Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar

Spanish Journal of Agricultural Research 2010 8(2), 299-307
ISSN: 1695-971-X

Performance and emissions of an agricultural diesel engine fuelled with different diesel and methyl ester blends

I. Milán[1], M. Camps[1], J. L. Ponce de León[2] and V. Sánchez-Girón[1]*

[1] *Departamento de Ingeniería Rural. ETSI Agrónomos. Universidad Politécnica de Madrid. Ciudad Universitaria, s/n. 28040 Madrid. Spain*

[2] *Estación de Mecánica Agrícola. Autovía A-42 (Madrid-Toledo), km 7. 28916 Leganés (Madrid). Spain*

Abstract

This paper shows the results of an investigation carried out to assess the application of different fuels produced by blending diesel fuel with methyl ester obtained from mixture of 75% (v/v) sunflower oil and 25% (v/v) used cooking oil on a Kubota agricultural indirect injection diesel engine, natural aspirated, and with a rated horsepower of 19.7 kW. Seven fuels, namely diesel fuel; 90:10, 80:20, 70:30, 50:50, 25:75 and 0:100 (%v/v) blends were prepared and tested for the performance of the diesel engine in accordance with the standardised OECD test code 2. The test results showed that the performance of the engine was satisfactory without a significant reduction in power output and torque with blends smaller than 50%. Fuel consumptions with biodiesel were higher than that when fuelled with diesel but differences were not very marked up to 30% blends. As the reduction of the engine thermal efficiency was less than the corresponding reduction in heating value of the different biodiesel blends, the latter resulted in a more complete combustion in comparison with diesel fuel. The oxides of nitrogen (NO_x) emissions were found to be reduced as the biodiesel concentration increase, particularly with 70% and 100% blends. The emissions of carbon monoxide (CO) were lower and increased at a lower rate with the oxygen concentration of the exhaust as the biodiesel blends were equal or higher than 50%.

Additional key words: biodiesel blends, engine emissions, engine performance, indirect injection diesel engine.

Resumen

Evaluación de las prestaciones y emisiones de un motor diésel de uso agrícola alimentado con diferentes mezclas de biodiésel

En este trabajo se evalúan las prestaciones de un motor Kubota diésel de uso agrícola, de inyección indirecta de combustible y con una potencia nominal de 19,7 kW, cuando se utilizan como combustibles gasóleo comercial (100:0), biodiésel puro (0:100), obtenido por mezcla de metil éster procedente en un 75% (v/v) de aceite de girasol y en un 25% (v/v) de aceite de freír, y diferentes mezclas de biodiésel que se corresponden con las siguientes proporciones de esos dos combustibles: 90:10; 80:20; 70:30; 50:50; 25:75 (%v/v). Las prestaciones del motor se determinaron siguiendo la metodología establecida en el código 2 de ensayos de la OCDE. Los resultados obtenidos pusieron de manifiesto que los valores de la potencia y del par motor medidos en los puntos de ensayo con mezclas de biodiésel inferiores al 50% fueron similares a los obtenidos con gasóleo. Los consumos de combustible fueron ligeramente superiores a los alcanzados con gasóleo cuando se utilizó biodiésel con un contenido en metil éster que no superó el 30%, observándose los aumentos más acusados de los mismos con mezclas iguales o superiores al 50%. El rendimiento térmico de las diferentes mezclas de biodiésel disminuyó en menor medida que su poder calorífico, indicando con ello que su combustión fue más completa que la del gasóleo. Las emisiones de óxidos de nitrógeno (NO_x) se redujeron a medida que aumentó el contenido de biodiésel en el combustible, particularmente con las mezclas del 70% y del 100%. Por lo que respecta a las emisiones de monóxido de carbono (CO), se observó que fueron menores, y crecieron a una menor tasa con la concentración de oxígeno de los gases de escape, cuando el contenido de biodiésel del combustible superó el 50%.

Palabras clave adicionales: inyección indirecta, metil éster, motor diésel agrícola, mezclas de biodiésel.

* Corresponding author: victor.sanchezgiron@upm.es
Received: 15-07-09; Accepted: 25-03-10.

M. Camps is member of the SEA.

Abbreviations used: BFC (brake fuel consumptions), BSFC (break specific fuel consumptions), DI (direct injection), HC (hydrocarbons), IDI (indirect injection), NO_x (oxides of nitrogen), OECD (Organisation for Economic Co-operation and Development), PM (particulate matter), PNAH (polynuclear aromatic hydrocarbons), @ (rated speed).

Introduction

Biodiesel is a renewable alternative fuel consisting of monoesters of vegetable oils and animal fats that can replace diesel fuel in compression ignition engines. It is an oxygenated fuel, 10% to 11% oxygen by weight, that produces less unburned hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM) than diesel-fuelled engines, but increases the production of oxides of nitrogen (NO_x) by 10% to 15% when fueling with 100% biodiesel (B100) (Van Gerpen *et al.*, 2007). Biodiesel is an environmental friend source of energy since the carbon dioxide (CO_2) produced in the engine's combustion chamber is recycled through the process of photosynthesis in growing the oilseeds; therefore, making it almost CO_2 neutral (Van Gerpen *et al.*, 2007).

The most common form of biodiesel in the United States is made with soybean oil whereas in Europe the latter is substituted for rapeseed oil. Monyem and Van Gerpen (2001) and Van Gerpen *et al.* (2007), among others, stated that using raw vegetable oils for extended periods of time may result in severe engine deposits, injector coking, piston ring sticking or broken piston rings, and a tendency to thicken lubricating oil causing sudden and catastrophic failure of the connecting rods and/or crankshaft bearings. Raw vegetable oils exhibit a high viscosity and extremely low volatility due to their polyunsaturated character. This high viscosity causes poor fuel atomization, large droplet size and thus high spray jet penetration. Consequently, the fuel is not distributed or mixed with the air required for burning in the combustion chamber and this result in poor combustion accompanied by loss of power and economy (Agarwal *et al.*, 2007). However, these effects can be reduced through transesterification of the raw oil to form monoesters which are known as biodiesel (Zhang *et al.*, 1988; Perkins *et al.*, 1991). Transesterification reduces the viscosity but maintains the cetane number and the heating value of biodiesel, which is about 12% less than diesel fuel on a mass basis. The use of biodiesel in Diesel engines require no hardware modifications either if it is blended with diesel fuel or used in its pure form (Agarwal *et al.*, 2007).

Interest in vegetable oil fuels or biofuels started in the early 1970s when the oil crisis arrived. Since then the challenging target the world has to face is how energy can be provided to meet the demands of a population growing in number and expectations. There is a general concern about the global warming effect likely produced by the greenhouse effect of the CO_2 being released to the atmosphere as fossil fuels are burned. This fact, together with the continuous price rise of the dwindling fossil fuels and the unstable supplies of petroleum, has been the key driver towards the growing interest in the transport and agricultural machinery industries in using biofuels produced from the biodegradable fraction of products such as food grains, crop residues and forestry residues (Roskilly *et al.*, 2008).

Numerous studies on the application of biodiesel on diesel engines have been carried out and results have shown that the performance of engines is comparable to that using fossil diesel fuel, whereas the emissions from a biodiesel fuelled engine are also comparable to or better than that fuelled with a fossil diesel fuel (Roskilly *et al.*, 2008). Ali *et al.* (1995) observed that the performance of two diesel engines was satisfactory without a significant reduction in power output with biodiesel blends up to 30%. Exhaust emissions except NO_x were reduced for both engines as the biodiesel concentration in the fuel increased. Similarly, Akasaka *et al.* (1997) found that under partial load conditions PM emissions of a diesel engine increased as the soy-based biodiesel concentration in the fuel increased. Agarwal (1998) observed an improved thermal efficiency, and a reduction in the break specific energy consumption and in the smoke opacity, in a biodiesel-fuelled engine compared to a diesel-fuelled engine. Comparing different blends with biodiesel obtained from waste cooking oil on particulate emissions of a direct injection compression ignition engine (DI), Lapuerta *et al.* (2007) reported a sharp decrease in smoke and particulate emissions as the biodiesel blend concentrations increased up to 70%. Similarly, while the engine efficiency was not significantly affected the fuel consumption increased with the biodiesel concentration.

Most of the research conducted comparing the engine performance and exhaust emissions from diesel engines fuelled with fossil diesel fuel and different biodiesel blends have been conducted on on-highway DI compression ignition engines. Very few investigations have been carried out in small size indirect injection compression ignition engines (IDI) to be used in agricultural and forestry tractors. The purpose of this study was to compare the performance and the exhaust emissions of an agricultural tractor diesel engine when fuelled with different rape-based biodiesel blends.

Table 1. Properties of diesel fuel and different fuel blends with methyl ester

	Diesel	B10	B20	B30	Standard
Lower heating value (MJ kg^{-1})	42.88	41.97	41.90	41.58	ASTM D 240-02
Density at 15°C (kg m^{-3})	841	845	849.1	853.3	EN ISO 12185
PNAH[a] (% m m^{-3})	3.6	3.0	2.6	2.3	EN ISO 12916
Sulphur content (mg kg^{-1})	22.9	20.0	17.5	14.9	EN ISO 20846
Ash content (% m m^{-1})	0.001	0.001	0.001	0.001	EN ISO 6245
Kinematic viscosity (mm^2 s^{-1})	3.103	3.168	3.245	3.333	EN ISO 3104

[a] PNAH: polynuclear aromatic hydrocarbons.

Materials and methods

Engine and instruments

The study was conducted at the OECD registered station that the Spanish Ministry of Environment and Rural and Marine Affairs has in the city of Leganés (Madrid). A Kubota tractor B3030 was used for the experiments. The latter was equipped with a Kubota V1505 four-cylinder, four stroke, natural aspirated IDI engine with a bore of 78 mm, a stroke of 78.4 mm, a displacement of 1498 cm^3, a compression ratio of 24:1, a rated power of 19.7 kW @ 2,600 rpm, and a maximum torque of 87.5 N m @1,600 rpm. The injection pump was an in-line with an all speed mechanical governor.

The tractor engine was coupled through the power take-off shaft to a Schenck W-700 (700 kW) eddy current dynamometer (Carl Schenck AG, Darmstadt, Germany). Fuel consumption was measured with an AVL-730 (AVL GMBH, Graz, Austria) mass measurement system in which fuel weight was measured over a selected time period. Exhaust gas temperature was measured using a K type thermocouple that was placed in the tail exhaust pipe. Oxides of nitrogen (NO_x) and CO were measured with a Testo 350 portable analyzer (Testo GMBH, Lenzkirch, Germany).

Fuels

A commercial diesel fuel for agricultural purposes was compared with a methyl ester obtained from mixture of 75% (v/v) sunflower oil and 25% (v/v) used cooking oil in the following blends: i) 100% diesel fuel; ii) B10, 90:10% (v/v) diesel: methyl ester; iii) B20, 80:20% (v/v) diesel: methyl ester; iv) B30, 70:30% (v/v) diesel: methyl ester; v) B50, 50:50% (v/v) diesel: methyl ester; vi) B70, 30:70% (v/v) diesel: methyl ester; and vii) B100, 100% methyl ester.

In order to compare the output performance, fuel consumption and exhaust emissions of the engine running on diesel and on biodiesel, the tested fuels were analysed to determine some basic properties that are depicted in Tables 1 and 2.

Unfortunately, the only properties that could be determined for fuel blends B50 and B70 were the lower heating value and the density. These values were 40.41 MJ kg^{-1} for B50 and 39.45 MJ kg^{-1} for B70, and 859.4 kg m^{-3} for B50 and 866.6 kg m^{-3} for B70, respectively.

Experimental procedure

Engine testing on the already mentioned fuels was performed following the OECD standard test code 2 for the official testing of tractor performance (OECD, 2008). The sequence of fuels used was in the same order given above. With each fuel blend, standard performance and exhaust emissions data were recorded and the engine was operated at the following operating points using OECD code 2:

— Point (1): rated power at rated engine speed.

— Point (2): 80% rated power at maximum speed. Heavy drawbar work.

Table 2. Methyl ester analysis

Fatty acid composition		Standard method
Free glycerine (%)	0.005	EN 14105
Monoglycerides (%)	0.290	EN 14105
Diglycerides (%)	0.085	EN 14105
Triglycerides (%)	0.066	EN 14105
Total glycerin (%)	0.098	EN 14105
Lower heating value (MJ kg^{-1})	37.98	ASTM D 240-02
Density at 15°C (kg m^{-3})	877	EN ISO 3675
Kinematic viscosity (mm^2 s^{-1})	3.9	EN ISO 3104

— Point (3): 80% rated power at 90% rated speed. Heavy drawbar or heavy power take-off work at standard speed.

— Point (4): 40% rated power at 90% rated speed. Light drawbar or light power take-off work at standard speed.

— Point (5): 60% rated power at 60% rated speed. Heavy drawbar or heavy power take-off work at economy power take-off speed.

— Point (6): 40% rated power at 60% rated speed. Light drawbar or light power take-off work at reduced speed.

When the engine was tested, it was equipped with all the accessories required for continuous operation of the tractor. The engine was warmed-up in idle conditions until correct oil pressure was established and was checked for any oil, water and fuel leaks. After completion of the warm-up the governor was set for rated power and the engine was operated for one hour. During this time period six readings evenly spread were taken of the torque, speed and fuel consumption. From these measured variables break power, break specific fuel consumption and break thermal efficiency were calculated. In the sixth reading, NO_x, CO and exhaust temperature measurements were made. This same procedure was followed for the additional five points and for all the fuels compared. At each fuel change lines and engine filters were drained prior to filling them with the next fuel and care was taken to ensure that the engine was flushed of the previous fuel blend. This was accomplished by feeding several litres of the fuel blend to be assessed into the engine and allowing the excess fuel in the return line to be diverted to a disposal fuel tank.

Statistical analyses were carried out as a complete randomised design with two fixed factors, fuel blend and engine operating point, and each of the six readings made during one hour of engine operation were considered as a replicate. Differences between mean values for the different engine performance variables considered were tested by the Duncan's least significance difference ($P < 0.01$). All statistical analyses were performed using the Statistica software package (Statsoft, 2003).

Results and discussion

Engine performance

Engine power outputs for all seven fuels tested and each operating point are included in Table 3. Systematically, the highest values of engine power were obtained with diesel and the lowest with B100. Although engine power averaged across operating points significantly decreased as the amount of methyl ester increased in the fuel, the statistical analysis did not detect any differences in the engine power measured in all six operating points with fuels B20 and B30, and also between diesel and B10 fuels in P5. The differences in averaged engine power with respect to the figures obtained with diesel were less than 1.5% when the biodiesel blends were not close to that of the B50; nonetheless, they increased from 4.1% to 6.5% for B50 and B100, respectively. Similarly, the statistical analysis verified that the engine power with each fuel was determined by the operating conditions.

The variation of the engine torque values in each operating point for each fuel tested can be seen in Table 4.

Table 3. Engine power (kW) for different fuel blends and different OECD engine testing points

Fuel blends	P1[1]	P2	P3	P4	P5	P6	Mean
Diesel	18.37 A a[2]	14.72 A b	14.71 A b	7.35 A d	11.03 A c	7.35 A d	12.25 A
B10	18.26 B a	14.65 B b	14.65 B b	7.32 B d	11.01 A c	7.31 B d	12.20 B
B20	18.06 C a	14.52 C b	14.52 C b	7.25 C d	10.89 B c	7.25 C d	12.08 C
B30	18.07 C a	14.50 C b	14.50 C b	7.25 C d	10.87 B c	7.25 C d	12.07 C
B50	17.61 D a	14.12 D b	14.10 D b	7.05 D d	10.58 C c	7.06 D d	11.75 D
B70	17.50 E a	14.02 E b	14.02 E b	7.01 E d	10.52 D c	7.01 E d	11.68 E
B100	17.20 F a	13.76 F a	13.75 F b	6.87 F d	10.31 E c	6.87 F d	11.46 F
Mean	17.87 a	14.32 b	14.32 b	7.16 d	10.74 c	7.16 d	

[1] P1, rated power at rated speed; P2, 80% rated power at maximum speed; P3, 80% rated power at 90% rated speed; P4, 40% rated power at 90% rated speed; P5, 60% rated power at 60% rated speed; P6, 40% rated power at 60% rated speed. [2] Means in each column followed by the same upper case letter are not significantly different between fuel blends ($P < 0.01$). Means in each row followed by the same lower case letter are not significantly different between OECD testing points ($P < 0.01$). Fuel blends LSD ($P < 0.01$) = 0.012; OECD testing points LSD ($P < 0.01$) = 0.011. Fuel blends × OECD testing points LSD ($P < 0.01$) = 0.030.

Table 4. Engine torque (N m) for different fuel blends and different OECD engine testing points

Fuel blends	P1[1]	P2	P3	P4	P5	P6	Mean
Diesel	62.43 A a[2]	49.17 A c	55.62 A b	27.88 A e	62.33 A a	41.84 A d	49.88 A
B10	61.81 B a	48.54 B c	55.03 B b	27.78 A e	61.88 B a	41.49 B d	49.42 B
B20	61.74 B a	48.37 C c	54.79 C b	27.33 B e	61.74 B a	41.04 C d	49.17 C
B30	61.60 C a	48.06 D c	54.44 D b	27.12 C e	61.53 C a	41.04 C d	48.96 D
B50	59.72 D a	46.88 E c	53.30 E b	26.81 D e	59.65 D a	39.79 D d	47.74 E
B70	59.65 D a	47.05 F c	53.30 E b	26.88 D e	59.72 D a	39.83 D d	47.69 E
B100	57.88 E a	45.21 G d	51.60 F c	25.83 E f	57.36 E b	38.54 E e	46.07 F
Mean	60.69 a	47.61 d	54.01 c	27.09 f	60.60b	40.51 e	

[1,2] See Table 3. Fuel blends LSD ($P < 0.01$) = 0.051; OECD testing points LSD ($P < 0.01$) = 0.047. Fuel blends × OECD testing points LSD ($P < 0.01$) = 0.124.

Consistently, the highest torque values were those of the diesel fuel and the lowest values were those of the B100. In each operating point engine torque decreased as the amount of methyl ester increased in the fuel, B20 and B30 blends showed a similar behaviour, and so did the B50 and B70 blends. Engine torque averaged across the operating points significantly decreased with the content of methyl ester of the fuel. The differences in average engine torque were 1% when substituting diesel fuel with the B10 blend. These differences did not surpass the 2% when using blends up to the B50 and the difference rose up to 7.6% when utilizing the B100 blend. The standard OECD test code establishes that the engine torque values, no matter which fuel is used, are different except for P1 and P5 points. In our case, the statistical analysis reflected this circumstance, except when we used B100 fuel, since engine torque in P1 was greater than in P5.

In each operating point, the smallest brake fuel consumptions (BFC) were always those which were obtained with diesel and the largest consumptions were obtained with B100 (Table 5). Similarly, when comparing the BFC averaged across the operating points it can be observed that the consumption increased as the content of methyl ester in the fuel increased. However, the statistical analysis did not detect significant differences in the average BFC of fuels B10, B20 and B30. The BFC was different in each operating point (Table 5), P6 having the smallest consumption and P1 the highest. Substituting diesel with B10, B20 and B30 led to an increase of the BFC of 4%, but this increase rose to 7% and 8% with B50 and B70, respectively, and it further rose to 12.1% when using B100.

The variations of the break specific fuel consumptions (BSFC) for all seven fuels tested and each operating point are included in Table 6. In all fuels tested, different BSFC were observed at each operating condition; indeed, the highest BSFC were obtained in the P4 operating condition and the lowest BSFC were obtained in P5. In every operating condition, the BSFC increased with the content of biodiesel in the fuel. Likewise, the smallest BSFC averaged across the operating points was achieved in the diesel and the highest was achieved with the B100. No significant differences were observed in the average BSFC with the B20 and B30 blends. B10, B20 and B30 blends resulted in a BSFC

Table 5. Brake fuel consumption (BFC) (kg h^{-1}) for different fuel blends and OECD engine testing points

Fuel blends	P1[1]	P2	P3	P4	P5	P6	Mean
Diesel	5.44 A f[2]	4.59 A e	4.15 A d	2.68 A b	2.84 A c	2.10 A a	3.63 A
B10	5.68 C f	4.70 B e	4.36 C d	2.82 B b	3.01 C c	2.19 B a	3.77 B
B20	5.62 B f	4.74 C e	4.38 D d	2.84 B b	3.01 C c	2.17 B a	3.79 B
B30	5.66 C f	4.76 C e	4.33 B d	2.82 B b	2.98 B c	2.18 B a	3.79 B
B50	5.76 D f	4.88 D e	4.44 D d	2.92 C b	3.04 D c	2.22 C a	3.88 C
B70	5.94 E f	4.95 E e	4.45 D d	2.92 C b	3.04 D c	2.24 C a	3.92 D
B100	5.92 E e	5.14 F d	4.68 E c	3.16 D b	3.17 E b	2.39 D a	4.07 E
Mean	5.72 f	4.82 e	4.40 d	2.88 b	3.01 c	2.21 a	

[1,2] See Table 3. Fuel blends LSD ($P < 0.01$) = 0.001; OECD testing points LSD ($P < 0.01$) = 0.001. Fuel blends × OECD testing points LSD ($P < 0.01$) = 0.033.

Table 6. Break specific fuel consumption (BSFC) (g kw^{-1} h^{-1}) for different fuel blends and OECD engine testing points

Fuel blends	P1[1]	P2	P3	P4	P5	P6	Mean
Diesel	296.11 A d[2]	311.91 A e	282.10 A b	364.26 A f	257.62 A a	285.96 A c	299.66 A
B10	311.17 B c	320.60 B d	297.70 B b	385.20 B e	273.74 B a	298.98 B b	314.56 B
B20	311.28 B d	326.76 C e	301.45 C c	391.73 D f	276.78 C a	299.17 B b	317.19 C
B30	312.98 B c	328.06 C d	298.57 B b	389.24 C e	274.20 B a	300.10 B b	317.86 C
B50	326.72 C c	345.46 D d	314.68 D b	413.91 E e	286.86 D a	314.96 C b	333.77 D
B70	339.42 D c	353.30 E d	317.05 D b	415.92 E e	288.64 D a	318.96 C b	338.88 E
B100	343.94 E c	373.51 F e	340.51 E b	460.24 F f	307.03 E a	348.15 D d	362.24 F
Mean	320.23 d	337.09 e	307.44 b	402.93 f	280.70 a	309.47 c	

[1,2] See Table 3. Fuel blends LSD ($P < 0.01$) = 0.867; OECD testing points LSD ($P < 0.01$) = 0.803. Fuel blends × OECD testing points LSD ($P < 0.01$) = 2.124.

averaged across the operating points between a 5% and a 6% higher than that of diesel. However, these percentages rose to 11.4%, 13.1% and 20.9% when B50, B70 and B100 were used, respectively.

As it can be seen in Table 7, the variations of the thermal efficiency obtained with the different fuels compared were similar to the variations already observed with the BSFC. In all fuels compared different thermal efficiencies were obtained in each operating point, the highest being in the P5 condition and the lowest in the P4 condition. In all six operating points, the highest values of engine power were obtained with diesel and the lowest with B100. This same trend was observed when thermal efficiency averaged across operating points was compared, and after the diesel the fuels with higher thermal efficiency were the B10 and B30, followed by the B20 and B70 and with an even lower efficiency the B50. In percentage terms, the average thermal efficiency of diesel was 6.4% higher than the B100, 3.7% higher than the ones in B70 and B20, and 2.5% higher than the B10 and B30 fuels.

In all tests carried out with the different fuels considered, the specifications of the injection pump and the injection timing remained constants. In these conditions, the engine never reached the same performance with the biodiesel fuels than with the neat diesel fuel. In percentage terms, this decrease in performance resulted small since the biodiesel blends were smaller than B50. While the content of methyl ester in the fuel increases, its density also increases and its heating value decreases in comparison to that of the diesel fuel. This happens in a smaller degree when the heating value is expressed in a volume basis rather than when it is expressed in a mass basis. The decrease in the heating values of the biodiesel blends resulted smaller than the increase in the observed fuel consumption required to produce 1 kW of output engine power. This circumstance was determined by the fact that in spite of the engine's thermal efficiency decreasing when the amount of biodiesel increased, the decrease did not decline in the same percentage as the heating value, making it evident that a more complete fuel combustion occurs when a higher percentage of biodiesel is used. Our observations verify those of other authors who have also compared the performance of different diesel engines working with different biodiesel blends (Ali *et*

Table 7. Thermal efficiency for different fuel blends and OECD engine testing points

Fuel blends	P1[1]	P2	P3	P4	P5	P6	Mean
Diesel	0.284 A d[2]	0.269 A e	0.298 A b	0.230 A f	0.326 A a	0.294 A c	0.283 A
B10	0.276 B c	0.268 A d	0.288 B b	0.223 B e	0.313 C a	0.287 C b	0.276 B
B20	0.276 B d	0.263 B e	0.285 C c	0.219 C f	0.310 D a	0.287 C b	0.273 C
B30	0.277 B c	0.264 B d	0.290 B b	0.222 B e	0.316 B a	0.289 B b	0.276 B
B50	0.273 C c	0.258 C d	0.283 C b	0.215 D e	0.311 D a	0.283 D b	0.270 D
B70	0.269 D d	0.258 C e	0.288 B b	0.219 C f	0.316 B a	0.286 C c	0.273 C
B100	0.276 C c	0.254 D e	0.278 D b	0.206 E f	0.309 D a	0.272 E d	0.266 E
Mean	0.276 d	0.262 e	0.287 b	0.219 f	0.314 a	0.284 c	

[1,2] See Table 3. Fuel blends LSD ($P < 0.01$) = 0.0009; OECD testing points LSD ($P < 0.01$) = 0.0008. Fuel blends × OECD testing points LSD ($P < 0.01$) = 0.0021.

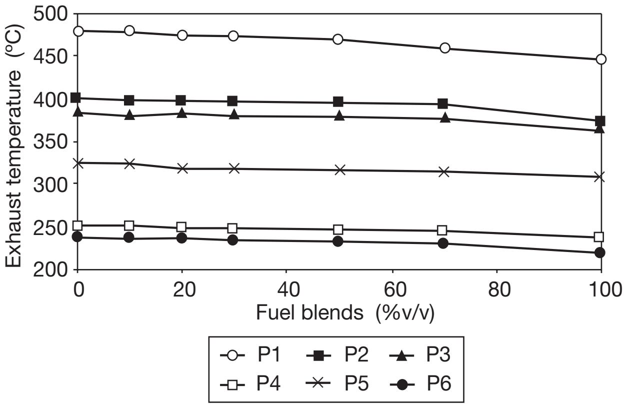

Figure 1. Variations of exhaust temperature with different fuel blends for OECD test points.

al., 1995; Roskilly *et al.*, 2008). On the other hand, Raheman and Phadatare (2004) observed that the output power, brake specific fuel consumption and thermal efficiency of a small diesel engine of 7.5 kW rated power improved noticeably when substituting diesel fuel with B20 and B30 of karanja methyl ester.

The exhaust gas temperature in all operating conditions as a function of the fuels considered is shown in Figure 1. The exhaust gas temperature decreased linearly as the content of methyl ester in the fuel increased, but the most pronounced decrease was observed when the blends B70 and B100 were utilized in the P1 operating conditions and when blend B100 was utilized in the P2 and P6 operating conditions. It can be seen in Figure 2 that the exhaust gas temperature exponentially decreased

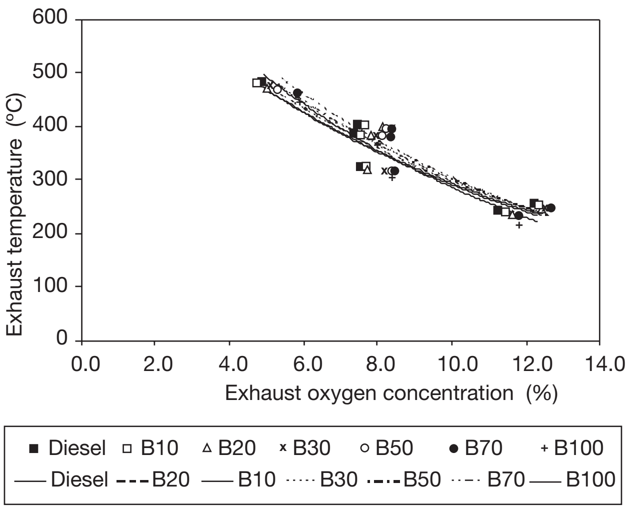

Figure 2. Variation of exhaust temperature with exhaust oxygen concentration for the fuel blends compared.

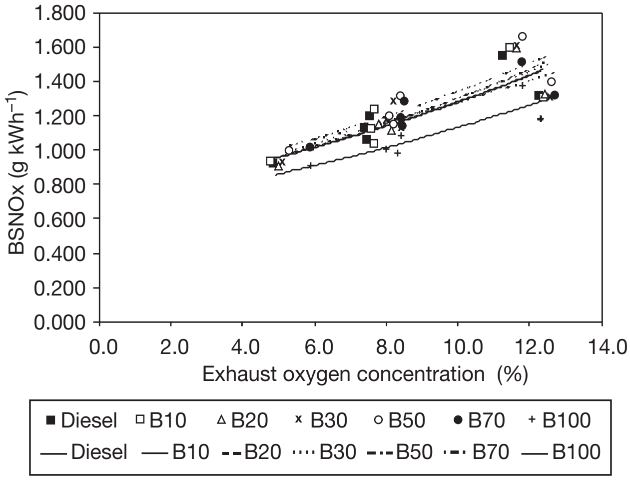

Figure 3. NOx emissions and exhaust oxygen concentration for the fuel blends compared.

with their oxygen concentration. The rate of temperature decrease was similar in all fuels compared (data not shown). The differences between the temperatures of the exhaust gases were small as the biggest difference were 7% and 8% when comparing diesel fuel and B100 in the P1 and P6 operating conditions, respectively, and the smallest difference was 5% when both fuels were compared in the operating conditions P3, P4 and P5. These differences are smaller than those observed in the specific fuel consumption; therefore, the amount of heat rejected with the exhaust gases increased as the amount of biodiesel in the fuel increased. On the other hand, a greater quantity of fuel burnt led to a smaller concentration of oxygen and a higher temperature in the exhaust gases.

The break specific emissions of NO_x as a function of the oxygen concentration in the exhaust at each operating point and for all fuel tested can be seen in Figure 3. The NO_x emissions rose exponentially with the content of oxygen in the exhaust gases, the smaller emissions corresponding to the B100 fuel. On average, the emissions with B100 were 8% less than the ones using neat diesel fuel. However, the rate of increase in emissions was similar in all fuels. The amount of NO_x emissions formed in an engine is highly dependent on combustion temperature, along with the concentration of oxygen present in combustion products (Wang *et al.,* 2000). The reduction on the NO_x emissions observed with B100 can be attributed to its lower exhaust gas temperature in comparison with the other fuels considered. The exhaust gas temperature is directly related to the temperature in the combustion chamber; therefore, the lower the former the lower the latter. Our

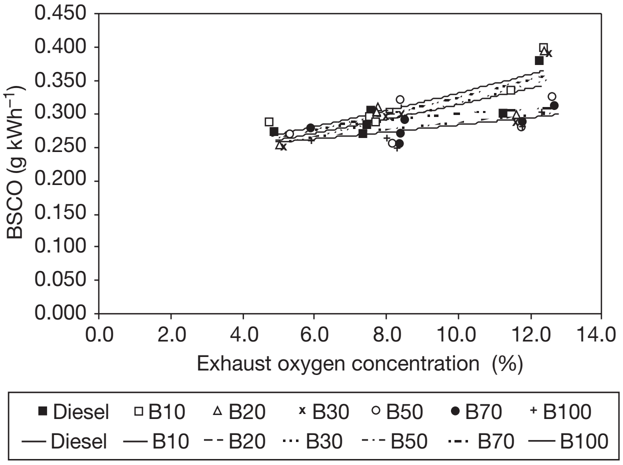

Figure 4. CO emissions and exhaust oxygen concentration for the fuel blends compared.

observations are in accordance with those made by Roskilly *et al.* (2008) who observed in two diesel engines that the NO_x emissions decreased when substituting the diesel fuel with biodiesel. As the percentage of methyl ester increases, more fuel needs to be injected in order to get the same power because lower energy content of biodiesel compared with diesel fuel. Canacki and Van Gerpen (2003) observed that the injection pump injects biodiesel earlier than diesel fuel. Biodiesel starts to burn earlier than diesel fuel as a result of the injection advance and the shortness of the ignition delay (Canacki, 2009). The smaller heating values of biodiesel and obviously its higher cetane number are responsible for the observed reduction in the NO_x emissions, since the higher the cetane number the shorter de ignition delay and more time is available for the fuel combustion to be completed (Raheman and Phadatare, 2004; Lin and Lin, 2007; Roskilly *et al.*, 2008).

For all operating points, Figure 4 shows that the break specific emissions of CO grew exponentially with the oxygen concentration in the exhaust gases, being B50, B70 and B100 the fuel blends with the smallest emissions and the smallest rate of increase in emissions. The rate of CO emissions with B100 and B70 fuel blends was 48% smaller to that of the neat diesel, and with B50 fuel blend that rate was 55% smaller to that of the diesel fuel. The greatest emissions of CO were obtained in the operating point P4, which are those where the engine is working in a very light load condition. In this case, the emission levels of CO (data not shown) with blends B10, B20 and B30 were greater than the emissions levels of diesel fuel. Similar observations to these mentioned above have been made by other authors, such as Raheman and Phadatare (2004) and Roskilly *et al.* (2008). At low loads, the temperature in the engine cylinder is also low and the atomisation of the biodiesel is inadequate due to its high viscosity. However, as the engine load is increased the temperature of the engine cylinder is higher and the biodiesel atomisation improves. This results in an improved air/fuel mixing, improved combustion and, therefore, a reduction in CO emissions (Roskilly *et al.*, 2008). Nevertheless, the higher oxygen content of the biodiesel blends B50, B70 and B100 made it easier their combustion and they resulted in lower CO emissions even at light loads.

Conclusions

Based on the results of the tests conducted with an agricultural diesel engine fuelled with different biodiesel blends the following conclusions may be drawn:

— Engine performance in terms of power and torque outputs with biodiesel blends smaller than 50% did not differ to a great extent from that of diesel fuelled engine performance.

— Fuel consumptions with biodiesel were higher than that when fuelled with diesel but differences were not very marked up to 30% blends. Furthermore, reduction in engine thermal efficiency was less than the corresponding reduction in heating value of the different biodiesel blends, indicating more complete combustion of methyl ester fuels in comparison with diesel fuel.

— NO_x emissions increased exponentially with oxygen concentration of the exhaust gas, but NO_x production was lower with 100% biodiesel than with the other fuels.

— CO emissions increased exponentially with oxygen concentration of exhaust gas, but the rate of the CO emissions was lower with biodiesel blends equal or higher than 50%.

Acknowledgements

The authors wish to thank the Spanish Ministry of Environment and Rural and Marine Affairs for the grant P-060240339 that made this study possible.

References

AGARWAL A.K., 1998. Vegetable oils *versus* diesel fuel: development and use of biodiesel in compression ignition engine. TERI Inf Digest on Energy 8, 191-203.

AGARWAL D., KUMAR L., AGARWAL A.K., 2007. Performance evaluation of a vegetable oil fuelled compression ignition engine. Renew Energ 33, 1147-1158.

AKASAKA Y., SUZUKI T., SAKURAI Y., 1997. Exhaust emissions of a DI diesel engine fueled with blends of biodiesel and low sulphur diesel fuel. SAE Technical Paper No. 972998. SAE, Warrendale, PA, USA.

ALI Y., HANNA M.A., LEVITICUS L.I., 1995. Emissions and power characteristics of diesel engines on methyl soyate ad diesel fuel blends. Bioresource Technol 52, 185-195.

CANACKI M., 2009. NOx emissions of biodiesel as an alternative diesel fuel. Int J Vehicle Design 50, 213-228.

CANACKI M., VAN GERPEN J., 2003. Comparison of engine performance and emissions for petroleum diesel fuel, yellow-grease biodiesel and soybean-oil biodiesel. T ASAE 44, 1429-1436.

LAPUERTA M., RODRÍGUEZ-FERNÁNDEZ J., AGUDELO J.R., 2007. Diesel particulate emissions from used cooking oil biodiesel. Bioresource Technol 99, 731-740.

LIN C.Y., LIN H.A., 2007. Engine performance and emissions characteristics of a three-phase emulsion of biodiesel produced by peroxidation. Fuel Processing Technol 88, 35-41.

MONYEM A., VAN GERPEN J.H., 2001. The effect of biodiesel oxidation on engine performance and emissions. Biomass and Energy 20, 317-325.

OECD, 2008. Standard code for the official testing of agricultural and forestry tractor performance [on line]. Organisation for Economic Co-operation and Development. Available in http://www.oecd.org/tad/tractor [26 November, 2008].

PERKINS L.A., PETERSON C.L., AULD D.L., 1991. Durability testing of transesterified winter rape oil (*Brassica napus* L.) as fuel in small bore, multi-cylinder DI, CI engines. SAE Technical Paper No. 911764. SAE, Warrendale, PA, USA.

RAHEMAN H., PHADATARE A.G., 2004. Diesel engine emissions and performance from blends of karanja methyl ester and diesel. Biomasss and Bioenergy 27, 393-397.

ROSKILLY A.P., NANDA S.K., WANG Y.D., CHIRKOWSKI J., 2008. The performance and the gaseous emissions of two small marine craft diesel engines fuelled with biodiesel. Appl Therm Eng 28, 872-880.

STATSOFT, 2003. STATISTICA 6.0 for windows. Stasoft Inc., Tusla, OK, USA

VAN GERPEN J., PETERSON C., GOERING C.E., 2007. Biodiesel: an alternative fuel for compression ignition engines. ASAE Distinguised Lecture No. 31. ASABE, St Joseph, MI, USA.

WANG W.G., LYONS D.W., CLARK N.N., GAUTAM M., NORTON P.M., 2000. Emissions from nine heavy trucks fuelled by diesel and biodiesel blend without engine modification. Environ Sci Technol 34, 933-939.

ZHANG Q., FELDMAN M., PETERSON C.L., 1988. Diesel engine durability when fuelled with methyl ester of winter rapeseed oil. ASAE Paper No. 881562. ASAE, St Joseph, MI, USA.