6.4% reduction in smoke emission, respectively, at all loads when compared to neat MOBD100. Hydroxyl group in the fuel and the oxygen atoms present in *n*-pentanol gets bonded during the phase of combustion and lowers the formation of soot (Devarajan et al. 2016, 2017a).

Deviation of smoke emissions for fuels with EGR rate (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 8. The comparative rise in smoke emission was observed for diesel, MOBD100, MOBD90P10, and MOBD80P20 at various fractions of EGR (10 and 20% flow rate). Oxygen content in the air reduces with EGR during the combustion and originates poor combustion (Hussain et al. 2012). Higher smoke emissions were observed as a result of lesser combustion temperature and oxygen content of fuels (Zhu et al. 2011). Overall smoke emissions at full load and 0% EGR conditions for diesel, MOBD100, MOBD90P10, and MOBD80P20 are 15.9, 14.5, 14.1, and 12.2% respectively.

Brake thermal efficiency

Deviation of BTE for fuels (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 9. BTE from biofuels is lesser than diesel (Agarwal et al. 2011; Yuvarajan et al. 2018; Venkata Ramanan and Yuvarajan 2015a). Adding 10 and 20 vol% of pentanol to MOBD100 resulted in 0.2 and 0.4% increase in BTE, respectively, at all loads when compared to neat MOBD100. The lower cetane number of pentanol leads to leaner combustion, minor heat loss, and more proportion of combustion at constant volume and result in slightly higher BTE (Zhu et al. 2011).

Deviation of BTE for fuels with EGR rate (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 10. Comparative fall in BTE was observed for diesel, MOBD100, MOBD90P10, and MOBD80P20 at various fractions of EGR (10 and 20% flow rate). Oxygen content in the air reduces with EGR during the combustion and originates poor combustion (Devarajan et al. 2016). Lower BTE was observed as a result of lesser combustion temperature and

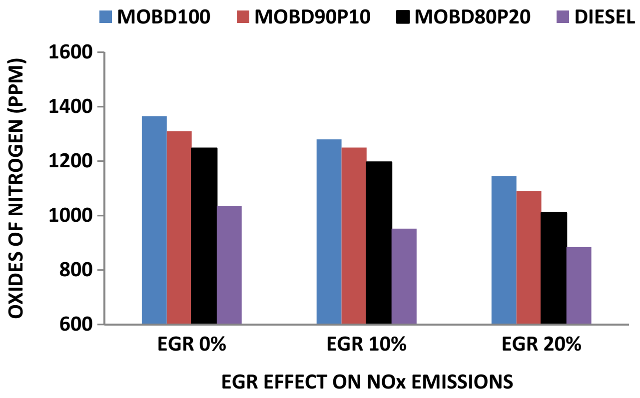

Fig. 6 Deviation of NO_X emissions for fuels with EGR

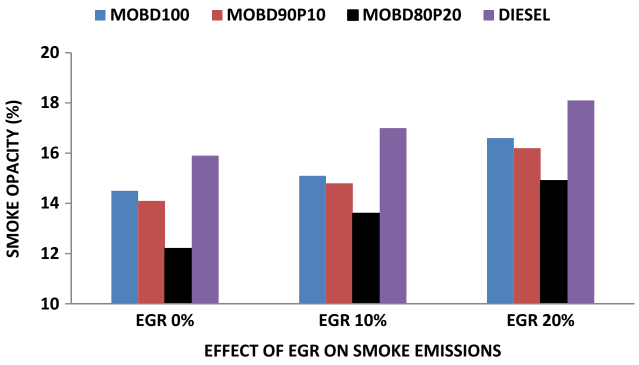

Fig. 8 Deviation of smoke emissions for fuels with EGR

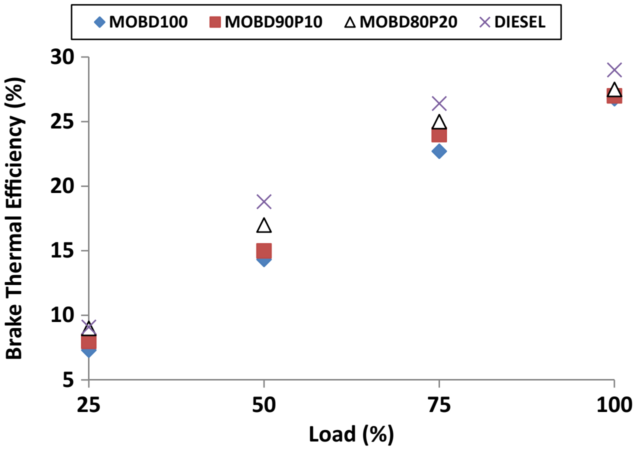

Fig. 9 Deviation of BTE for fuels

oxygen content of fuels (Devarajan et al. 2017a). BTE at full load and 0% EGR conditions for diesel, MOBD100, MOBD90P10, and MOBD80P20 are 29, 26.7, 27, and 27.5%, respectively.

Brake-specific fuel consumption

Deviation of BSFC for fuels (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 11. BSFC from biofuels is lesser than diesel (Venkata Ramanan and Yuvarajan 2015b; Devarajan et al. 2017c). Adding 10 and 20 vol% of pentanol to MOBD100 resulted in 0.6 and 1.1% decrease in BSFC, respectively, at all loads when compared to neat MOBD100. This is due to the improved oxidation reaction of oxygen molecules present in pentanol. Pentanol's higher energy improves the combustion rate and results in lower BSFC (Zhu et al. 2011). Pentanol also enhances the heat transfer rate between the fuel and air and exchange the momentum among the fresh charge and burnt products inside the combustion chamber (Agarwal et al. 2011).

Deviation of BSFC for fuels with EGR rate (diesel, MOBD100, MOBD90P10, and MOBD80P20) is exemplified in Fig. 12. BSFC for diesel, MOBD100, MOBD90P10, and MOBD80P20 reduces at various fractions of EGR (10 and 20% flow rate). Oxygen content in the air reduces with EGR during the combustion and originates poor combustion (Devarajan et al. 2017a). Lower BSFC was observed as a result of lesser combustion temperature and oxygen content of fuels (Devarajan et al. 2016). BSFC at full load and 0% EGR conditions for diesel, MOBD100, MOBD90P10, and MOBD80P20 are 0.17, 0.21, 0.2, 0.18 kg/kW/h, respectively.

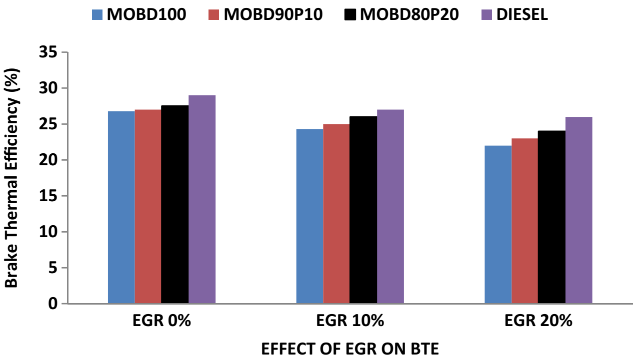

Fig. 10 Deviation of BTE for fuels with EGR

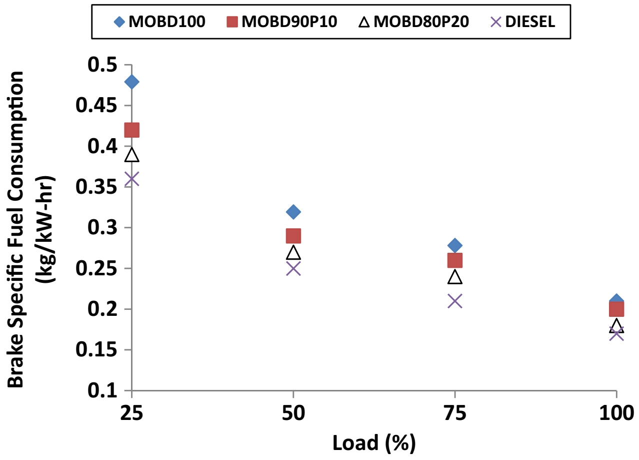

Fig. 11 Deviation of BSFC for fuels

Conclusion

This work examines the effect of *n*-pentanol/neat biodiesel blends on emission and performance of unmodified research engine. Two pentanol-biodiesel blends denoted as MOBD90P10 and MOBD80P20 which match to 10 and 20 vol% of pentanol in biodiesel, respectively, were used as fuel in research engine at 10 and 20% EGR rates. The following findings were found on engine's emission:

1. Pentanol gets miscible with mahua oil biodiesel without any separation of phase.
2. Pentanol does not require any solvents/surfactants for blending with mahua oil biodiesel.

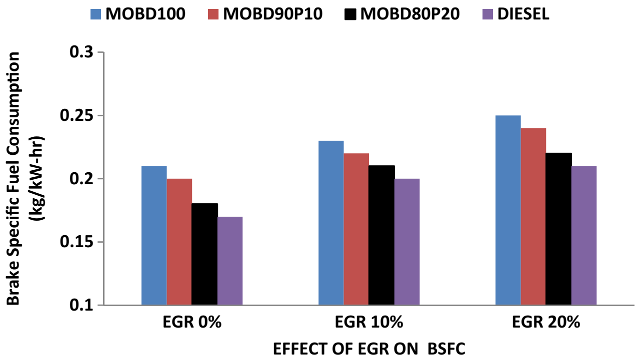

Fig. 12 Deviation of BSFC for fuels with EGR

3. CO and HC emissions remained low for biodiesel pentanol-blended fuel. A maximum reduction of up to 4.2 and 3.6% of was CO and HC emissions obtained respectively for MOBD80P20 than MOBD100. However, these emissions increased with EGR introduction.
4. NO_x and smoke emissions drop drastically with increasing pentanol concentration. A maximum reduction of up to 3.9 and 6.4% of NOx and smoke emissions was obtained, respectively. EGR further reduces the NOx with a minor increase in other smoke emissions of the neat biodiesel and alcohol blends.
5. BTE increased and BSFC reduced with increasing pentanol fraction in biodiesel. Nevertheless, both the parameters suffered at 10 and 20% EGR rate.

In summary, from this study, it has been experimentally found that the engine emissions during mahua biodiesel are well within the current emission standards. In addition, pentanol is an excellent higher alcohol which can be potentially employed with lower NO_X, CO, smoke, and HC emissions. Therefore, the mahua biodiesel and pentanol blends can be best suited to diesel engines at 10 and 20% EGR rates.

References

Agarwal D, Singh SK, Agarwal AK (2011) Effect of Exhaust Gas Recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine. Appl Energy 88:2900–2907

Anderson A, Devarajan Y, Nagappan B (2017) Effect of injection parameters on the reduction of NOx emission in neat bio-diesel fuelled diesel engine. Energy Sources, Part A 40(2):186–192. https://doi.org/10.1080/15567036.2017.1407844

Atmanli A (2016) Comparative analyses of diesel–waste oil biodiesel and propanol, n-butanol or 1-pentanol blends in a diesel engine. Fuel 176:209–215. https://doi.org/10.1016/j.fuel.2016.02.076

Barabas I, Todoruț A, Baldean D (2010) Performance and emission characteristics of an CI engine fueled with diesel–biodiesel–bioethanol blends. Fuel 89(12):3827–3832. https://doi.org/10.1016/j.fuel.2010.07.011

Bhaskar K, Nagarajan G, Sampath S (2013) Optimization of FOME (fish oil methyl esters) blend and EGR (exhaust gas recirculation) for simultaneous control of NO and particulate matter emissions in diesel engines. Energy 62:224–234

Devarajan Y, Jayabal RK, Ragupathy D, Venu H (2016) Emissions analysis on second generation biodiesel. Front Environ Sci Eng 11:1

Devarajan Y, Munuswamy DB, Nagappan B (2017a) Emissions analysis on diesel engine fuelled with cashew nut shell biodiesel and pentanol blends. Environ Sci Pollut Res 24(14):13136–13141. https://doi.org/10.1007/s11356-017-8915-7

Devarajan Y, Nagappan BK, Munuswamy DB (2017b) Performance and emissions analysis on diesel engine fuelled with cashew nut shell biodiesel and pentanol blends. Korean J Chem Eng 344:1021–1026

Devarajan Y, Munuswamy DB, Mahalingam A (2017c) Performance, combustion and emission analysis on the effect of ferrofluid on neat biodiesel. Process Saf Environ Prot 111:283–291. https://doi.org/10.1016/j.psep.2017.07.021

Dincer K (2008) Lower Emissions from Biodiesel Combustion. Energy Sources, Part A 30(10):963–968. https://doi.org/10.1080/15567030601082753

Hasimoglu C (2012) The Effects of Biodiesel on Performance and Exhaust Emissions of a Low Heat Rejection Diesel Engine. Energy Sources, Part A 34(6):570–580. https://doi.org/10.1080/15567031003627955

Hussain J, Palaniraja K, Alagumurthi N (2012) Effect of Exhaust Gas Recirculation (EGR) on Performance and Emission characteristics of a Three Cylinder Direct Injection Compression Ignition Engine. Alex Eng J 51:241–247

Ibrahim A (2016) Performance and combustion characteristics of a diesel engine fuelled by butanol–biodiesel–diesel blends. Appl Thermal Eng 103:651–659

Joy N, Devarajan Y, Nagappan B, Anderson A (2017) Exhaust emission study on neat biodiesel and alcohol blends fueled diesel engine. Energy Sources, Part A 40(1):115–119. https://doi.org/10.1080/15567036.2017.1405119

Karthikeyan S, Prathima A (2016) Environmental effect of CeO2 nanoadditive on biodiesel. Energy Sources, Part A 38(24):3673–3679. https://doi.org/10.1080/15567036.2016.1177624

Li L, Wang J, Wang Z, Xiao J (2015) Combustion and emission characteristics of diesel engine fueled with diesel/biodiesel/pentanol fuel blends. Fuel 156:211–218. https://doi.org/10.1016/j.fuel.2015.04.048

Mahalingam A, Devarajan Y, Radhakrishnan S, Vellaiyan S, Nagappan B (2017) Emissions analysis on mahua oil biodiesel and higher alcohol blends in diesel engine. Alex Eng J. https://doi.org/10.1016/j.aej.2017.07.009

Nalgundwar A, Paul B, Sharma SK (2016) Comparison of performance and emissions characteristics of DI CI engine fueled with dual biodiesel blends of palm and jatropha. Fuel 173:172–179

Venkata Ramanan M, Yuvarajan D (2015a) Performance Study of Preheated Mustard Oil Methyl Ester on Naturally Aspirated CI Engine. Appl Mech Mater 787:761–765. https://doi.org/10.4028/www.scientific.net/amm.787.761

Venkata Ramanan M, Yuvarajan D (2015b) Emissions Analysis of Preheated Methyl Ester on CI Engine. Appl Mech Mater 812:21–25. https://doi.org/10.4028/www.scientific.net/amm.812.21

Yilmaz N, Atmanli A (2017a) Experimental evaluation of a diesel engine running on the blends of diesel and pentanol as a next generation higher alcohol. Fuel 210:75–82. https://doi.org/10.1016/j.fuel.2017.08.051

Yilmaz N, Atmanli A (2017b) Experimental assessment of a diesel engine fueled with diesel-biodiesel-1-pentanol blends. Fuel 191:190–197

Yilmaz N, Atmanli A, Trujillo M (2017) Influence of 1-pentanol additive on the performance of a diesel engine fueled with waste oil methyl ester and diesel fuel. Fuel 207:461–469. https://doi.org/10.1016/j.fuel.2017.06.093

Yilmaz N, Atmanli A, Vigil FM (2018) Quaternary blends of diesel, biodiesel, higher alcohols and vegetable oil in a compression ignition engine. Fuel 212:462–469. https://doi.org/10.1016/j.fuel.2017.10.050

Yuvarajan D, Venkata Ramanan M (2016) Experimental analysis on neat mustard oil methyl ester subjected to ultrasonication and microwave irradiation in four stroke single cylinder Diesel engine. J Mech Sci Technol 30(1):437–446. https://doi.org/10.1007/s12206-015-1248-x

Yuvarajan D, Ravikumar J, Babu MD (2016) Simultaneous optimization of smoke and NOxemissions in a stationary diesel engine fuelled with diesel–oxygenate blends using the grey relational analysis in the Taguchi method. Anal Methods 832:6222–6230

Yuvarajan D, Dinesh Babu M, BeemKumar N, Amith Kishore P (2018) Experimental investigation on the influence of titanium dioxide nanofluid on emission pattern of biodiesel in a diesel engine. Atmos Pollut Res 9(1):47–52. https://doi.org/10.1016/j.apr.2017.06.003

Zhu R, Wang X, Miao H, Yang X, Huang Z (2011) Effect of dimethoxymethane and exhaust gas recirculation on combustion and emission characteristics of a direct injection diesel engine. Fuel 90(5):1731–1737. https://doi.org/10.1016/j.fuel.2011.01.035