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Araştırma Makalesi / Research Article

Pamuk Yağı Biyodizeli-Eurodizel Karışımlarının Tam Yükte Yanma, Performans ve Emisyonlara Etkisinin Deneysel Olarak İncelenmesi

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Anahtar kelimeler
Alternatif yakıtlar; Biyodizel; Pamuk yağı; Yanma karakteristikleri; Motor performansı; Egzoz emisyonları.

Özet

Bu çalışmada, pamuk yağı biyodizelinin değişik oranlarda eurodizel yakıtına ilavesinin yanma, motor performansı ve emisyonlar üzerindeki etkisi incelenmiştir. Deneyler tam yükte ve 1500 dev/dak ile 3000 dev/dak arasında 500 dev/dak aralıklarla gerçekleştirilmiştir. Deneylerde eurodizel yakıtına (CB0), % 10, %20 ve %50 pamuk yağı biyodizeli eklenerek (sırasıyla CB10, CB20 ve CB50 olarak isimlendirilen) elde edilen yakıt karışımları kullanılmıştır. Elde edilen bu yakıt karışımları elektrik dinamometresi ile yüklenebilen tek silindirli, dört zamanlı, hava soğutmalı, direk püskürtmeli bir dizel motorunda test edilmiş ve sonuçlar referans eurodizel yakıtı ile karşılaştırılmıştır. Sonuçlar, referans eurodizel yakıtına pamuk yağı biyodizeli ilavesinin tüm devirler için motor gücü ve torkunda çok az düşüşe neden olduğunu göstermektedir. Özgül yakıt tüketiminde ise küçük bir artış gözlenmiştir. Tam yükte tüm devirler için pamuk yağı biyodizeli ilavesiyle birlikte CO, HC ve is emisyonlarının azaldığı, NO_x emisyonlarının ise arttığı gözlenmiştir. Pamuk yağı biyodizeli karışımlarının tutuşma gecikmesi, pamuk yağı biyodizelinin düşük setan sayısı nedeniyle eurodizelden daha uzun olduğu gözlenmiştir. Ateşleme gecikmesi daha uzun olduğundan, ısı salınım hızı çok hızlı bir şekilde artmış ve yanma süresi kısalmıştır. Yakıtların maksimum yanma basınçları önemli bir değişiklik göstermemiştir.

Experimental Investigation of the Effect of Cottonseed Oil Biodiesel-Eurodiesel Mixtures on Combustion, Performance and Emissions at Full Load

Keywords
Alternative fuels; Biodiesel; Cottonseed oil; Combustion characteristics; Engine performance; Exhaust emissions.

Abstract

In this study, the effect of the addition of cottonseed oil biodiesel to eurodiesel fuel at different ratios on combustion, engine performance, and exhaust emissions was investigated. Tests were performed at full load and from 1500 rpm to 3000 rpm at 500 rpm intervals. In the experiments, fuel mixtures obtained from eurodiesel fuel (CB0), 10%, 20%, and 50% cottonseed oil biodiesel (named as CB10, CB20 and CB50 respectively) were used. The resulting fuel mixtures were tested in a four-stroke, direct-injection, air-cooled, single-cylinder diesel engine that could be loaded with an electric dynamometer. And the results are compared with the reference eurodiesel fuel. The results show that the fuel cottonseed oil biodiesel addition to the reference eurodiesel causes a very little decrease in engine power and torque for all rpms. A slight increase in specific fuel consumption was observed. It has been observed that with the addition of cottonseed oil biodiesel for all rpms at full load resulted in a decrease in smoke, HC, and CO emissions and an increase in NO_x emissions. It has been observed that the ignition delay of cottonseed oil biodiesel mixtures is longer than in eurodiesel due to the low cetane number of cottonseed oil biodiesel. As the ignition delay is longer, the heat release rate has increased very quickly and the combustion duration has been shortened. The maximum combustion pressures of the fuels did not show a significant change.

1. Introduction

The use of petrol-based diesel engines is increasing. Because of this, the fuel requirement is also increasing. Increasing air pollution, the rapid increase in petroleum costs, on the other hand decreasing oil reserves, has directed researchers to improve alternative fuels. One of these fuels is biodiesel (Emiroğlu and Keskin 2010). Biodiesel that does not contain any sulfur, aromatic hydrocarbons, oil residues is called clean fuel or green fuel (Çaynak et al. 2009). Furthermore, biodiesel with a cetane number between 49 and 62 improves combustion efficiency and decreases exhaust emissions of a diesel engine.

Biodiesel and mixtures of biodiesel with diesel generally reduce hydrocarbons, carbon monoxide, sulfur oxides and smoke emissions while increasing nitrogen oxides (Keskin et al. 2007). The use of biodiesel is an economically important advantage for countries that import petroleum like Turkey (Keskin et al. 2008).

Biodiesel is obtained by a chemical process called transesterification or esterification in which the raw materials (fats or oils) reaction with alcohols (ethyl or methyl). In this chemical reaction, alkaline catalysts (like potassium hydroxide and sodium hydroxide) or acid catalysts (like hydrochloric acid and sulfuric acid) are used. After the reaction, glycerin, a by-product of the reaction, is separated from biodiesel by a centrifuge or settling tank. The type and amount of catalysts and alcohols, time of reaction temperature and time, pressure, free fatty acid content, and water content in oil or fat are the basic factors, which have been investigated in many studies (Keskin et al. 2010). Edible (e.g. sunflower oil, canola oil, etc.) or non-edible (e.g. pongamia oil, jatropha oil, etc.) vegetable oils, animal fats, and waste cooking oils are some of the raw materials for producing biodiesel (Karabaş, 2013; Aksoy, 2016; Aysal et al. 2014; Berchmans and Hirata 2008; Naik et al. 2008; Uyumaz et al. 2017; Bayrakceken, 2011; Keskin, 2016).

The low freezing point and the low pour point of corn oil, canola oil, sesame oil, cotton oil and soybean oils make them the alternative for diesel fuel (Sarıdemir and Albayrak 2015). In the production of biodiesel in the world, rapeseed (canola), soybean, and sunflower oils are widely used as feedstocks (Azcan and Danışman 2006). Fig. 1 shows the types and amounts of oil seeds production in Turkey between 2004 and 2013. One of the most produced oil seeds is cotton seed as seen in Fig. 1 (Eryilmaz et al. 2016).

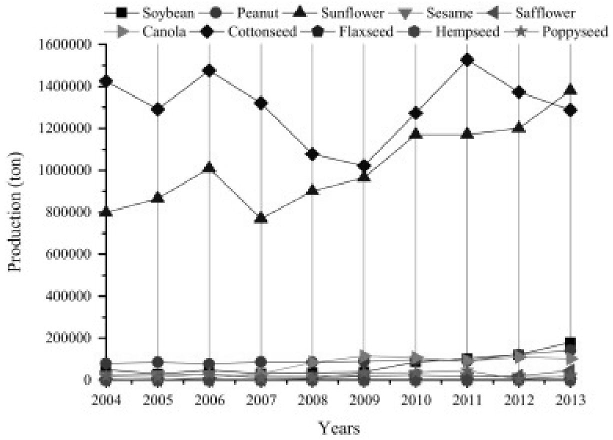

Figure 1. Types and amounts of oil seeds production in Turkey (Eryilmaz et al. 2016).

In Turkey, 882 thousand tons of cotton fibers are produced, with 1160 kg per hectare in 760 thousand hectare harvest area. Therefore cotton is one of the important agricultural products of Turkey. Also, cottonseed which is an important vegetable oil source contains about 17-21% fat. Only 15% of this oil can be recovered (Pütün, 2010).

Cottonseed oil contains di-unsaturated fatty acids (49-58% linoleic acid, linolenic acid traces), monounsaturated fatty acids (15-20% oleic acid, palmitoleic acid traces) and saturated fatty acids (22-26% palmitic acid, 2-5% stearic acid and behenic, arachidic and myristic acid traces). Esterified cotton seed does not contain phosphorus and sulfur. Also, it contains the higher ratio of ester and alkane. These properties make the cotton seed oil an environmentally friendly alternative fuel candidate (Balaji and Cheralathan 2014).

In previous studies, the parameters of biodiesel production from cottonseed oil were investigated (Azcan and Danışman 2006; Rashid et al. 2009; Shu et al. 2009), and the performance and exhaust emissions of diesel fuel-cottonseed oil biodiesel mixtures were investigated (Aydın and Bayındır 2010; Kahraman et al. 2013) and no detailed study of combustion performance and characteristics was found. Combustion characteristics are very important in interpreting engine performance and exhaust emissions in an engine. Combustion characteristics; maximum cylinder gas pressure and crank angle position, heat release, cumulative heat release, ignition delay resulting from combustion and injection times, total combustion duration and instantaneous combustion duration (Türkcan et al. 2009; Çelik et al. 2015).

In this study, the effect of cottonseed oil biodiesel-eurodiesel mixtures at certain ratios on the combustion, performance, and exhaust emissions of a direct injection diesel engine was experimentally investigated.

2. Materials and Method

In this study, the effect of cottonseed oil biodiesel-eurodiesel mixtures on the engine performance and emissions were examined. For this purpose, the fuel mixtures called CB10, CB20 and CB50 are obtained by mixing 10%, 20% and 50% by cottonseed oil biodiesel with eurodiesel used as a reference. The prepared fuel mixtures were tested in a single cylinder, air cooled, four-stroke, direct injection diesel engine that could be loaded with an electric dynamometer. The results were compared with the reference eurodiesel fuel. Experiments were performed at full engine load and from 1500 rpm to 3000 rpm at 500 rpm intervals. Some basic features of eurodiesel and cottonseed oil biodiesel fuels are presented in Table 1. At the beginning, eurodiesel fuel called CB0 was used to get a reference. Subsequently, experiments were conducted with fuel mixtures called CB10, CB20 and CB50. The prepared fuel mixtures were tested under the same conditions to compare with the eurodiesel fuel. In the experiments, a four-stroke, single cylinder, air cooled, direct injection diesel engine was used. The technical characteristics of the diesel engine (Lombardini 15 LD 350) used in the experiments are shown in Table 2.

Table 1. Some specifications of the experiment fuels

Properties	Eurodiesel	CB
Kinematics viscosity (mm^2/s) (40 °C)	2.4	4.32
Density (kg/m^3) (15 °C)	831.5	884
Flash point (°C)	70	180
Cetane number	58.8	53.6
Lower heating value (MJ/kg)	43.2	39

Kemsan brand electrical dynamometer (15 kW, 3000 rpm) was used to load the diesel engine. The engine torque was determined using a Kistler 4550A torque meter. An encoder (Kistler 2614B) was mounted to the crankshaft in order to determine the engine speed, top dead center (TDC), and crank angle. A piezoelectric pressure sensor (A3 Kistler 6052C) and a charge amplifier (5064) were used to measure the cylinder pressure (CP). The cylinder pressure was measured at a resolution of 0.1 degrees crankshaft angle. The schematic representation of the experimental setup is shown in Figure 2. Emissions were measured using a Mobydick 5000 Kombi brand gas analyzer. The characteristics of the gas analyzer and opacimeter are seen in Table 3.

Table 2. Technical characteristics of the experiment engine

Characteristics	Value
Maximum power	7.5 kW/3600 rpm
Maximum torque	16.6 Nm/2400 rpm
Bore × stroke	82 mm × 66 mm
Displacement	349 cm^3
Compression ratio	20.3/1
Injection pump type	QLC type
Injection nozzle	0.22 x 4 holes x 160°
Fuel delivery advance (°CA)	20 BTDC
Intake valve open/close (°CA)	10 BTDC/42 ABDC

Before all experiments, the engine was run until stable data output had been obtained. Heat release rate, maximum cylinder pressure, and its location, combustion start and end locations, maximum pressure and heat dissipation ratios according to crank angle were calculated using KiBox Cockpit software. All data received from KiBox were used by taking averages of 100 cycles.

Table 3. The specifications of the opacimeter and exhaust gas analyzer

Emissions	Range	Accuracy
Smoke (m^{-1})	0-20	0.01
CO (%,v/v)	0~10	0.01
HC (ppm)	0~20000	1
NO_x (ppm)	0~5000	1

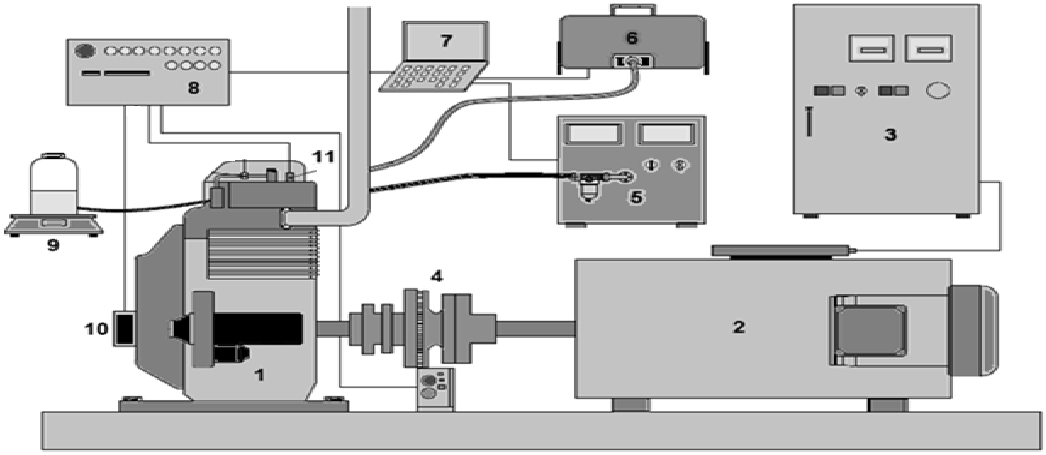

Figure 2. Schematic representation of the experimental setup.

The heat release rate (HRR) was calculated by equations (1):

$$\frac{dQ_n}{d\theta} = \frac{k}{k-1} p \frac{dV}{d\theta} + \frac{1}{k-1} V \frac{dp}{d\theta} \quad (1)$$

The wall heat loss is not taken into account when calculating HRR. In Equation 1, k is the constant polytropic exponent and it was taken as 1.37 in this study. The start of combustion (SOC) corresponds to 5% of the total heat release and the end of combustion (EOC) corresponds to 90% of the total heat release. The combustion duration (CD) is the difference between the SOC and the EOC. The start of injection (SOI) is the crankshaft angle at which the fuel line pressure reaches the injector opening pressure. For the engine used in the experiments, this value is 207 bar. The ignition delay (ID) is the period interval from the SOI to the SOC. The change in cylinder pressure, heat release, and ignition delay according to crankshaft angle and fuel type were analyzed.

3. Results and Discussion

The effects of cottonseed oil biodiesel mixtures compared to those of eurodiesel, on engine performance (engine torque, engine power, brake specific fuel consumption, brake thermal efficiency), emissions (NO_x, smoke, CO, and HC) and combustion characteristics have been studied on a direct injection diesel engine.

Fig. 3 shows the variations in engine power for eurodiesel and different fuel mixtures at full load. The results indicate that there are no remarkable differences in the measured engine power between eurodiesel and fuel mixtures at the beginning. However, the difference is noticeable at high engine speeds. The measured engine power for fuel mixtures is lower than that of the eurodiesel fuel. The lower heating value of the cottonseed oil biodiesel is accountable for this decrease (Kaplan et al. 2006; Büyükkaya 2010).

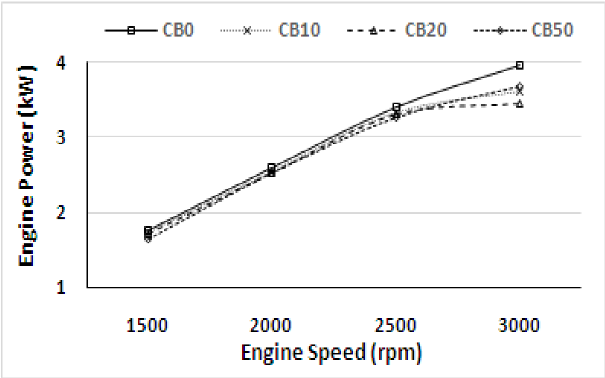

Figure 3. The variations in engine power for eurodiesel and different fuel mixtures at full load.

Fig. 4 indicates the variations in engine torque for eurodiesel and different fuel mixtures at full load. For all fuels, the engine torque increases from the beginning with increasing of engine speed until the 2500 rpm. Then it decreases as the engine speed increases further.

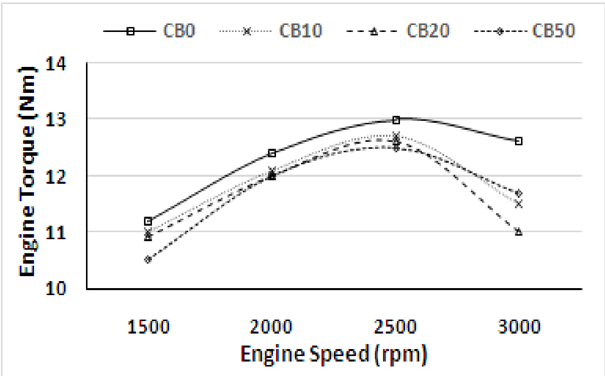

Figure 4. The variations in engine torque for eurodiesel and different fuel mixtures at full load.

Maximum engine torque was obtained at 2500 rpm for all fuels. At 2500 rpm, engine torque of B10 was the closest to the eurodiesel. A pronounced torque drop was observed for fuel mixtures respect to eurodiesel. The higher viscosity and the lower heating value of the cottonseed oil biodiesel are responsible for this reduction (Usta 2005; Çetinkaya et al. 2005; Büyükkaya 2010).

The brake specific fuel consumption (BSFC) is the ratio of the fuel consumption to the brake power of the engine (Karabektas, 2009).Fig. 5 shows the changes in the BSFC with engine speed for eurodiesel and different fuel mixtures at full load condition. The decrease of the volumetric efficiency, the increase of the friction, and the deterioration of the combustion increase the BSFC at high engine speeds. Therefore, the BSFC value decreases with the rise of the engine speed until the 2500 rpm and then slightly rises with a further rise of the engine speed for test fuels. Because at the medium engine speeds the physical and chemical properties of fuels are better for a complete combustion, the lowest BSFC values are around 2500 rpm for all fuels. Eurodiesel has the lowest BSFC value for all engine speeds. The BSFCs of biodiesel fuel mixtures are higher than that of eurodiesel for all engine speeds because of the lower heating value and higher viscosity of biodiesel. For this reason, the quantity of fuel introduced into the cylinder for the requested energy input has to be greater with the biodiesel (Labeckas and Slavinskas 2006; Gümüş 2010).

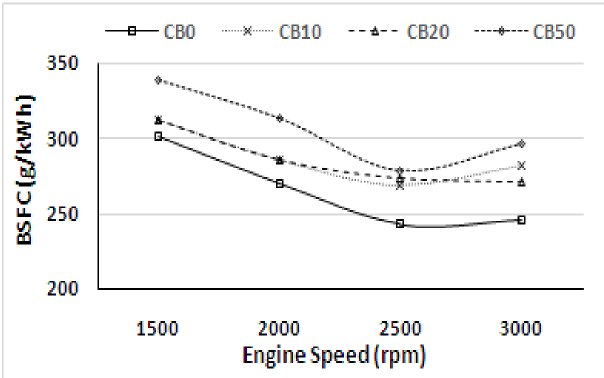

Figure 5. The variations in the BSFC with engine speed for eurodiesel and different fuel mixtures at full load.

Thermal efficiency is the rate among the engine power and the energy introduced through fuel injection. It is the product of the lower heating value and the injected fuel mass flow rate. Therefore, the adverse of thermal efficiency is often referred to as BSFC. The brake thermal efficiencies (BTE) of the engine fuelled with eurodiesel, CB10, CB20, and CB50 fuels are shown in Fig. 6. Eurodiesel has the highest BTE value for all engine speeds. BTE rises with rising engine speed up to 2500 rpm and reaches a maximum value. At 3000 rpm, the BTE diminished for all test fuels. The cause is inadequate air causing insufficient combustion of the fuel (Büyükkaya 2010). The BTE diminished as the biodiesel content raised in the mixture for all conditions because of the lower heating value of the mixture (Usta et al. 2005; Gümüş 2010).

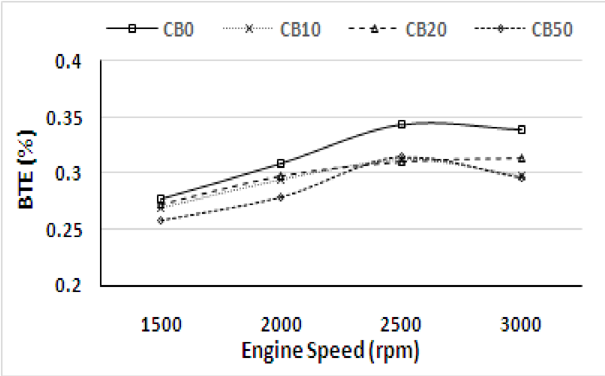

Figure 6. The BTE of the engine fuelled with eurodiesel and fuel mixtures at full load.

The NO_x emissions of the engine for eurodiesel and biodiesel mixture fuels are shown in Fig. 7. For all fuels, the NO_x emissions are the highest at 2500 rpm. Because the maximum torque and best combustion are obtained at these engine speeds. On the other hand, because of there is not enough time for complete combustion, NO_x emissions are diminishing at high engine speeds. NO_x variations of the biodiesel mixtures with respect to engine speed indicated parallel tendency with that of the eurodiesel (Usta et al. 2005). The NO_x emissions of the biodiesel mixtures were slightly higher than those of the eurodiesel.

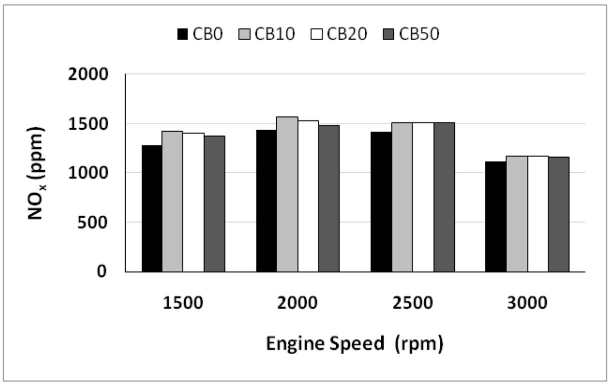

Figure 7. The NO_x emissions of the engine for eurodiesel and biodiesel mixtures.

The oxygen content and the lower cetane number of biodiesel are the reasons for higher NO_x emissions (Karabektas, 2009). Another reason for higher NO_x emissions is that the injection process is slightly advanced with biodiesel. The biodiesel's physical properties such as viscosity and density could cause such an advance (Lapuerta et al. 2008).

Fig. 8 shows the CO emission for eurodiesel and fuel mixtures. The CO emission generally decreases with the increasing engine speed (An et al. 2012). CO emissions are high because of poor fuel atomization and uneven distribution of small fuel particles in the combustion chamber at low speeds. For all biodiesel mixtures, the CO emission is lower than eurodiesel. The additional oxygen content in the biodiesel which enhances a precise combustion of the fuel reduces CO emissions. (Pinto et al. 2005; Lapuerta et al. 2008).

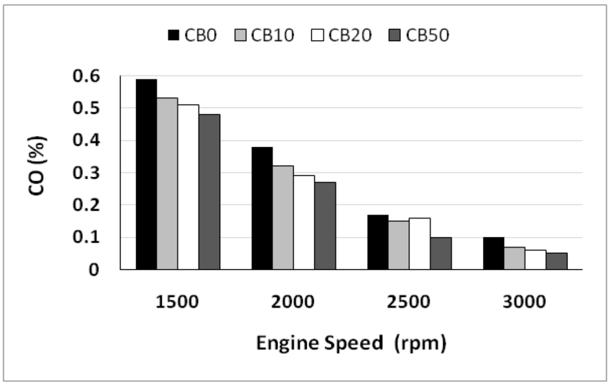

Figure 8. The CO emissions for eurodiesel and fuel mixtures.

The changes of HC emissions for eurodiesel and biodiesel mixtures are shown in Fig. 9. Unburned HC emissions are quite small for all test fuels. The HC emissions of biodiesel mixture fuels were lower than that of eurodiesel. The oxygen content in the biodiesel leads to a more complete and cleaner combustion (Pinto et al. 2005; Lapuerta et al. 2008). HC emissions for all fuels are higher at low engine speeds because of the local oxygen deficiency and incomplete combustion. The HC emissions decrease with the increasing engine speed because of the better combustion.

Fig. 10 shows the variations in the smoke with engine speed at full load condition for all the fuels. The smoke for the cottonseed oil biodiesel mixtures is lower than eurodiesel fuel (Chauhanet al. 2012).

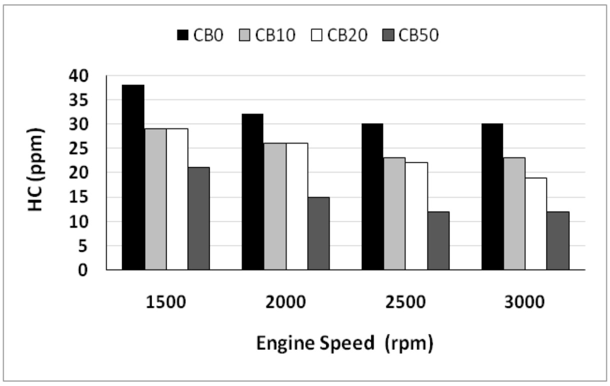

Figure 9. The changes of HC emissions for eurodiesel and biodiesel mixtures.

The oxygen weight content of biodiesel is higher than that of eurodiesel (Qi et al. 2010; Büyükkaya 2010). This reduction is mainly caused by enhanced soot oxidation and reduced soot formation. The absence of aromatic content and the oxygen content in biodiesel can be cited as the main reasons (Lapuerta et al. 2008).

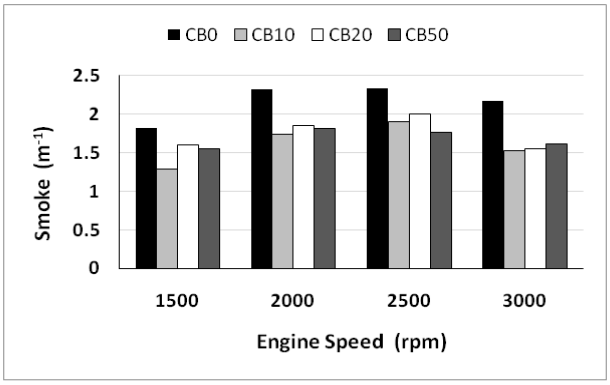

Figure10. The variations in the smoke with engine speed at full load condition for all the fuels.

The start of injection, influenced by the changes in physical properties of fuels such as the viscosity, density, and compressibility, affects the combustion characteristics, performance and exhaust emissions of the engine (Shahabuddin et al. 2013). The variations in the start of fuel injection change the ignition delay, cylinder pressure, and heat release rate. Table 4 shows the injection and combustion behaviors of experiment fuels for different engine speeds at full load.

The high viscosity fuels cause the fuel line pressure to rise quickly and the injection to start earlier. Because the fuel line pressure increases as the engine speed decreases, the fuel injection starts earlier. The injection of eurodiesel and low ratio biodiesel mixtures starts at the latest due to its low viscosity at low engine speeds. When the ratio of cottonseed oil biodiesel in the eurodiesel increases, injection starts earlier at all engine speeds. The injection of the CB50 starts about 1 °CA earlier compared to eurodiesel at all engine speeds.

One of the important parameters in the combustion event is the ignition delay. The ignition delay is defined as the time interval between the SOI timing and SOC timing (Ozsezen et al. 2009). It affects the combustion characteristics, performance, and emissions of compression ignition engine. It is affected by the chemical and physical properties of the fuels (Canakci 2007). Among them, cetane number, viscosity, and oxygen content of fuel are the most significant parameters influencing the ignition delay. The numerical values of ignition delay of experiment fuels versus engine speeds at full loads are given in Table 4. The results show that cetane number, viscosity, and oxygen content of fuel have a significant effect on the ignition delay as expected. The higher cetane number usually results in a shorter ignition delay (Ozener et al, 2014). Also, increasing the engine speed causes the longer ignition delay for all fuels.

Since biodiesel addition decreases the cetane number of the fuel mixtures, biodiesel mixtures have a longer ignition delay than eurodiesel. Among biodiesel mixtures, CB50 has higher ignition delay than others. This is because CB50 has higher kinematic viscosity and lower cetane number than the other experiment fuels.

The increase in fuel viscosity results in increased penetration, slower mixing, poor atomization, and reduced cone angle. These events result in a longer ignition delay (Ozener et al. 2014).

Table4. The injection and combustion behaviors of experiment fuels for different engine speeds at full load

Speed (rpm)	Fuels	SOI (°CA)	ID (°CA)	SOC (°CA)	EOC (°CA)	CP_{max} (bar)	ACP_{max} (°CA)	CD (°CA)	HRR_{max} (J/°CA)
1500	CB0	-12.8	7.4	-5.4	45.0	81.8	5.3	50.3	28.0
	CB10	-12.6	7.2	-5.4	44.0	80.8	5.3	49.4	25.6
	CB20	-12.7	7.2	-5.5	43.2	80.7	5.2	48.6	25.7
	CB50	-13.7	8.5	-5.2	42.8	79.4	5.3	48.1	24.8
2000	CB0	-11.7	8.5	-3.2	42.3	82.6	6.6	45.5	26.3
	CB10	-11.7	8.5	-3.2	43.9	80.1	6.5	47.2	24.5
	CB20	-11.8	8.6	-3.2	42.2	81.2	6.6	45.4	25.6
	CB50	-12.7	9.5	-3.2	43.2	80.4	6.6	46.4	24.7
2500	CB0	-10.5	9.5	-1.0	41.5	78.8	8.1	42.5	24.6
	CB10	-10.5	9.5	-1.0	40.5	77.8	8.2	41.9	23.6
	CB20	-10.6	9.6	-1.0	40.2	77.4	8.0	41.1	24.2
	CB50	-11.5	10.4	-1.1	40.0	77.5	8.2	41.0	24.2
3000	CB0	-9.4	10.4	1.0	42.9	73.2	9.9	42.0	23.1
	CB10	-9.3	10.5	1.2	39.2	71.4	8.4	38.0	23.4
	CB20	-9.3	10.4	1.1	38.6	71.3	7.6	37.5	23.7
	CB50	-10.4	11.4	1.0	38.3	71.8	8.8	37.4	23.5

The combustion characteristics like CP and HRR are the most significant parameters affecting the engine performance and exhaust emissions. These parameters are influenced by the heating value of the fuel. The changes in cylinder pressure of the different fuel mixtures according to the crank angle under different engine speeds at full load are seen in Fig. 11. In addition, numerical values of maximum cylinder pressures (CP_{max}) and their locations (ACP_{max}) are shown in Table 4. The CP_{max} did not indicate any important change when changing the fuels. However, the maximum pressure is achieved when fuelling with eurodiesel fuel (Ozener et al, 2014). The heat release rate is used to identify the fraction of fuel burned in the premixed mode, the start of combustion, and differences in combustion rates of fuels (Canakcı et al. 2009; Büyükkaya 2010). The heat release rates of the eurodiesel fuel and different fuel mixtures at full load and at the different engine speeds are seen in Fig. 12.

Also, numerical values of HRR_{max} are viewed in Table 4. Due to the evaporation of the fuel that accumulates during the ignition delay negative HRR is initially observed. On the other hand, it will be positive during the combustion process. Table 4 shows the change of the combustion duration according to the fuel type at full load. The combustion duration is calculated based on the time between the start of combustion and ninety percent cumulative heat release (Sakthivel et al. 2014). Because the ignition delay is longer the heat release rate increases very rapidly and the burning time is shortened (Çelik et al. 2015).

4. Conclusions

In this study, the effect of the various ratios cottonseed oil biodiesel additions in eurodiesel fuel on performance, combustion, and exhaust emission characteristics of a single-cylinder direct-injection diesel engine was investigated at full load condition. The following conclusions can be obtained from this study:

- The cottonseed oil biodiesel addition to the eurodiesel causes a very little decrease in engine power and torque for all rpms.
- A slight increase in BSFC was observed with the cottonseed oil biodiesel addition to the eurodiesel.

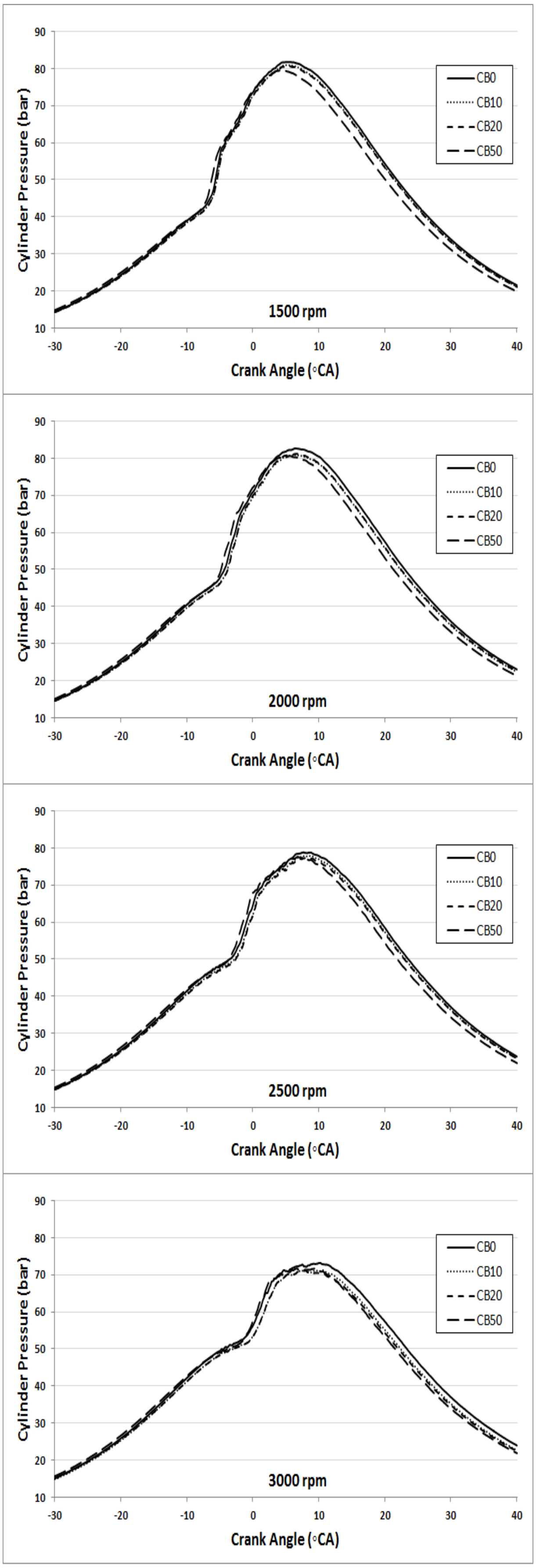

Figure 11. The changes in the cylinder pressure of the different fuel mixtures according to the crank angle under different engine speeds at full load.

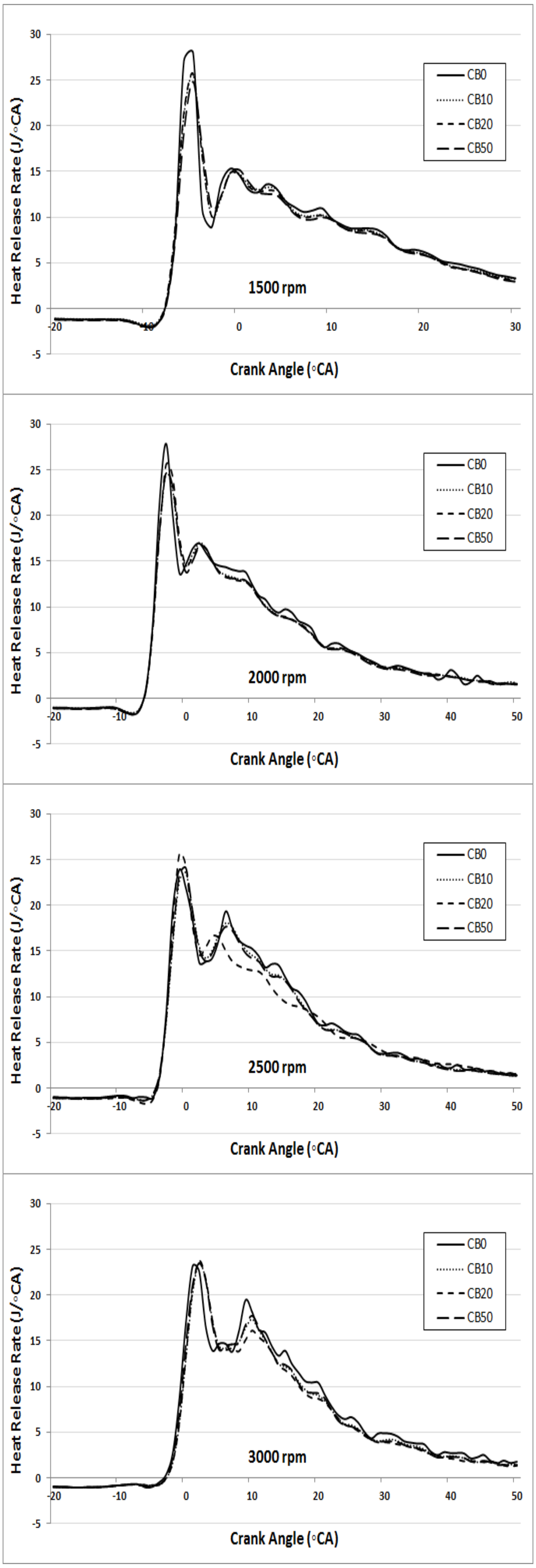

Figure 12. The changes in the heat release rates of the different fuel mixtures according to the crank angle under different engine speeds at full load.

- The addition of cottonseed oil biodiesel for all rpms at full load resulted in a decrease in smoke, HC, and CO, emissions and an increase in NO_x emissions.
- The ignition delay of cottonseed oil biodiesel mixtures is longer than the eurodiesel due to the low cetane number of cottonseed oil biodiesel.
- As the ignition delay is longer, the heat release rate has increased very quickly and the combustion duration has been shortened.
- The maximum combustion pressures of the fuels did not show a significant change.

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