INTERNATIONAL JOURNAL OF AUTOMOTIVE SCIENCE AND TECHNOLOGY
2017, VOL. 1, NO:1, 22-28
www.dergipark.gov.tr/ijastech

Experimental Analysis of Performance, Combustion and Injection Characteristics of Biodiesels Obtained from Waste Cooking and Canola Oils

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Abstract

This study investigates the injection and combustion parameters of a heavy duty diesel engine fueled with biodiesels such as waste palm oil methyl ester (WPOME) and canola oil methyl ester (COME). In this study, the engine tests were conducted at 1000, 1500 and 2000 rpm of constant engine speeds under the full load condition. The experimental results show that when the heavy duty diesel engine was fueled with WPOME or COME, the engine performance weakened in comparison with the fossil diesel fuel (FDF); on average, the brake power reduced by 4.2% while brake specific fuel consumption (*bsfc*) increased by 9.2%. But, the net indicated work areas obtained by use of biodiesels were slightly wider than pure FDF. When using biodiesels in the test engine, the start of injection timing take placed earlier than FDF.

Keywords: Methyl esters, heavy duty diesel engine, performance, combustion, injection

Manuscript
Received 14.02.2017
Revised 15.03.2017
Accepted 17.03.2017

1. Introduction

Biodiesel as an alternative fuel for diesel engines is an important issue for the countries; especially their energy depend on foreign petroleum sources. At the same time, increasing global concern due to environmental pollution from internal combustion engines has generated much attention on vegetable diesel fuels. In the last quarter century, these issues have triggered various research studies to replace FDF with biodiesel in many countries. Since last 15 years, some diesel engine manufacturers allow using neat biodiesel or its blends instead of FDF. The guarantees only apply to biodiesel that fulfills the ASTM D 6751-03 for USA and EN 14214 for European Union.

Biodiesel can be produced from low-cost feedstocks such as waste vegetable or frying oils. Some studies [1-5] have shown that biodiesel from waste vegetable or frying oils has little or no change in the diesel engine performance. Reed et al. [6] converted waste cooking oil to its methyl and ethyl esters, and tested neat biodiesel and 30% blend of biodiesel with diesel fuel in a diesel engine. They reported that no significant difference occurred in the engine power and performance. Ulusoy et al. [7] investigated the effects of biodiesel produced from waste frying oil on the performance and emissions of a Fiat Doblo vehicle using a 1.9 DS diesel engine. The results showed a 3.35% reduction in wheel force and wheel power reduced by 2.03%. When the fuel consumptions were compared, they saw that biodiesel consumption was 2.43% less than that of No. 2 diesel fuel. Yoshimoto et al. [8] reported similar result about the *bsfc*. In that study, the *bsfc* of neat biodiesel was lower than that of diesel fuel at high loads. Dorado et al. [9] worked on the waste olive oil methyl ester as a fuel for a direct injection diesel engine. After running the engine with the methyl ester, a minor loss (2%) in power and a larger increase (26%) in *bsfc* took place in their study.

The fuel properties of biodiesel show some variations when different feedstocks are used, it has higher cetane number, near-zero sulphur, and free aromatic compared to conventional diesel fuels [10, 11]. The fuel properties of biodiesel are affected by its fatty acids content which causes differences in the injection, combustion and performance characteristics of the engine. Canakci and Van Gerpen [12] prepared two different biodiesel from soybean oil and yellow grease with 9% free fatty acids to investigate the effect of the biodiesel on a direct injection diesel engine. They found that the brake specific fuel consumption (*bsfc*) for both biodiesels increased approximately 14% when compared with No.2 diesel fuel. They also observed that the start of injection timing for two biodiesel fuels occurred earlier than No.2 diesel fuel. Similar results have been reported by Ozsezen et al. [13] who investigated combustion characteristics of waste

palm oil methyl ester and its blends with FDF for an indirect injection diesel engine.
Although the use of biodiesel in diesel engines has been discussed for many years, the combustion evaluations need the experimental values. The full load condition test is very important to understand the combustion behaviors of the biodiesel in heavy duty diesel engine and its effects on the engine performance. In this study, the differences in the combustion and injection characteristics of the biodiesels have been experimentally investigated with three dimension graphics and their effects on the engine performance and emissions have been discussed.

2. The Properties of test fuels

In this study, biodiesel was produced from waste frying palm oil in the Fuel Laboratory of Department of Automotive Technologies in Kocaeli University. The feedstock was supplied by Kocaeli Uzay Gıda (Frito-Lay Chips Factory).

To produce biodiesel from the used vegetable oil, a small-scale transesterification reaction had been carried out in laboratory condition, thus, the reaction inputs such as catalyst amount, molar ratio, reaction temperature and time had been determined. Then, big scale production process was applied using stainless steel reactor tank and other equipment. Finally, biodiesel was prepared using methanol to oil ratio of 6:1 with potassium hydroxide (KOH) as catalyst (1% of oil by weight). After solving KOH catalyst in methanol at room temperature, the moisture-free used frying oil was added to the reaction tank to start the transesterification reaction. The mixture was agitated throughout 4 hours at 55~60ºC. After glycerol separation, the biodiesel was washed with warm distilled water. The washing was repeated four times. COME and FDF were purchased from commercial suppliers. Fuel specifications of the WPOME were determined by MRC-TUBITAK (Marmara Research Center-The Scientific and Technological Research Council of Turkey) using the European standard test methods (EN 14214). The fuel properties of the COME and FDF were taken from the manufacturer companies. The fuel properties of the WPOME, COME and FDF are shown in Table 1.

3. Engine Test Material and Methods

Engine tests were carried out on a water-cooled, naturally aspirated, heavy duty diesel engine. Engine specifications are shown in Table 2. As seen in Fig. 1, the engine was coupled to a hydraulic dynamometer to provide brake load (error ±2% N). A magnetic pickup was fixed over the engine flywheel gear to determine the crankshaft position. A water-cooled cylinder pressure transducer (Kistler model 6061B) was mounted on the first cylinder head to measure the cylinder gas pressure. A pressure transducer (Kistler model 6005) was installed in the fuel line of the first cylinder to obtain the fuel line pressure. A charge amplifier (Kistler model 5064A1) was used to produce output voltages proportional to the charge and then they were converted to digital signals. The cylinder gas and fuel line pressure signals were recorded by a computer using a digital device (Advantech PCI 1716 multifunctional data acquisition board). The cylinder gas pressure data of 50 engine cycles were collected with a resolution of 0.25º crank angle.

Table 2. Specification of the test engine

Model of engine	6.0 L Ford Cargo
Type	Water-cooled, direct injection, naturally aspirated and four stroke
Number of cylinder	Inline 6 cylinders
Bore x Stroke	104.80 x 114.90 mm
Compression ratio	15.9: 1
Injection pump	Mechanically controlled in-line type
Injection opening pressure	19.7 MPa
Nozzle hole diameter and number	0.3 mm and 4
Maximum power	81 kW at 2600 rpm
Maximum brake torque	335 Nm at 1500 rpm
Idle rotation speed	625 - 675 rpm

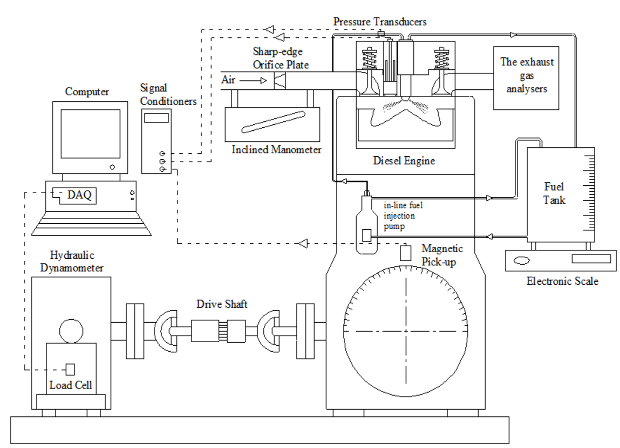

Fig.1. Experimental set-up

The injector opening pressure specified by the manufacturer is 19.7 MPa which were used in the ignition delay calculation. Fuel consumption was determined by weighing fuel used for a period of time on an electronic scale (error ±1g).

Air consumption was measured using a sharp edged orifice plate (ISO 5167 (1980)) and inclined manometer (error ±3%).

The relative humidity (error ±3%Rh+1) and ambient temperature (error ±1ºC) were monitored by a hygrometer. Six different digital thermocouples (error ±1ºC) monitored the temperatures of the intake air, fuel, engine oil, exhaust gas, coolant inlet and outlet.

Full load characteristic of the heavy duty diesel engine fueled with WPOME and COME was determined at constant engine speed mode (1000, 1500 and 2000 rpm, ±25 rpm). The test procedure was repeated to find the maximum power output for each fuel at the constant engine speed. All tests were completed without any modifications on the test engine. The tests were carried out under steady-state condition. The engine was sufficiently warmed up for each test and exhaust gas temperature was maintained certain level. During the tests, the engine did not show any starting difficulties when it was fueled with biodiesels, and it ran satisfactorily throughout the entire tests.

Table 1. Fuel properties of the WPOME, COME and FDF

	EN 14214					
Property	**Unit**	**Limits**	**Method**	**WPOME**	**COME**	**FDF**
Typical formula				$C_{18.08}H_{34.86}O_2$	$C_{19}H_{35}O_2$	$C_{14\text{-}15}H_{25\text{-}26}$
Average molecular weight	g/mol			284.17	295.5	194-206
Heating value	MJ/kg			38.73	39.00	42-43
Density	kg/m^3, 15ºC	860–900	ISO 3675	875	883.2	820-860
Kinematic viscosity	mm^2/s, 40ºC	3.5–5.0	ISO 3104	4.401	4.491	2 - 4.5
Flash point	ºC	120 min	ISO 3679	70.6	176	55 min
Sulfated ash content	% (m/m)	0.02 max	ISO 3987	0.0004	0.005	0.01 max
Cold filter plugging point	ºC	+5 : -20	EN 116	+10	-8	-15 max
Carbon residue	% (m/m)	0.30 max	ISO 10370	0.0004	0.28	0.30 max
Cetane number		51 min	ISO 5165	60.4		46 min
Total contamination	mg/kg	24 max	EN 12662	9.03	14	24 max
Copper strip corrosion	3 h at 50ºC	No.1 max	rating	No.1A	No.1A	No.1A
Oxidation stability	hour, 110ºC	6.0 min	EN 14112	10.1	12	25 min
Acid value	mg KOH/g	0.50 max	EN 14104	0.15	0.31	
Iodine value	g iodine/100g	120 max	EN 14111	62	107	
Monoglyceride content	% (m/m)	0.8 max	EN 14105	0.26 max	0.68	
Diglyceride content	% (m/m)	0.2 max	EN 14105	0.05	0.13	
Triglyceride content	% (m/m)	0.2 max	EN 14105	0.04 max	0.11	
Free glycerol	% (m/m)	0.02 max	EN14105-06	0.01	0.01 max	
Total glycerol	% (m/m)	0.25 max	EN 14105	0.06	0.21	
Ester content	% (m/m)	96.5 min	EN 14103	96.5	99.4	
Phosphorus content	mg/kg	10 max	EN 14107	2.9	1 max	
Distillation						
Initial boiling point (IBP)	ºC			331	334	160
90% recovered	ºC			348	350	360

4. Result and Discussion

4.1. Engine Performance Results

Fig. 1 shows a comparison of the brake power and *bsfc* values obtained for WPOME, COME and FDF over the speed range at the full load condition. When the test engine was fueled with WPOME and COME, the maximum engine power output slightly dropped while the *bsfc* increased with compared to the FDF. Indeed, these downward in the maximum brake power and upward in the *bsfc* are normal due to the lower energy content of the biodiesels. In the case of using the biodiesels, higher amount of fuel is consumed to achieve the similar maximum brake power causing an increase in the *bsfc*. As seen in Table 1, the heating values of the biodiesels are approximately 8-10% lower than that of FDF. The comparison of the maximum brake power and *bsfc* values is given in Fig.2.

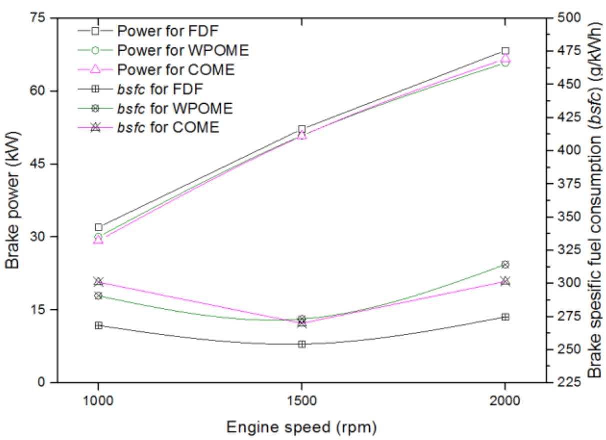

Fig.2. Comparison of the brake power and *bsfc* values for test fuels

In this study, the maximum brake power for FDF, WPOME and COME at 2000 rpm under full load condition was measured as 68.3 kW, 65.8 kW and 66.6 kW, respectively. On average, the brake power of WPOME and COME compared with those of the FDF over the speed range at full load condition, decreased by 3.2% and 4.7%, respectively. At 2000 rpm of engine speed, the *bsfc* for WPOME and COME is 11.6% and 8.9% higher than that of FDF, respectively. On average, the *bsfc* of WPOME and COME compared with those of the FDF over the speed range at full load condition, increased by 9% and 9.4%, respectively.

It was seen that the measured maximum power values by using the WPOME is higher while the *bsfc* of the WPOME is lower than that of the COME. This case can be explained with the different density and energy content of the biodiesel. It should be noted that *bsfc* is the actual mass of the fuel consumed. The test engine has a mechanically controlled in-line type fuel injection pump; the engine load is controlled by the fuel injection volume. For the same volume, more biodiesel fuel, based on the mass, was injected into the combustion chamber than that of FDF due to their higher densities. Simultaneously, the fuel properties such as higher density and kinematic viscosity influence the atomization ratio which causes a slowing down in the fuel-air mixing rates.

4.2. Combustion Results

The combustion characteristics of the biodiesels can be compared by means of cylinder gas pressure, instantaneous pressure rise rate and heat release rate. Fig. 3 shows a comparison of the cylinder gas pressure values and instantaneous pressure rise rate obtained for WPOME, COME and FDF over the speed range at the full load condition. Russell and Haworth [14] have stated that the pressure waves in the cylinder during the combustion indicate engine knock or noise. Both biodiesels had no trace of knock and the cylinder gas pressure smoothly varied at 1000, 1500 and 2000 rpm under full load condition. Nonetheless, the cylinder gas pressure of the FDF which was used as reference fuel varied slightly unsmooth compared with the biodiesels.

Pressure rise rate (PRR) is an indicator of the energy release rate of the combustion process in cylinder [15]. The PRR in an engine combustion chamber utilizes a considerable influence on the peak pressure developed, the power produced and the smoothness with which the forces are transmitted to the piston [16]. From the past to the present, some research used the PRR to investigate the acoustic or vibration energy emitted by engine [17, 18]. PRR was calculated with the first derivative of the pressure signal. Numerical differentiation of the acquired pressure signals was conducted on a per-engine-cycle basis using a central difference method which is given in following eq.1.

$$\frac{dP_i}{d\theta} = \frac{dP_{i+1} - dP_{i-1}}{2\theta} \qquad (1)$$

Where, dP_i represents the discrete pressure signal and $d\theta$ represents the change in crank angle degree between two pressure values. As known, The PRR is to decrease together with increasing in engine speed, therefore, calculated peak $dP/d\theta$ values decreased with increasing in engine speed for all operating conditions.

As seen in the Fig.3, the maximum cylinder gas pressures of the biodiesels are higher than that of the FDF due to biodiesels' higher *bsfc* amounts, cetane number, boiling point, oxygen content, and advance in the start of injection (SOI) timing. Especially, the oxygen content of the biodiesels increases fuel-air mixing rate in cylinder compared to the FDF, and this situation may lead to extend the combustion duration. When the test engine was fueled with biodiesels, an increase took place in the cylinder gas pressure. Although both biodiesels have nearly same energy content, the differences in the *bsfc* values and hydrogen-carbon ratios between WPOME and COME caused to too small variations in their cylinder gas pressures. In fact, this result indicates that the engine converts the fuel energy to the mechanical energy almost equally for both biodiesels.

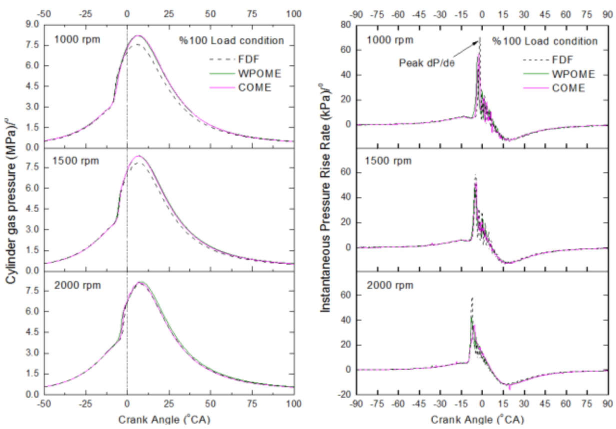

Fig.3. Comparison of the cylinder gas pressures and instantaneous pressure rise rate for test fuels

The combustion characteristics of the biodiesels show that they can be used securely in an unmodified diesel engine instead of the FDF. Because, when the test engine is operated under full load condition, the mechanical loading is at the maximum level. The differences in the peak cylinder gas pressure point during the maximum mechanical loading may lead performance loses and engine fault. When the biodiesels were used, the peak point of the cylinder gas pressure very slightly closed to the top dead center (TDC). The peak cylinder gas pressure for WPOME and COME was measured 8.34 MPa and 8.33 MPa at 6.75° CA ATDC, while the peak cylinder gas pressure for FDF was 7.89 MPa occurring at 7° CA ATDC at 1500 rpm of engine speed. These values show that the peak cylinder gas pressure for the biodiesels was 0.45 MPa higher and occurred 0.25° CA earlier than those of FDF.

Heat release calculations are an attempt to get some information about the combustion process in an engine. A number of approaches to heat release ($\dot{Q}_n$) analysis have been present in the literature. The most widely used one was developed by Krieger and Borman [19] which is given in following eq.2.

$$\dot{Q}_n = \frac{\lambda}{\lambda - 1} P \frac{dV}{d\theta} + \frac{1}{\lambda - 1} V \frac{dP}{d\theta} \tag{2}$$

where, λ is the ratio of specific heats which was taken as 1.35, θ is crank angle, P is cylinder gas pressure, and V is cylinder volume. In this model, the heat release rate is calculated according to the first law of thermodynamics applied to a control volume. The cylinder volume is calculated from the geometry as a function of the crank position. The temperature gradients, pressure waves, non-equilibrium conditions, fuel vaporization, and mixing can be ignored. The calculated heat release rates as the function of crank position are shown in Fig. 4.

All test fuels indicated a rapid premixed burning followed by a diffusion (start of mixing-controlled) combustion period which is typical for a naturally aspirated diesel engine.

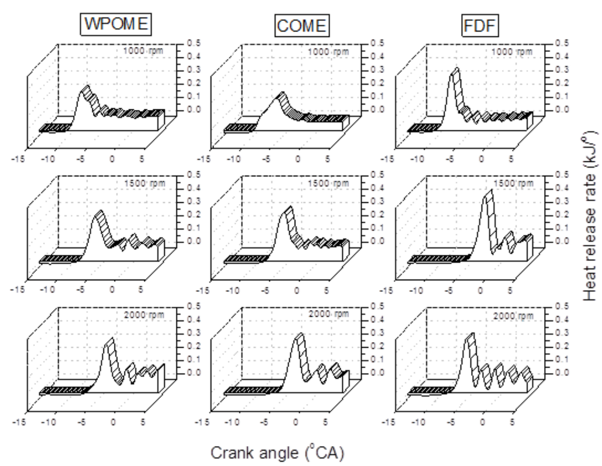

Fig.4. Comparison of the heat release rates for test fuels

As seen in the figure, the starts of combustion (SOC) timing for biodiesels are earlier than FDF due to their earlier SOI timings. The SOC timing of the WPOME and COME was taken place at 9.75° CA before top dead center (BTDC), while the SOC timing in the case of FDF was occurring at 7.25° CA BTDC at 1500 rpm of engine speed. This value shows that the SOC timing with the use of the biodiesels advanced 2° CA compared to FDF. The premixed combustion phase for both biodiesels was found longer than that of FDF. This situation can be explained with the vaporization of biodiesel which is more slowly than FDF and contributes less premixed combustion. However, its oxygen content and cetane number affect SOC timing.

4.3. Injection Results

In this study, the start of injection timing (SOI) was determined from the fuel injection line pressure data. Fig. 5 shows the comparison of the injection line pressures for the fuels tested.

As seen in the figure, when the test engine was fueled with biodiesels, the SOI timing occurred earlier than that of FDF. The SOI timing for WPOME and COME is 0.75° and 1.25° CA earlier than that of FDF, respectively. This behavior is related with the density, viscosity and compressibility of the fuels. As mentioned earlier, the biodiesel has slightly higher density (see Table 1), which affects the fuel compression process in the volumetric injection pump. Hence, the needle nozzle lifted more rapid when using biodiesel. This case leads to advance in SOI timing. Kegl and Hribernik [20] reported that the higher viscosity of biodiesel leads to reduced fuel losses during injection process, to faster evolution of pressure and thus to advanced injection timing. Furthermore, lower vapor content in the high pressure injection system could be another reason for advanced injection timing, since decreasing the vapor volume causes to decrease in the injection delay which results in advanced injection timing.

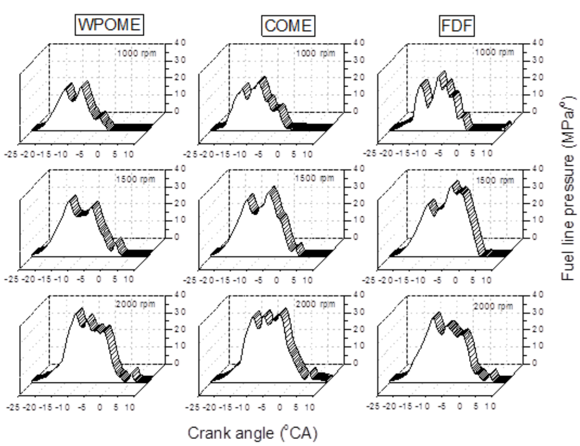

Fig.5. Comparison of the fuel line pressures for test fuels

The compressibility and kinematic viscosity of the biodiesel have effect on the injection process. If the same fuel pump is used at the same speed for all test fuels, the injection characteristics of the fuels will not be same with each other. Some researchers [21-23] have shown that the compressibility of biodiesel is lower than that of diesel fuel. Therefore, the rate of liquid pressure rise of biodiesel goes up and the injection timing advances.

In addition to the above findings, it is noted that some researchers [24- 26] showed the biodiesel influence on tribology characteristics of a diesel engine with a mechanically controlled fuel injection system. They were found out an increase in the pump surface roughness when biodiesel was used. The deposits on the cylinder head were higher than in the case of fossil diesel fuel. A quick build-up of carbon deposits on the injector nozzles was also observed. Injector deposition was found also critical for biodiesel.

5. Conclusion

When the test engine was fueled with WPOME and COME, the maximum engine power slightly dropped while the *bsfc* was higher than that of FDF, respectively. The experimental results show that when the heavy duty diesel engine was fueled with WPOME or COME, on average, the brake power reduced by 4.2% while brake specific fuel consumption (*bsfc*) increased by 9.2%. Although both biodiesels using in this study have approximately same energy content, it was seen slight variations in the cylinder gas pressure dispersions due to the differences in *bsfc* values. Both biodiesels didn't show any trace of knock and the cylinder gas pressure smoothly varied. The peak cylinder gas pressure point did not show any significant difference between WPOME and COME. SOC timing for each biodiesel was obtained 2° CA earlier than FDF due to their earlier SOI timings. The premixed combustion phase for both biodiesels carried out at more wide range of crank angle in terms of the FDF. The maximum cylinder gas pressure was occurred within the range of 2.5 to 6° CA ATDC for all tested fuels. When biodiesels were used, the peak of cylinder gas pressure slightly closed to TDC compared with FDF. The test engine fueled with biodiesels, the start of nozzle needle carry out at earlier crank angles than those of FDF and peak injection pressure is higher than that of FDF. This behavior concerns the different densities of the fuels.

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