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Performance, emission, and heat release analyses of a direct injection diesel engine running on diesel and soybean ester blends

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Abstract: Conventional diesel and soybean-based biodiesel blends were analyzed as the fuel of a direct injection (DI) compression ignition engine in order to investigate their performance and suitability. The tests were conducted on an air-cooled single cylinder DI diesel engine. Engine torque, brake power, and brake-specific fuel consumption results associated with each of these fuel blends were collected under certain operating conditions. The CO_2, CO, and NO_x emissions were measured and the in-cylinder pressure was collected and analyzed.

The performance characteristics of soybean–diesel blends were similar to those of conventional diesel fuel and the blends showed slightly higher torque and power output compared to the conventional diesel fuel. The results indicate that the soybean ester has great potential as an alternative fuel for diesel engines.

Key words: Alternative fuel, diesel engine, performance, biodiesel, soybean

1. Introduction

In recent years, the price of petroleum has been increasing rapidly; therefore researchers are seeking alternative fuel sources. They have produced different kinds of vegetable oil-based fuels as an alternative for CI engines, which it is not a novel idea. A century ago, Rudolf Diesel tested vegetable oil as a fuel for his engine (Shay, 1993). Currently, researchers are focused on producing reliable and viable fuel from vegetable oil, biodiesel (transesterified oil esters), and biogas for diesel engines. Vegetable oils are widely available in rural areas and can be easily blended with diesel in the neat and esterified (biodiesel) forms. Some of them (e.g., Jatropha oil, karanji oil, coconut oil, sunflower oil, rapeseed oil, and neem oil) have already been tested in internal combustion engines and the results are available in the literature (Reddy et al., 2006).

Biodiesel is nontoxic and has low emission profiles; therefore it is environmentally beneficial (Krawezyk, 1996). Biodiesel has a higher cetane number than petroleum diesel fuel and it contains 10%–11% oxygen by weight (Canakci et al., 2006). The viscosity of vegetable oils is several times higher than that of diesel fuel. Viscosity affects the properties of fuel flow, such as spray atomization, consequent vaporization, and air–fuel mixing in the combustion chamber (Pramanik, 2003; Puhan et al., 2005; Ramadhas et al., 2005). It is crucial to reduce the viscosity of vegetable oils and this can be done in a number of ways, such as preheating, blending with diesel, thermal cracking, and transesterification (Pramanik, 2003; Puhan et al., 2005).

Biodiesel can be used directly in CI engines without substantial modifications to the engine (Laforgia,

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1995). Biodiesel does not contain sulfur or any aromatic compound, which can be considered an advantage. The high production cost of biodiesel compared to petroleum-based diesel is a major barrier to its commercialization. Production expenses are approximately one and a half times greater than those of petroleum-based diesel depending on the feedstock oil type (Zhang et al., 2003). The recycling of waste cooking oil would reduce the cost of biodiesel. Nevertheless, recycled cooking oil is not sufficient to reduce the costs by itself; thus farmers should increase their production capacity of oil crops (e.g., sunflower, rapeseed). The combustion of biofuels and fossil fuels produces CO_2, which accumulates in the atmosphere and leads to many environmental problems such as the greenhouse effect. On the other hand, the crops, which are the source of biofuels, absorb the CO_2; therefore the balance of the ecosystem is sustained (Al-Widyan et al., 2002; Zhang, et al., 2003; Ramadhas et al., 2005).

Biodiesel is most commonly produced from soybean oil in the United States and from rapeseed oil in Europe, using methanol as a catalyst. In the United States, biodiesel must meet ASTM specifications designated in ASTM D-6571; in Europe EN 14214 (for auto-biodiesel) and EN 14213 (heating fuel–biodiesel) specifications must be met (Canakci, 2007).

In recent years, the use of biodiesel in the automotive industry has been continuously increasing, especially in France and Germany (Carraretto et al., 2004). In France, blends with diesel oil are widely used and, in Germany, many engines can be fuelled by pure biodiesel. The calorific value of biodiesel is 12% lower than that of fossil diesel fuel (Antolin et al., 2002). However, some studies reported that biodiesel can create slightly higher engine power than conventional diesel fuel (Kalam et al., 2003). This is due to the more complete combustion with the fuel oxygen in the fuel-rich flame zone (Gonzalez et al., 2000; Leung, 2001; Kalam et al., 2003).

Usta et al. (2005) used a hazelnut soapstock/sunflower oil mixture and diesel blends in a 4-cylinder, 4-stroke, turbocharged indirect injection diesel engine. In their study, the CO emissions of the blend were higher at low speed and lower at high speeds than those of diesel fuel, although the blend resulted in higher CO_2 emissions over the experimental speed range. At partial loads, they noted that the blend did not cause significant changes in the CO and CO_2 emissions. NO_x emissions slightly increased due to the higher end of combustion temperature and the presence of fuel oxygen with the blend at full load. However, the increasing emissions of NO_x slowed down with decreasing load. Gomez et al. (2000) fuelled a Toyota indirect injection, naturally aspirated, 2000 cm^3 displacement diesel engine with vegetable-based waste cooking oil methyl ester. The usage of waste cooking oil methyl ester resulted in significantly lower smoke opacity and reduced CO, CO_2, and SO_2 values, whereas O_2, NO_2, and NO levels were higher compared to the diesel fuel. Leung (2001) studied the properties of biodiesel produced from used waste cooking oil and animal fats from restaurants as feedstock. A reduction in air pollutants of 1.5% to 44% was observed for pollutants other than NO, which had a slight reduction at the idle condition but increased by about 16% at 2500 rpm. Guo et al. (2002) reported that biodiesel reduced smoke and HC emissions, while NO_x emissions changed slightly. Ulusoy et al. (2004) investigated the effects of used frying oil origin biodiesel on engine performance and emissions in a 4-cylinder, 4-stroke diesel engine. Biodiesel presented a reduction of 8.59% in CO emissions and an increase of 2.62% in CO_2 emissions. NO_x emissions increased by 5.03%, while HC and particulate emissions decreased by 30.66% and 63.33%, respectively. Schumacher et al. studied B10, B20, B30, and B40 soybean biodiesel blends on a 6V92TA Detroit Diesels corporation diesel engine at an Environmental Protection Agency (EPA) certificated test cell. They reported fuelling biodiesel/diesel blends effectively reduced particulate matter, unburned hydrocarbons, and carbon monoxide, while increasing nitrogen oxide emissions. The optimum blend ratio based between the trade-off of PM decrease and NO_x increase is B20.

In Usta's (2005) study, detailed experimental results are given on the performance and emissions of a turbocharged indirect injection diesel engine fuelled with tobacco seed oil methyl ester. The results showed that the addition of tobacco seed oil methyl ester to diesel fuel reduced CO and SO_2 emissions while resulting in slightly higher NO_x emissions. In Carraretto et al.'s (2004) study, CO emissions were reduced but those of NO_x were increased. Salvatore et al. (1993) fuelled a turbocharged DI diesel engine with methyl ester of rapeseed oil. Researchers reported that, for the same injection advance as conventional diesel, methyl ester promoted a rise in NO_x emissions and decrease in HC and CO together with a strong reduction in smoke. Chio (1997) conducted tests on biodiesel blended with diesel fuel at concentrations of 20% and 40% by volume in a single cylinder caterpillar engine. A slight increase in NO_x was observed as the biodiesel concentration increased.

The aim of the present study was to explore the effect of soybean biodiesel on CI engine performance. For this purpose, a single-cylinder, 4-stroke DI diesel engine was utilized to evaluate the general performance of biodiesel, diesel, and biodiesel–diesel blends.

2. Experimental setup and methodology

The experimental analysis was carried on a single-cylinder, naturally aspirated 4-stroke diesel engine. A schematic diagram of the test setup is shown in Figure 1 and the specifications of the engine are listed in Table 1. The engine was mounted on an engine test bed consisting of a DC dynamometer, emission measurement instruments, and a control panel. An incremental encoder with 0.1° CA resolution was used for monitoring the engine speed and TDC pick-up. Fuel consumption was measured using a gravimetric fuel flow meter. A Kistler 6052 B piezo pressure transducer, Kistler 5011 B charge amplifier, and LeCroy wave surfer 24Xs 4 channel digital oscilloscope were utilized for acquisition of the in-cylinder pressure data. Prior to the data collection, the engine was fuelled with conventional diesel fuel in order to warm up for 10 min. Throughout all tests, the injection timing (25° BTDC) was kept fixed. The tests were carried out for the full rack position of the engine. The engine speed was varied for 10 different values with the changing of the resistance from the control panel, which was connected to the DC dynamometer. The gaseous pollutant emissions were measured with an AVL DiCom 4000 gas analyzer. The specifications of the ester fuel are listed in Table 2.

Table 1. Technical specifications of the test engine.

Total displacement	454 cm^3
Number of cylinders	Single
Stroke length	80 mm
Bore	85 mm
Compression ratio	17.5:1
Max. torque @ 2000 rpm	28.5 Nm
Max. power @ 3000 rpm	7.5 kW

3. Experimental results and discussion

The effects of soybean fuel addition on the engine torque and power are shown in Figures 2 and 3, respectively. In the experiments, the speed of the engine was varied between 1500 and 3250 rpm. Note that when soybean diesel was blended up to 50% on a volume basis with the diesel fuel no significant difference was observed in the engine torque or power. However, a small increase was obtained in torque with B50 fuel. In general, addition of soybean diesel did not cause any reduction in the torque or power of the engine. The blends presented slightly higher torque and power than the diesel fuel. This outcome could be explained by the higher density, higher viscosity, and better combustion of the blends (Usta, 2005). When fuelling with methyl esters, higher torque and power were observed; this result could be attributed to the beneficial effect of oxygen content of methyl esters, causing more complete combustion (Usta, 2005; Usta et al., 2005).

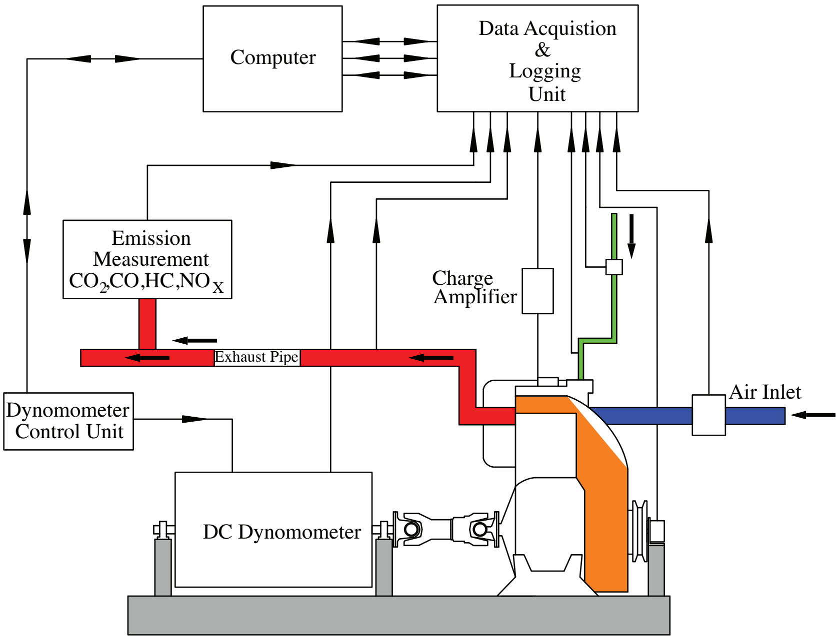

Figure 1. Schematic layout of the test bench.

Table 2. Test fuel specifications.

			DIN EN 14214		
Parameter	Standard	Result	Min.	Max.	Unit
Ester content	DIN EN 14103	96.9	96.5	-	% (m/m)
15 °C density	DIN EN ISO 12185	883.4	860	900	kg/m^3
40 °C viscosity	DIN EN ISO 3104	4.512	3.5	5	mm^2/s
Flash point	DIN EN ISO 3679	123	120	-	°C
CFPP	DIN EN 116	–18	-	-	°C
Sulfur content	DIN EN ISO 20884	1.3	-	10	mg/kg
Carbon residue (10%)	DIN EN ISO 10370	0.15	-	0.3	% (m/m)
Cetane number	ISO 5165	54.1	51	-	
Water content	DIN EN ISO 12937	357	-	500	mg/kg
Copper strip	DIN EN ISO 2160	1	1	1	Corr. degree
110 °C oxidation stability	DIN EN 14112	7.1	6	-	h
Acid	DIN EN 14104	0.36	-	0,5	mg KOH/g
Iodine	DIN EN 14111	115	-	120	g Iodine/100 g
Methanol content	DIN EN 14110	0.11	-	0.2	% (m/m)
Free glycerol	DIN EN 14111	0.01	-	0.02	% (m/m)
Monoglyceride content	DIN EN 14105	0.5	-	0.8	% (m/m)
Diglyceride content	DIN EN 14105	0.12	-	0.2	% (m/m)
Triglyceride content	DIN EN 14105	0.04	-	0.2	% (m/m)
Total glycerol	DIN EN 14105	0.16	-	0.25	% (m/m)
Phosphorus content	DIN EN 14107	< 0.5	-	10	mg/kg

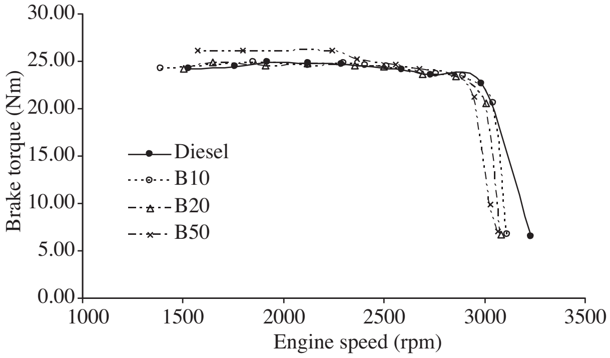

Figure 2. Variation in torque values.

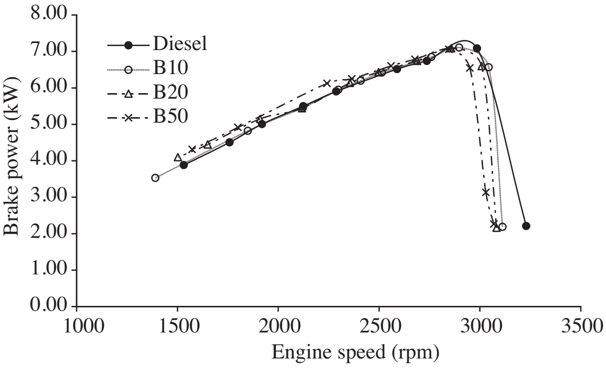

Figure 3. Variation in brake power values.

When fuelling with blends the maximum torque of the engine was obtained at 2000 rpm. The increases in the torque with B20 and B50 blends were 3.4% and 4.80% at 2000 rpm, respectively. However, no torque change was observed with B10 for this operating point. The maximum power values of the engine were obtained at 3000 rpm for both fuels and when fuelling with blends negligible changes (±0.1) were observed.

The variations in the BSFC values of the diesel fuel and the blends are shown in Figure 4. The BSFC values of the blends were slightly lower than those of the diesel fuel. The BSFC at the maximum power was 285 g/kWh with diesel, and 270 g/kWh, 265 g/kWh, and 268 g/kWh with B50, B20, and B10 fuels, respectively.

The combustion of fossil fuels produces CO_2, which accumulates in the atmosphere and leads to many environmental problems. The combustion of biofuels also produces CO_2 but absorption of the crops keep the CO_2 level in balance (Al-Widyan, 2002; Ramadhas, 2005). Figure 5 illustrates the CO_2 values of the experimental fuels at different operating conditions. The maximum CO_2 emission was observed with diesel and the minimum was observed with B50. In general, CO_2 values of the blends were close to each other. Compared to the blends, the diesel emitted more CO_2 at the maximum power speed of 3000 rpm. A higher amount of CO_2 in exhaust emission is an indication of complete combustion (Al-Widyan et al., 2002; Ramadhas et al., 2005).

Figure 6 shows the variation in CO values with engine speed. The experimental results with the blends exposed significant reductions in CO. The reduction may be explained by the extra fuel oxygen (Usta, 2005). The minimum CO emission was at about 3000 rpm with B50. In addition, the blends present very similar values at 3000 rpm. The maximum CO emissions were obtained at 1500 rpm with diesel. For the low load operating conditions with the decreased AFR the CO emissions were lower compared to high load conditions (Salvatore et al., 1993; Al-Widyan et al., 2002; Silva et al., 2003; Ramadhas et al., 2005; Usta, 2005; Usta et al., 2005).

It was determined that the combustion of biofuels and NO_x emissions depends on both the composition and chemical structure of fatty acids (Graboski, 1998) and fuel properties (Labeckas, 2009). In the literature, there are 2 different interpretations about NO_x production of biodiesel. Some researchers (Graboski et al., 1998; Gonzalez et al., 2000; Agarval et al., 2001; Monyem et al., 2001) have reported higher NO_x production, while others (Kalam et al. 2002; Dorado et al., 2003; Lin et al., 2003) have shown lower NO_x emissions (Canakci, 2007). Figure 7 shows the variation in NO_x with engine speed. It can be seen from this figure that the maximum NO_x values were obtained with the blends. In addition, NO_x emission of the conventional diesel was lower than that of biodiesel blends. NO_x emission slightly increases due to the higher combustion temperature and the presence of fuel oxygen with the blend at full load (Usta et al., 2005). In Gomez et al.'s (2000) study

NO_2 and NO levels were higher when compared to those of diesel fuel. In Leung's (2001) study, NO had a slight reduction at the idle condition but increased about 16% at 2500 rpm with biodiesel. Ulusoy et al. (2004) observed an increase of 5.03%. In Usta's (2005) study, the addition of tobacco seed oil methyl ester to diesel fuel reduced CO and SO_2 emissions while causing slightly higher NO_x emissions. In Carraretto et al.'s (2004) study, the NO_x was increased.

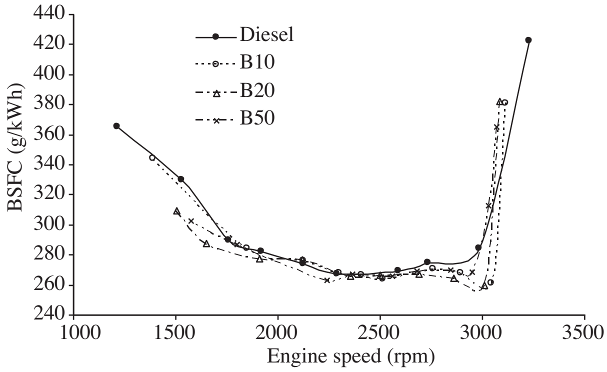

Figure 4. Variation in the BSFC values.

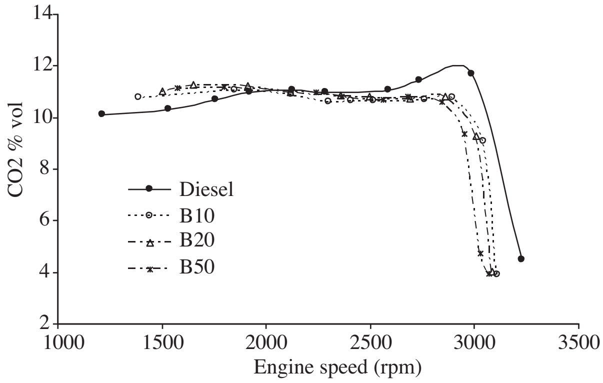

Figure 5. Variation in the CO_2 emissions.

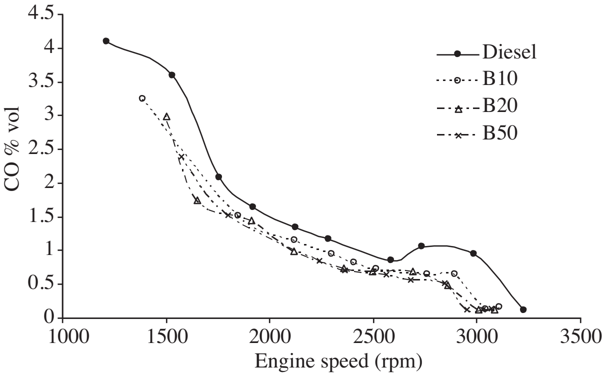

Figure 6. Variation in the CO emissions.

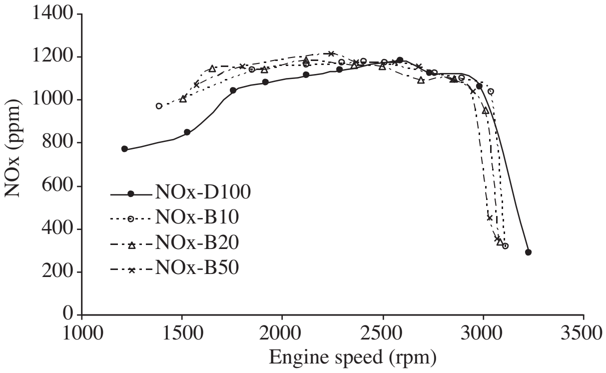

Figure 7. Variation in the NO_x emissions.

The heat release rate of the fuel generates a variation in gas pressure and temperature within the engine cylinder. It strongly affects the fuel economy, power output, and emissions of the engine (David et al., 1975; Heywood, 1988; Banapurmath et al., 2008). The first law equations of thermodynamics are commonly used for the heat release calculation of internal combustion engines. This is a simplified expression, but it provides acceptable results. In this equation, dQ_w denotes the heat transfer to the walls (Heywood, 1998; Brunt et al., 1999; Leung, 2001; Canakci, 2007; Banapurmath, 2008).

$$\frac{dQ_{hr}}{dt} = \frac{\gamma}{\gamma - 1}.p\frac{.dV}{dt} + \frac{1}{\gamma - 1}.V.\frac{dp}{dt} + \frac{dQ_w}{dt} \tag{1}$$

The gamma (γ) alters according to the mixture temperature and composition. Related studies state gamma to be a function of temperature (Brunt et al., 1996). In the expression given below, T denotes the temperature in Kelvin. The results of this expression at 1000 K and 2000 K are 1.3 and 1.27, respectively.

$$\gamma = 1.35 - 6.0 \times 10^{-5} \times T + 1.0 \times 10^{-8} T^2 \tag{2}$$

In Eq. (1), the heat transfer to the walls (dQ_w) can be computed with the formula given below (Egnell, 2000, 2001). In this expression, h_c (W/Km^2) represents the heat transfer coefficient. In the literature, this coefficient can be determined with different equations. The most common used equation is Woschni's (1967) correlation, which is given in Eq. (4).

$$\frac{dQ_w}{dt} = h_c x A_w (T_g - T_w) \tag{3}$$

$$h_c = 3.26.B^{-0.2}.P^{0.8}.T^{-0.55}w^{0.8} \tag{4}$$

In Woschni's correlation,

B: cylinder bore (m),

p: instantaneous cylinder pressure (kPa),

T: temperature (K)

w: local average gas velocity (m/s).

Equation (1) is solved using Matlab© and the heat release rate is obtained. The rate of heat release for the test fuels at the maximum power operating conditions is depicted in Figure 8. The first peak occurs during the premixed combustion phase. It is the result of the rapid combustion of the injected fuel portion that vaporized and mixed with the air during the period of ignition delay. The heat release curve in the premixed combustion phase is relatively independent of the load, because the initial mixing is independent of the duration of the injection. The second peak takes place during the mixing–controlled combustion. The heat release during this phase depends on the duration of the injection. As the duration prolongs, the amount of injected fuel increases, thus resulting in growth of the magnitude and the duration of the mixing–controlled heat release (Ferguson et al., 2001). The outcome shows that the premixed combustion phase of diesel provides a higher rate of heat release than diesel–biodiesel blends. Both the rate of heat release and its maximum values decrease with the increase in soybean ester proportion in the blends. These results were similar to those in Banapurmath's (2008) study. Nevertheless, the mixing–controlled phase of each fuel displays similar behavior in general.

The in-cylinder pressure data at maximum load (2000 rpm) are given in Figure 9 for diesel fuel and blends. The cylinder pressure curves for the soybean ester blends reveal that their ignition delays are almost the same as that of the diesel fuel. Here, the pressure values obtained from the experiments are closer to Rakopoulos's (2007) experimental results.

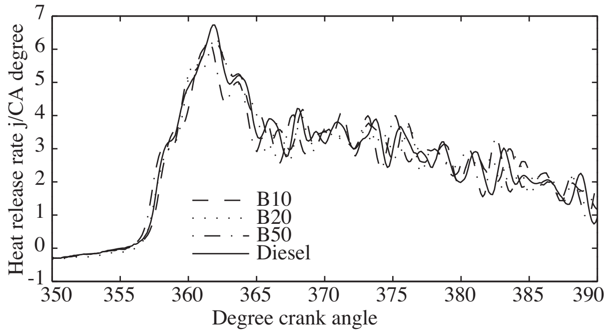

Figure 8. Variation in the heat release rate.

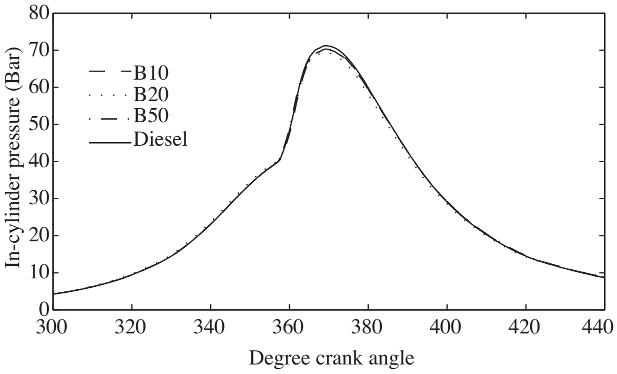

Figure 9. Variation in the cylinder pressure.

4. Conclusions

In this study, soybean ester was tested in a single cylinder, 4-stroke DI diesel engine. By using soybean ester–diesel blends, the engine operated smoothly without any notable problems.

The maximum torque generated by the soybean ester blends (B20, B50) was higher than that of diesel fuel operations. In general, the performance characteristics of soybean ester blends were closer to those of diesel fuel. CO, NO_x, and CO_2 emissions were very similar or lower than those of diesel fuel.

The rate of heat release in the premixed combustion phase of diesel was higher than that of diesel–biodiesel blends. Both the rate and maximum value of heat release decreased with the higher percentage of soybean ester in the blends. On the other hand, the mixing–controlled phase exhibited similar behavior for each fuel.

Biodiesel represents one of the best alternatives as a renewable fuel for diesel engines from economic, energy and environmental protection perspectives. Due to its structural nature and carbon cycle, biodiesel is a fuel that does not contribute to the greenhouse effect (Ahouissoussi, 1997).

As a result, the findings of this work clearly indicate that soybean ester blends have no negative impact on engine performance and can be easily used as the fuel of diesel engines.

Nomenclature

AFR	air/fuel ratio	DC	direct current
ASTM	American Society for Testing and Materials	DI	direct injection
B10	blend with 10% biodiesel and 90% diesel fuel	EN	European norm
B20	blend with 20% biodiesel and 80% diesel fuel	EPA	Environmental Protection Agency
B50	blend with 50% biodiesel and 50% diesel fuel	HC	hydrocarbon emission
BSFC	brake specific fuel consumption	NO_x	nitrogen oxide emission
BTDC	before top dead center	O_2	oxygen
CA	crank angle	RPM	revolutions per minute
CI	compression ignition	SO_2	sulfur dioxide
CO	carbon monoxide emission	TDC	top dead center
CO_2	carbon dioxide emission		

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