Technology

Pak. J. Sci. Ind. Res. 2009 **52** (4) 217-227

Effects of Biodiesel from Soybean Oil on the Exhaust Emissions of a Turbocharged Diesel Engine

Asad Naeem Shah[ab]*, G. E. Yun-shan[a], TAN Jian-wei[a] and He Chao[c]

[a]School of Mechanical and Vehicular Engineering, Beijing Institute of Technology, Beijing 100081, P.R. China
[b]Department of Mechanical Engineering, University of Engineering and Technology, Lahore 54000, Pakistan
[c]School of Transportation, Mechanical and Civil Engineering, Southwest Forestry College, Kunming, 650224, P.R. China

(received August 23, 2008; revised June 2, 2009; accepted June 8, 2009)

Abstract. This paper presents the regulated emissions in the light of cylinder pressure and heat release rate (HRR) from a 4-stroke direct injection (DI) diesel engine fuelled with neat soybean oil-based biodiesel, commercial diesel and 20% biodiesel-diesel blend. The engine was run using electrical dynamometer at four different engine conditions. The experimental results revealed that brake power (BP) of the engine decreased but brake specific fuel consumption (BSFC) increased with biodiesel as compared to diesel. Relative to diesel, the maximum combustion pressure (MCP) was higher; however, HRR curves were not much deeper in the ignition delay (ID) periods and the premixed combustion peaks were lower with biodiesel. Carbon monoxide (CO), total hydrocarbons (HC), smoke opacity, and particulate matter (PM) emissions decreased by 3% to 14%, 32.6% to 46%, 56.5% to 83%, and 71% to 87.8%, respectively; however, oxides of nitrogen (NO_x) increased by 2% to 10% with biodiesel, compared to the commercial diesel. Both smoke and NO_x pollutants were greatly influenced by the MCP. CO, HC, and PM emissions were higher at lower load conditions compared to higher load conditions, but NO_x and smoke pollutants were higher at higher load conditions relative to lower load conditions.

Keywords: diesel engine, direct injection, biodiesel, heat release rate, regulated emissions

Introduction

In the face of the unrelenting use of fossil fuels and its determental effects on human life and environment, finding alternative sources of energy has gained particular significance. Biodiesel, commonly referred to fatty acid methyl or ethyl esters, is produced by the transesterifcation process of the vegetable oils, waste cooking oils and animal fats in the presence of methanol or ethanol as catalyst. It is gaining increasing attention as alternative fuel for diesel engines over the past few years, owing to its clean burning and environmental friendly characteristics. It is renewable, technically feasible, environmentally acceptable, and readily available substitute fuel (Correa and Arbilla, 2006). It has ultra low sulphur (Ebiura *et al.*, 2005) and is non toxic and biodegradable (Turrio-Baldassarri *et al*., 2004) with improved lubricating efficiency (Agarwal *et al.*, 2003), higher flash point, higher cetane number and high oxygen content (Krahl *et al*., 2003). According to Ramadhas *et al.* (2005), biodiesel and its blends with fossil diesel can be used as alternative fuels in compression ignition (CI) engine without modification or adjustment in it.

In, Germany, Italy, France, Austria and Sweden, other European Community member countries and USA, specific legislations have been enacted to promote the production and use of biodiesel (Dube *et al*., 2007; Demirbas, 2007; Korbitz, 1999; Krawczyk, 1996).

India is producing around 6.7 million tons of non-edible oils from plants such as Karanji *(Pongamia glabra)*, castor, linseed, neem *(Azadirachta indica)*, kusum *(Schleichera trijuga)*, and palash (*Butea monosperma*) (Agarwal *et al.*, 2003).

Many studies focussed on regulated emissions have revealed that biodiesel reduces CO, HC and PM emissions (Raheman and Ghadge, 2007; Lebeckas and Slavinskas, 2006; Dorado *et al*., 2003). However, if some authors claim decrease in NO_x pollutants with biodiesel (Agarwal and Rajamanoharan, 2009; Dorado *et al*., 2003; Peterson and Reece, 1996), majority has unanimously reported that NO_x emissions increase with biodiesel (Karabektas *et al*., 2008; Szybist *et al*., 2007; Agarwal *et al*., 2006; Usta, 2005). These discordant findings concerning the emissions of NO_x pollutants are still a dilemma for researchers working on the exhaust emissions of diesel engines fuelled with biodiesel, particularly when the engine is unmodified.

The current work is an effort to investigate, and hence compare the exhaust emissions including CO, HC, smoke and PM

*Author for correspondence; E-mail: naeem_138@hotmail.com

pollutants from an unmodified diesel engine fuelled with biodiesel (B100), diesel (D), and 20% biodiesel-80% diesel (v/v) blend (B20), together with cylinder pressure and heat release studies at different engine conditions. In addition to this, it has also been attempted to study the brake power (BP) and brake specific fuel consumption (BSFC) of the engine at these engine conditions. Prior to this, the authors have reported that B100 and B20 have shorter ignition delay, less maximum rate of pressure rise (MRPR), less brake specific energy consumption (BSEC), a low premixed combustion amount, early start of fuel injection, higher maximum combustion pressure (MCP), and more BSFC compared to fossil diesel (Shah *et al.*, 2009a).

Materials and Methods

Test engine, fuels and working conditions. The tests were performed on a turbocharged, direct injection, heavy duty and intercooled diesel engine (FAW-WDEW 4CK, China made) having a mechanical injection system and working without exhaust gas recirculation (EGR) or any other devices. No modification or adjustment was made in the engine. Detailed specifications of the engine (Shah *et al.*, 2009a, 2009b, 2008), are listed in Table 1. The engine was run on an electrical dynamometer (Schenck HT350, Germany) as shown in Fig. 1.

Three test fuels D, B100, and B20 were used in this study, using D as a reference or baseline fuel. Biodiesel was produced from the soybean oil by the process of transesterification, and the diesel was purchased from the pump, and is representative of fuel being sold in Beijing, China. The main properties of the test fuels are given in Table 2.

Table 1. Engine specifications.

Number of cylinders	4
Bore (mm)	110
Stroke (mm)	125
Displacement (litre)	4.752
Compression ratio	16.8
Rated power (KW/rpm)	117/2300
Maximum torque (N.m/rpm)	580/1400
Nozzle hole diameter (mm)	0.23
Number of nozzle holes	6

The experiments were performed in accordance with the engine conditions given in Table 3. Maximum torque speeds (1400 r/min and 1800 r/min) were selected for the study. The engine load (torque) was measured with the help of torque flange and was read along with speed and throttle position directly on monitor supported by a software "Automation System STARS Rev. 1.5" in the control room. In order to measure the fuel flow rate, PLU (Pier Berg) was used, and fuel flow rate was also read in the control room. Crank angle was found with the help of a sensor (2613A, Kistler Corporation) giving a signal for the top dead center (TDC) and the instantaneous pressure in the cylinder was found receiving the signals through Piezo-electric sensor (6125B, Kistler Corporation). These signals were stored on a high speed computer based

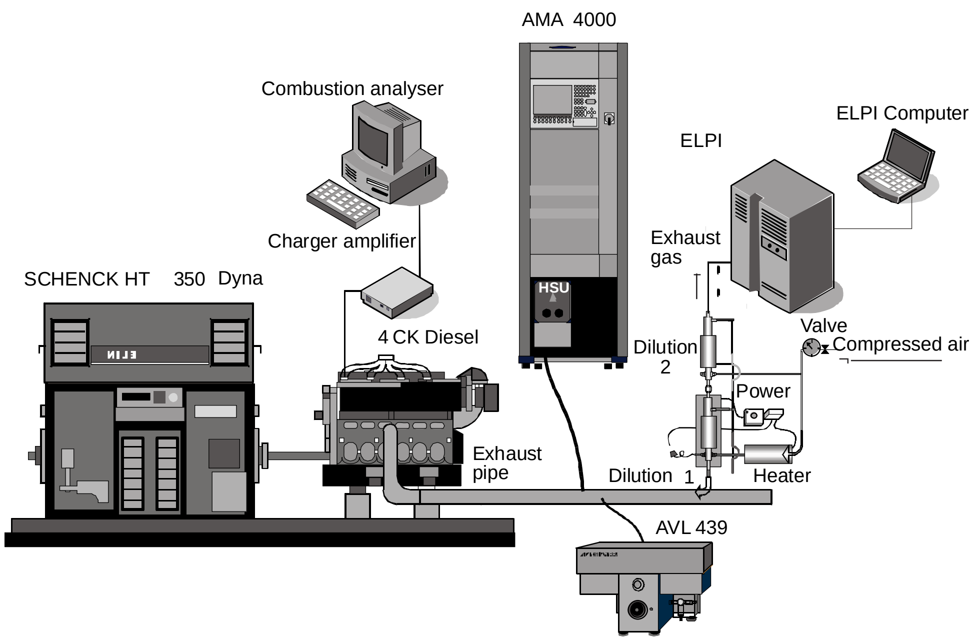


Fig. 1. Experimental setup.

Table 2. Properties of fuels.

Properties	Fuels and blends			Test Method*
	B100	B20	D	
Density (kg/m^3)	875	845.5	841	SH/T 0604
Viscosity (mm^2/s) at 20 °C	7.1	4.3	4.0	GB/T 265
Lower heating value (MJ/kg)	37.3	41.7	42.8	GB/T 384
Sulphur content (mg/litre)	24.5	n/a	264	SH/T 0253-92
Cetane number	60	n/a	52	GB/T 386-91
Carbon content (%)	77	n/a	87	SH/T 0656-98
Hydrogen content (%)	12	n/a	13	SH/T 0656-98
Oxygen content (%)	11	n/a	0	Element analysis

*Chinese standard

Table 3. Engine conditions.

	Speed (r/min)	Load (%)
Engine condition 1	1400	10
Engine condition 2	1400	50
Engine condition 3	1800	50
Engine condition 4	1800	75

digital data acquisition system and were processed with specially developed software using combustion analyzer dewetron (DEWE-5000). Heat release analysis (HRA) was carried out with a special software using Dewetron (DEWE-5000). HRA was performed in accordance with the first law of thermodynamics using single-zone model and making simplified assumptions (Heywood, 1988). In order to measure the temperatures of engine oil and coolant, PT-100 (sensors) were used, while exhaust temperature was measured using thermocouple (k-series).

Exhaust emissions such as HC, CO, and NO_x were measured by heated flame ionization detector (FID), non-dispersive infrared analyzer (NDIR), and chemiluminescent detector (CLD), respectively, using analytical package AMA4000 (Austria). Smoke was measured with an opacimeter using AVL439, which measured the opacity of the exhaust emissions in term of light extinction coefficient (m^{-1}).

For the calculation of PM mass, electrical low pressure impactor (ELPI, Dekati Ltd. Finland) was used. An ELPI is a real time particle number concentration measuring device (Shah *et al.*, 2009b). It consists mainly of corona charger, a low pressure cascade impactor and a multichannel electrometer. Prior to introduction to the impactor, the particles are charged by the corona charger where the aerosol is cut-off by different size scopes, and thus electrometer detects their current which is converted into a particle concentration (He, *et al.*, 2008). In order to avoid overloading of the electrometer, the exhaust gas was diluted with dry, particle free and pressurized air using an ejector diluter (Dekati Ltd. Finland) having an overall dilution ratio of 64. The ejector diluter consists of a set of filters, a dryer, a temperature controller, a pressurized air heater and two diluters having a dilution ratio of 8 for each. The detailed specifications of the above discussed equipments are listed in Table 4.

Results and Discussion

Effect of biodiesel on BP and BSFC. As shown in the Fig. 2 (a), brake power (BP) of the engine was almost unaffected by B20; however, it decreased by 5.8%, 1.5%, 2.7%, and 3.3% at

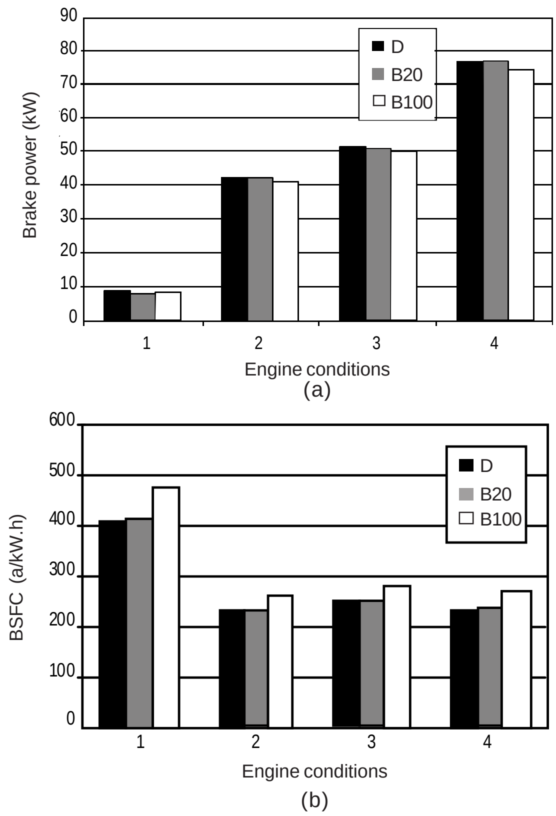


Fig. 2. Effect of biodiesel on (a) brake power and (b) BSFC, at different conditions.

engine conditions 1, 2, 3, and 4, respectively, in case of B100 compared to commercial diesel. This finding is consistent with those of previous studies that BP decreases with the use of biodiesel as compared to diesel (Lin *et al*., 2006). Kaplan *et al.* (2006) compared biodiesel from sunflower oil and fossil diesel and reported that the loss of torque and power ranged between 5% and 10%.

Brake specific fuel consumption (BSFC) is the mass of fuel consumed per brake power (kW) developed by the engine in one hour. Fig. 2 (b) shows a noticeable increase in BSFC of the engine with B100; however, there was a nominal increase in it with B20, relative to diesel. In case of B100, BSFC increased by 16.4%, 14.4%, 14%, and 17% at engine conditions 1, 2, 3, and 4, respectively, as compared with the diesel fuel. These findings are in good agreement with those of earlier studies (Turrio-Baldassarri *et al.,* 2004; Alam *et al.,* 2004). The Southwest Research Institute of USA has reported that fuel consumption with biodiesel from pure soybean oil increased from 13% to 18%, compared with diesel, while with B20, variation in BSFC ranged from -3% to 9% (Wedel,1999).

This decrease in BP and increase in BSFC with B100 is attributed to the lower heating value and more density of the biodiesel compared to fossil diesel. Tsolakis (2006) has reported that higher bulk modulus of biodiesel helps the pressure to be developed faster in the fuel injection system compared to the lower bulk modulus of diesel. Consequently, the fuel injection commences earlier in case of biodiesel with higher pressure and rate, resulting in the increase in mass of biodiesel compared to that of diesel at the same crank angle in degree (CAD). According to Choi *et al.* (1997), higher viscosity of biodiesel is helpful in reducing the fuel losses during the injection process compared to diesel. This reduction in fuel losses helps in faster development of pressure, and hence advances the injection timing.

Effect of biodiesel on the combustion. Figure 3 presents the cylinder pressure and HRR of the engine for the three test fuels used in this study. It is obvious that MCP of the engine is higher with B20 and B100, relative to diesel for all the engine conditions. Although the increase in MCP with B20 is very small, it becomes noticeable with B100 at all the engine conditions. Particularly at engine conditions 2 and 4, the MCP with B100 becomes 5.5% and 4.7% higher, respectively, relative to diesel fuel.

This increase in MCP with B100 and B20 is attributed to their physical and chemical properties. Higher cetane number, better fuel atomization, faster flame propagation speed, higher density, lower compressibility (higher bulk modulus), oxygen

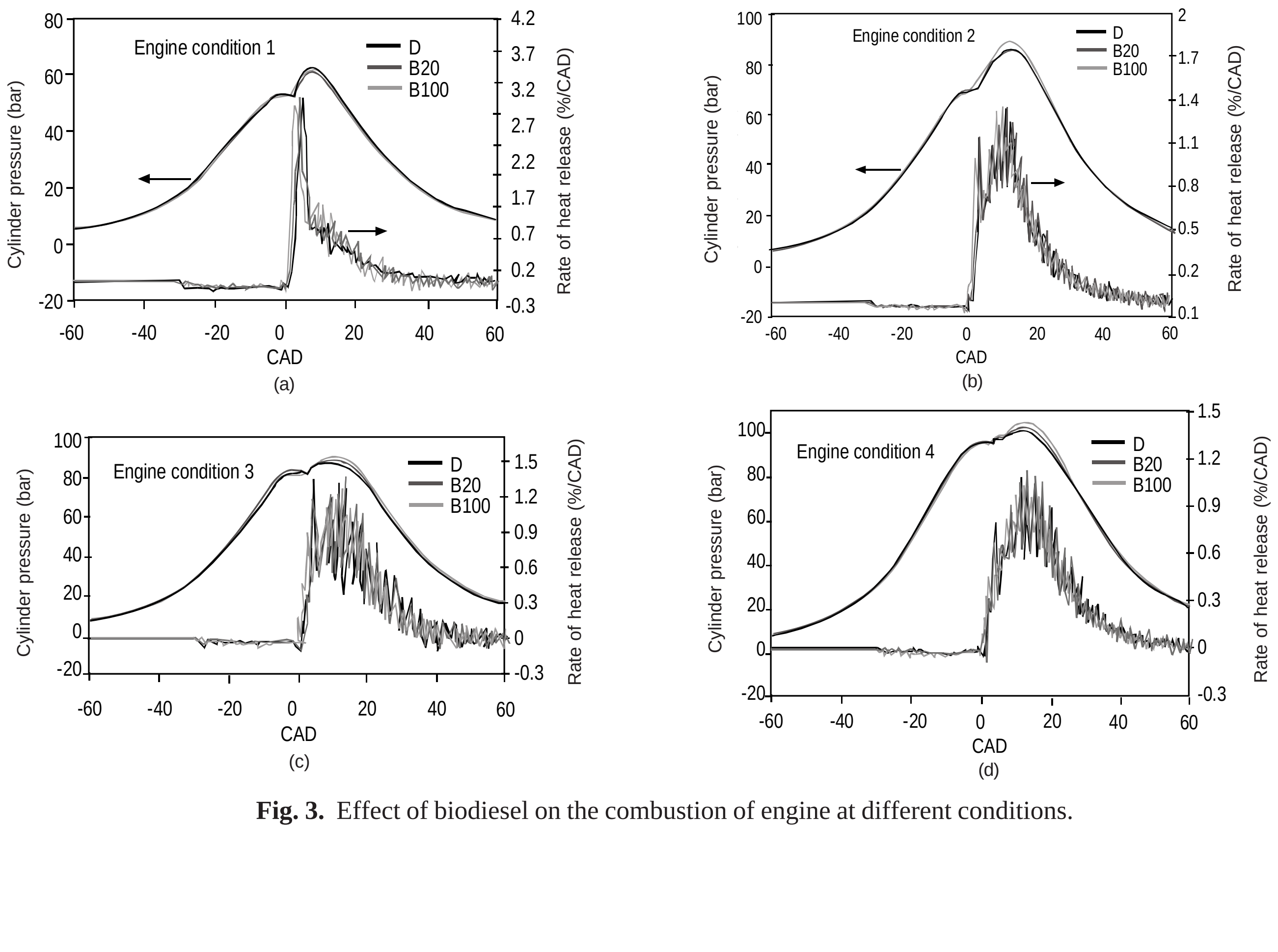


Fig. 3. Effect of biodiesel on the combustion of engine at different conditions.

enrichment and simple chemical structure of the biodiesel are responsible for advancing the combustion process. Higher cetane number of biodiesel reduces the ignition delay, thus results in earlier combustion due to which MCP becomes higher with B100 and B20, relative to diesel (Shah *et al.,* 2009a). Furthermore, biodiesel is an alkyl ester containing internal oxygen atoms which promote the burning of impurities under the same condition of use (Kegl, 2008).

In order to study the HRR, it is important to understand the premixed and diffusion combustion periods. The lowest point on HRR curve between premixed combustion peak and diffusion combustion peak is the point which divides the combustion into premixed and diffusion periods (Xiaoming *et al.,* 2005). According to Zhang and Van Gerpen (1996), heat release curves show a negative trend during the ignition delay period due to endothermic reaction in the combustion chamber (CC), which becomes positive when auto-ignition occurs. Heat release curves are deeper with diesel during this ID period; particularly, at engine condition 3 and 4 the trends are more prominent and distinguishable as shown in the Fig. 3. This indicates smaller endothermic heat with biodiesel, and hence justifies the claim that biodiesel having higher cetane number exhibits shorter ID.

Heat release curves reflect smaller premixed burning peaks with biodiesel, relative to diesel as shown in Fig.3. This may be due to the lower volatility and shorter ID with biodiesel compared to diesel. In case of diesel fuel, more fuel-air mixture is formed due to longer ID, which produces a larger premixed burn peak (Zhang and Van Gerpen, 1996).

Effect of biodiesel on the emissions. ***CO Emission.*** As presented in Fig. 4 (a), CO emissions decrease with B100 and B20 compared to diesel. Relative to diesel, B20 exhibits 19%, 12.5%, 12.3%, and 6.8% reduction in CO pollutants at engine conditions 1, 2, 3, and 4, respectively. There is 2.9%, 5%, 14.2%, and 6.8% decrease in CO emissions with B100 at engine conditions 1, 2, 3, and, 4 respectively, compared with commercial diesel. Similar results have also been reported by other researchers (Choi *et al.,* 1997; Krahl *et al.,* 1996). Last *et al.* (1995) fuelled a 4-stroke DI heavy duty engine with 10%, 20%, 30%, 50% and 100% biodiesel from soybean oil and reported that with respect to diesel fuel there were 10%, 8%, 18%, 6% and 14% reductions in CO emissions, respectively.

The oxygen enrichment and simple chemical structure of biodiesel are major contributors to the reduction of CO emissions with B100 and B20, compared with diesel. The oxygen enrichment in biodiesel promotes the combustion, hence reduces the CO emissions. Unlike fossil diesel, biodiesel has minor short-chain compounds capable of being converted to carbon dioxide (CO_2) more easily (Guarieiro *et al.,* 2008), and thus results in better oxidation and complete combustion. Higher cetane number is also an important factor for the reduction of the possibility of fuel-rich mixture formation, and hence for the reduction of CO emissions (Hansen and Jensen, 1997). Moreover, earlier start of fuel injection, shorter ID and MCP also play a vital role in the reduction of CO emissions.

The experimental results show that CO emissions are higher at condition 1 relative to condition 2 and at condition 3 relative to condition 4, for all the test fuels. This may be due to the large excessive air-fuel ratio and relatively larger ID at low loads (conditions 1 and 3) compared to higher loads (conditions 2 and 4) for the respective speeds. Consequently over-lean mixture area increases, and thus oxidation rate is decreased.

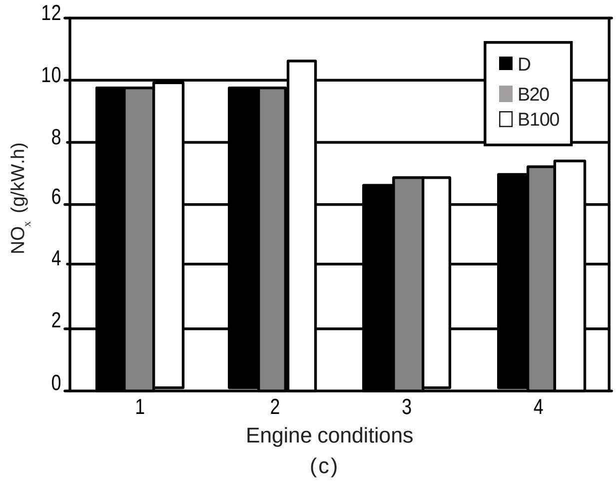
It is also evident from Fig. 4 (a) that CO emissions are higher at engine condition 3 relative to condition 2 which means these emissions are higher at higher speed relative to lower speed for all the test fuels. This increase in CO pollutants can be attributed to decrease in the temperature in the CC at higher speed compared to lower speed, because higher speeds increase the turbulence in the CC, and hence increase the heat loss to the CC walls, ultimately reducing the combustion temperature (Shah *et al.,* 2008). Moreover, Collier *et al.* (1995) have also reported that engine speed affects the swirl characteristics, injection timing and combustion temperature of the engine. So, this relatively lower temperature in CC plays an effective role in the reduction of oxidation rate of CO, and results in the increase of CO emissions.

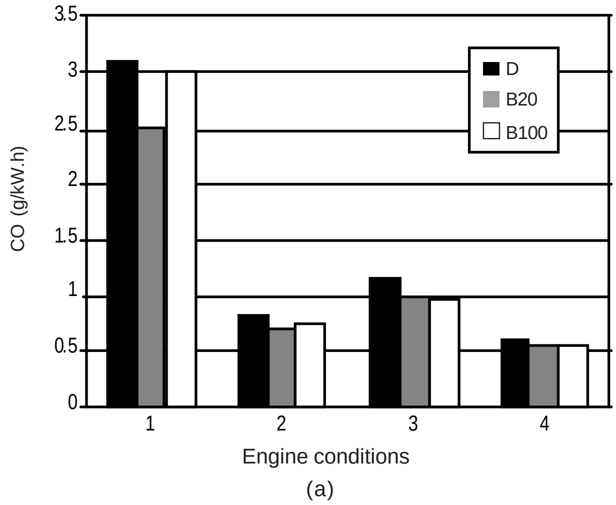
HC emissions. HC emissions decrease by 19%, 20%, 20.8%, and 13% with B20 at engine conditions 1, 2, 3, and 4, respectively, relative to diesel fuel (Fig. 4(b)). The abatements in HC pollutants with B100, compared with the diesel are 43.8%, 44.6%, 46.3%, and 32.6% at engine conditions 1, 2, 3, and 4, respectively. These findings are consistent with those of Peterson and Reece (1996) who performed experiments on a diesel engine fuelled with blends of biodiesel with and without catalytic converter, and reported 50% reduction in HC emissions. Similar findings were also claimed by Last *et al.* (1995) who fuelled the engine with 10%, 20%, 30%, 50% and 100% biodiesel from soybean oil and reported that with respect to diesel fuel there were 28%, 32% and 75% reduction in HC emissions with 10%, 20% and 100% biodiesel, respectively.

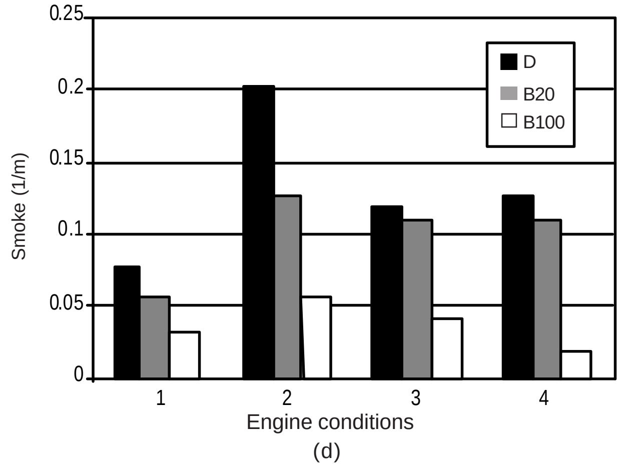
Possible reasons for the reduction of HC emissions with biodiesel are additional oxygen content leading to more complete and cleaner combustion, higher cetane number resulting in reduction in ID and the advanced fuel injection causing the increase in MCP, thus increasing the combustion temperature. Moreover, higher final distillation points for diesel fuel causes incomplete vaporization and burning of its final fraction, thus increasing the HC emissions with diesel (Turrio-Baldassarri *et al.*, 2004).

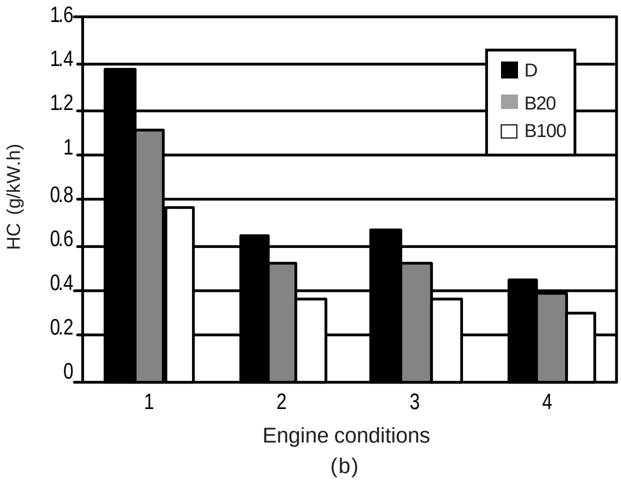
Fig. 4 (b) reveals more HC emissions at engine condition 1 relative to condition 2, and at engine condition 3 relative to condition 4 for the three test fuels. It also shows that HC pollutants are almost same at engine conditions 3 and 4 for the test fuels. Reasons for more HC emissions at lower loads relative to higher loads are the same as those for CO emissions.

NO_x emissions. B20 exhibits a nominal increase in NO_x pollutants at engine conditions 1 and 2; however, it reflects 2.2% and 5.5% increase in them at conditions 3 and 4, respectively, relative to diesel (Fig. 4(c)). In case of B100, there are 2%, 10%, 3.4%, and 7% increase in NO_x emissions at engine conditions 1, 2, 3, and 4, respectively, compared with diesel fuel. These results are in good agreement with those of other studies (Karabektas, *et al.*, 2008; Szybist *et al.*, 2007; Agarwal *et al.*, 2006; Usta, 2005).









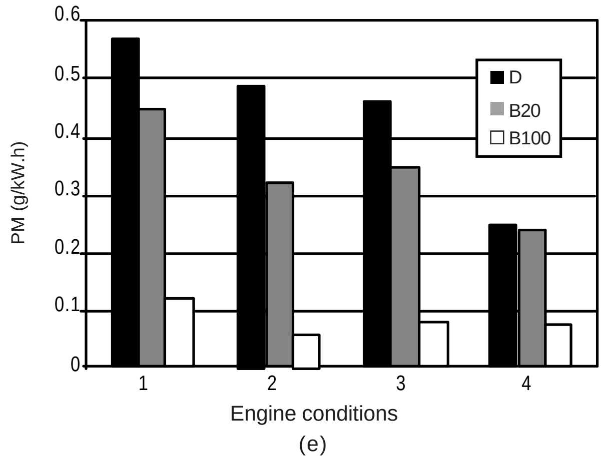


Fig. 4. Effect of biodiesel on (a) CO; (b) HC; (c) NOx; (d) smoke and (e) PM emissions.

Table 4. Specifications of the equipments used in the study

Dynamometer	Company: $Dynas_3$ Schenck Pegasus GmbH; Standard delivery scope: AC induction motor, torque measuring flange, speed measuring system, variable frequency driver, digital test standard controller x-actDE; asynchronous machine: radial forced draft, frequency exchange by eddy current brake, speed up to 10,000 r/min, low mass moment of inertia; frequency converter: high dynamical field-oriented current and torque regulation; full four quadrant operation, double IGBT technique; integrated main filter; torque-meter and speed acquisition: dynamically correct, high mechanical overload capacity, availability of an electronic R-cal, short and low inertia torque flange; speed acquisition: two separate sensors for converter and test standard control, 512 marks/revolution for $Dynas_3$ LI and HT, 1024 marks/revolution for $Dynas_3$ HD.
Fuel flow rate measuring device	Company: Pierburg-Gruppe PLU, Pierburg Luftfahrt Gearate Union GmbH, NEUSS; PLU V2: nominal measuring range 1 = 0.5...60 L/h, nominal measuring range 2 = 1...120 L/h; standard equipment: PLU 4000, temperature sensor PT 100 with transducer; optional equipment: inlet pressure reducers (regular fuels and alcohol-resistant), density meter with built-in PT1000 temperature sensor.
AMA 4000	Company: Pierburg Instruments GmbH Neuss Germany; flow rate: 10-15 L/min; dimensions: 665 mm × 900 mm × 2000 mm (W × D × H); weight: 450 kg; power distributor: 115V ± 10% 50/60 Hz, 230 V ± 10% 50/60 Hz; response time T-90 (via cooler): 3 sec (FID); ambient conditions: sample input pressure = ±300 hPa, temperature = 5-35°C; humidity = 5-80 %; FID 4000 (for non-diluted hot measurements): THC = 0 – 20.000 ppm C_3 (4 measuring ranges definable), CH_4 = 0 – 20.000 ppm C_1; CLD 4000 (for non-diluted hot measurements): NO_x = 0 – 10.000 ppm (4 measuring ranges definable); IRD 4000 measuring ranges: CO h = 0 – 10%, CO_2 h = 0 – 20% (4 measuring ranges difinable).
Combustion analyzer (DEWE-5000)	Company: DEWETRON GESMBH, Graz, Austria; no. of slots for DAQ or PAD modules: 16; total PCI – slots: 5; weight of the instrument: 17 kg; hard disk: 250 GB; data throughout: 30 to 45 MB/s; Power supply: 90 to 260 V_{ac}; display: 1280 × 1024 pixel; processor: Intel Pentium 4 (2.8 G Hz); Ram: 1 GB; operating system: Microsoft WINDOWS XP Professional; operating temperature: 0 - 50°C; storage temperature: -20 to +70°C; humidity: 10 to 80% non cond.
AVL 439 (Opacimeter)	Company: AVL GmbH Graz Austria; application area: engine test beds for static and steady state modes; method of operation (measurement principle): Beer-Lambert Law; gas flow rate: 40…45 L/min; measuring unit: measuring chamber, light unit, detector unit; warm up time: 20-30 min; measuring value out put: opacity N [%] or absorption k [m^{-1}]; measuring range: N = 0…100 % or k = 0…10 m^{-1}; rise time: 0.1 sec (at flow rate 40 L/min); sampling rate for opacity signal: 50 Hz; exhaust gas temperature: 0…600°C; Exhaust gas pressure: -100-+400 mbar; power supply: 230 V; dimensions: 650 mm × 420 mm × 450 mm (W × H × D); weight: 47 kg.
Electrical low pressure impactor (ELPI)	Company: Dekati Ltd. Finland; particle size range: 0.03-10 ìm with filter stage 0.007-10 ìm; number of channels: 12; time resolution: 2-3 sec; Operating conditions: ambient temperature = 5-40°C, ambient humidity = 0-90% non-condensing; aerosol conditions: gas temperature = < 60°C and < 200°C with heated impactor; weight: 35 kg; electric power: 110/220-240 V, 50-60 Hz, 200W; pressure under the first stage: 100 mbar; pump specifications (10 lpm ELPI): minimum 7 m^3/h at 100 mbar abs; computer specifications: Pentium processor, color monitor, MS-Windows 95™, 98™, NT 4.0™, XP™ or 2000™.
ELPI dilutor	Company: Dekati Ltd., Finland; sample air flow (inlet): 10 or 30 L/min; diluted sample flow (outlet): 60 L/min; dilution ratio: 1:8; dilution air pressure: 2 bar; temperature (operating conditions): 0-450°C; total length: 360 mm; max.diametre: 120 mm; inlet, outlet and exhaust: 12 mm male pipe for each; dilution air: 8 mm female; material: AISI 316; gaskets: copper.

Increase in NO_x pollutants with biodiesel may be due to the improved combustion caused by the advanced injection discussed earlier. Monyem and Van Gerpen (2001) and Senatore *et al.* (2000) have also reported increase in NO_x emissions and the role of advanced injection. Moreover, high oxygen concentration in biodiesel plays a significant role in the increase of MCP and temperature and thus increases the NO_x pollutants with biodiesel compared to fossil diesel. According to Cardone *et al.* (2002), physical properties of biodiesel like viscosity, density, compressibility and sound velocity play a significant role in increasing the fuel injection duration and thus are responsible for advancing the combustion process. This advanced combustion causes the increase in NO_x emissions with biodiesel, relative to commercial diesel.

It is worthwhile to note that NO_x pollutants of biodiesel are 10% and 7% higher than those of diesel fuel at engine conditions 2 and 4, respectively. These are the conditions at which percentage difference of two fuels in terms of their NO_x is higher, compared with other two conditions (conditions 1 and 3). As discussed earlier, relative to diesel, biodiesel has 5.5% and 4.7% higher MCP at engine conditions 2 and 4, respectively, which means that the percentage difference of two fuels in terms of their MCP is also higher at engine conditions 2 and 4 compared to other two conditions 1 and 3. This implies that higher the MCP, more are the NO_x pollutants. Higher MCP indicates higher temperature in the cylinder which in turn is responsible for higher NO_x emissions. This is the reason for emission of more NO_x with biodiesel compared to diesel, particularly at engine conditions 2 and 4.

It is important to consider that NO_x are higher at engine condition 2 (lower speed) relative to condition 3 (higher speed). Since at higher speed, CC temperature is lower compared to that at lower speed as discussed earlier so there are appreciable abatements in NO_x at condition 3 for the test fuels. This finding further strengthens the argument that higher temperature in the CC leads to increase in NO_x emissions.

Smoke emissions. Smoke emissions were recorded using light extinction coefficient which is the absolute light absorption unit indicating the quantity of light absorbed at a distance of 1 m. Figure 4 (d) demonstrates that smoke emissions decrease by 25%, 36.6%, 9.1% and 13.6% with B20; and 56.5%, 71.7%, 64%, and 83% with B100 at engine conditions 1, 2, 3, and 4, respectively, relative to diesel fuel.

Decrease in smoke emissions with B20 and B100 is ascribed to increase in oxidation rate of soot with biodiesel compared to fossil diesel. According to Jung *et al.* (2006), oxidation velocity of biodiesel soot is about six times higher compared to that of diesel soot. Song *et al.* (2006) reported faster oxidation of soot by biodiesel of soybean oil compared with fossil diesel. Moreover, lower final boiling point of biodiesel reduces the probability of tar or soot to be formed which are often seen in diesel (Lapuerta *et al.*, 2002).

It is interesting to note that like NO_x emissions discussed above, percentage difference of biodiesel and diesel in terms of smoke opacity is also higher at engine conditions 2 and 4, compared with other two conditions i.e. 1 and 3. The only exception is that in case of NO_x, biodiesel shows higher increase, but in case of smoke it reveals higher abatement in emissions at both these engine conditions. This connotes the trade off between NO_x and smoke emissions of biodiesel.

It is clear from Fig. 4 (d) that smoke is higher at engine condition 2 relative to condition 1 for all the test fuels, and it is also higher at condition 4 relative to condition 3 with diesel and B20; however B100 shows lower smoke emissions at condition 4 compared to condition 3. This increase in smoke at higher load with respect to lower load is ascribed to the formation of rich mixture in CC. However, the decrease in smoke emissions with B100 may be due to the optimum air/fuel ratio that might have occurred at this load level for B100.

PM emissions. PM emissions decrease by 21%, 34.7%, 25.3%, and 3.2% with B20; and 78.9%, 87.8%, 82.72%, and 71.3% with B100 at engine conditions 1, 2, 3, and 4, respectively, relative to diesel (Fig. 4(e)). Above findings are in good agreement with those of Canakci and Van Gerpen (2001) who reported 65% reduction from the tests performed on diesel engine fuelled with biodiesel from soybean oil.

The reduction in PM emissions with B20 and B100 is attributed to the oxygen enrichment resulting in more complete combustion, relative to diesel. In addition to this, lack of aromatic content in biodiesel is also responsible for the reduction of PM emissions, because aromatic content is considered as soot precursor contributing to the PM emissions (Lapuerta *et al.*, 2002). Moreover, nominal sulphur content in biodiesel may help in the reduction of PM emissions by biodiesel compared to diesel (Choi *et al.*, 1997). This sulphur content is responsible for the sulphate formation, and hence for PM emissions.

As shown in Fig. 4 (e), PM pollutants are higher at engine condition 1 compared to condition 2, and at engine condition 3 relative to condition 4 for the test fuels. This may be due to the higher HC emissions at engine conditions 1 and 3 as compared to their corresponding conditions 2 and 4 as shown in Fig. 4 (b).

Conclusions

Following important points have been concluded from the present experimental study:

- At different engine conditions, BP of the engine remained almost unaffected by B20, but it decreased by 1.5% to 5.8% with B100, relative to fossil diesel.
- There was a marginal increase in BSFC with B20; however, B100 exhibited 14% to 17% increase in BSFC as compared to diesel for different engine conditions.
- B20 revealed a nominal increase in MCP; however, B100 exhibited a noticeable increase in it which reached to 5.5% with B100, when compared with commercial diesel.
- Relative to B20 and B100, diesel showed deeper HRR curves during the ignition delay periods and larger premixed combustion peaks.
- At different engine conditions, B20 exhibited 6.8% to 19% reduction, and B100 reflected 3% to 14% abatement in CO pollutants, compared with commercial diesel. CO pollutants were higher at lower load relative to higher load, and at higher speed relative to lower speed.
- HC emissions were reduced by 13% to 20.8% with B20, and 32.6% to 46.3% with B100 as compared to diesel for different engine conditions. HC pollutants were higher at lower load relative to higher load.
- NO_x pollutants increased by 2.2% to 5.5% with B20, and 2% to 10% with B100, relative to fossil diesel fuel. NO_x emissions were greatly influenced by the MCP, and increased with increase in MCP. NO_x emissions were higher at higher load relative to lower load, and at lower speed as compared to higher speed.
- Smoke opacity was considerably affected by biodiesel, and reduced by 9% to 36.6% with B20 and 56.5% to 83% with B100 with respect to diesel, at different engine conditions. The MCP showed a significant impact on smoke emissions and a trade-off between smoke and NO_x was observed. Smoke emissions were higher at higher load, compared with lower load.
- B20 and B100 showed 3.2% to 34.7% and 71.3% to 87.8% abatement in PM emissions, respectively, as compared to the commercial diesel fuel. PM emissions were higher at lower load relative to higher load.

Acknowledgement

The authors acknowledge the financial supports of National Laboratory of Auto-Performance and Emission Test, Beijing Institute of Technology (BIT), Beijing, P. R. China under its project # 50576063.

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