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Exhaust emissions from a Diesel engine fueled with transesterified waste olive oil☆

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Abstract

The exhaust emissions of a Diesel direct injection Perkins engine fueled with waste olive oil methyl ester were studied at several steady-state operating conditions. Emissions were characterized with neat biodiesel from used olive oil and conventional Diesel fuel. Results revealed that the use of biodiesel resulted in lower emissions of CO (up to 58.9%), CO_2 (up to 8.6%, excepting a case which presented a 7.4% increase), NO (up to 37.5%), and SO_2 (up to 57.7%), with increase in emissions of NO_2 (up to 81%, excepting a case which presented a slight reduction). Biodiesel also presented a slight increase in brake-specific fuel consumption (lower than 8.5%) that may be tolerated due to the exhaust emission benefits. Combustion efficiency remained constant using either biodiesel or Diesel fuel. The proposed alternative for Diesel fuel could significantly decrease the enormous amount of waste frying oil, furthermore becoming less dependent on fossil oil imports and decreasing environmental pollution.

Keywords: Biodiesel; Pollution; Used frying oil

1. Introduction

Alternative fuels for Diesel engines have become increasingly important due to increased environmental concerns, and several socioeconomic aspects. In this sense, vegetable oils and animal fats represent a promising alternative to conventional Diesel fuel. However, several chemical properties of oils and fats, among them are the high viscosity and high molecular weight, cause poor fuel atomization and low volatility, leading to incomplete combustion and severe engine deposits, injector coking and piston ring sticking [1]. Research has shown that one way to improve the fuel properties of oils and fats is their transesterification [2–6]. Transesterification is a chemical reaction which refers to the conversion of an organic acid ester into another ester of the same acid, so-called biodiesel, using an alcohol, in the presence of a catalyst. This process provides a fuel that can be utilized in unmodified Diesel engines.

Moreover, several approaches have found that this new fuel seems to emit far less of the most regulated pollutants than standard Diesel fuel, among them is CO_2. That means biodiesel contributes to reduce greenhouse gas emissions compared to conventional Diesel [7–11]. Also, the use of biodiesel results in substantially lower emissions of carcinogenic compounds, as compared to conventional Diesel fuel. In this sense, Ryu et al. [12] found that methyl soyate inhibits contamination by microorganisms, while bacteria presence increases in distillate water as well as in Diesel fuel.

In other sense, nitric oxide and nitrogen dioxide are very important in polluted air. Collectively designated NO_x, regionally high NO_2 concentrations can cause severe air quality deterioration. Practically all anthropogenic NO_x enters atmosphere as a result of the combustion of fossil fuels. Most NO_x entering the atmosphere from pollution sources does so as NO generated from internal combustion engines. Like carbon monoxide, NO attaches to

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hemoglobin and reduces oxygen transport efficiency. However, the concentration of nitric oxide normally is much lower than that of carbon monoxide so that the effect on hemoglobin is much less [13]. Moreover, Mittelbach and Tritthart [14] observed lower emissions after the use of waste frying oil methyl ester, excepting NO_x values which were higher compared with reference US-2D fuel.

Acid rain, caused by the deposition on the earth's surface of aqueous acids such as SO_2, is mostly due to industrial operations and fossil fuel combustion. As a result of its widespread distribution and effects, acid rain is an air pollutant that may pose a threat to the global atmosphere [13].

According to economic reasons, used frying oil is also an interesting feedstock for biodiesel production [14,15]. In fact, in Spain, edible vegetable oil consumption is approximately 600,000,000 l/year. Most of this oil (70%) is olive oil and is primarily used for deep-frying processes [6]. According to the INE (Spanish National Institute of Statistics) about 74,000,000 l of waste olive oil is collected per year, which is an approximate value since most of the household waste frying oil is thrown through the drainage. In this sense, transesterification of waste olive oil to produce biodiesel could decrease the waste disposal problem.

Although several approaches have described the use of biodiesel from vegetable oils or animal fats [2–5,7–9], research concerning biodiesel from used frying oil, and from waste olive oil in particular, is insufficient, and nonexistent, respectively, and more research is needed.

In this sense, the aim of this work is to carry out a preliminary emission test of a Diesel direct injection engine fueled with biodiesel from waste olive oil at several steady-state operating conditions. Emissions data includes carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO, NO_2 and NO_x) and sulfur dioxide (SO_2). This paper also reports on the effect of waste olive oil methyl ester upon combustion efficiency and brake-specific fuel consumption (BSFC).

2. Methods and equipment

2.1. Fuel description

Waste olive oil was collected from several Spanish hospital kitchens and filtered from solid impurities using a 27 μm diameter, paper no. 1305 from ALBET (Filtros Anoia SA, Barcelona, Spain). Only hospital fryers were used as a source for uniformity reasons. The used oil was transesterified using methanol in the presence of KOH. Waste olive oil methyl ester (100%) was used for the emission test. Some fuel properties of both used olive oil methyl ester and European Fatty Acid Methyl Ester (FAME) standard draft (prEN 14105) are shown in Table 1.

2.2. Equipment

The fuel tests were performed with a 2500 cm^3, three cylinder, four-stroke, water-cooled, 18.5:1 compression ratio, direct injection Diesel engine Perkins AD 3-152. The maximum torque was 162.8 Nm at 1300 rpm, and the maximum engine power was 34 kW at 2250 rpm (DIN 6270-A). The engine was not new but reconditioned to original specifications.

In order to measure the emissions, combustion efficiency (comb. eff.) and BSFC during operation, the actual driving conditions on the road were simulated on the dynamometer. The engine dynamometer was an electric Froment testing device (model XT200), with maximum engine power of 136 kW and ±1.44 kW of accuracy at 100% of the engine speed (reported by the National Institute of Agricultural Engineering, UK), as described by Dorado et al. [15]. The fuel was metered by a positive displacement gear type sensor, using a Froment Electronic Fuel Flow Monitor (FM502), as described by Dorado et al. [15].

The engine speed was measured by the Froment testing device and monitored electronically to the nearest 5 rpm. Data at a number of atmospheric conditions were collected

Table 1
Fuel properties of waste olive oil methyl ester and European FAME standard draft (prEN 14105)

Chemical property	Method	prEN 14105	Waste olive oil methyl ester
Density at 15 °C (kg/m^3)	EN ISO 3675	860–900	882.3
Kinematic viscosity at 40 °C (mm^2/s)	ASTM D445 * IP-71 * BS188	3.5–5.0	5.29
Flash point (°C)	ASTM-D-2709	> 101	169
Cetane index	ASTM-D-4737/96a	> 51.0	58.7
Iodine value	UNE 55.013	< 120–125	78
Cold filter plugging point (°C)	IP-309/96	–	−9
Cloud point (°C)	ASTM-D-2500	–	−2
Pour point (°C)	ASTM-D-97	–	−6
Gross heating value (MJ/kg)	ISO 1928	–	39.67

in order to correct the BSFC and power, following the SAE standard J1349 (June 1983).

Emission tests were carried out with a portable pollution emissions monitor, model 9950, from Teledyne Brown Engineering, USA. It consists of a stainless steel probe which is connected to a monitor by a flexible hose. Once the autozero is completed, the probe can be inserted into the sample stream. The model incorporates advanced microprocessor technology which provides a menu-driven interface with all functions through front panel controls and a large LCD display. The model provides an emission analysis with an accuracy of better than ±3% of full scale. It measures SO_2, O_2, CO, NO_x ($NO + NO_2$) and calculates the concentration of CO_2.

In addition, it also allows to calculate the net combustion efficiency. Combustion efficiency was calculated using the indirect method which relies on knowing the heat value, measuring the waste heat in the exhaust gas, and attributing the difference to lost efficiency. The equation for combustion efficiency is determined as follows

$$\text{Percent Efficiency} = \frac{100(H_{\text{fuel}} - H_{\text{exhaust gas}})}{HV_{\text{fuel}}} \quad (1)$$

where H is enthalpy, defined as energy + (pressure × volume), and HV is the maximum heat available from burning the fuel. The $H_{\text{exhaust gas}}$ is determined as follows

$$H_{\text{exhaust gas}} = \frac{H_{CO_2} + H_{H_2O} + H_{SO_2} + H_{O_2} + H_{N_2}}{w} \quad (2)$$

where w is the molecular weight of the fuel.

2.3. Emission tests

The engine test cycle was tailored after the '8-mode cycle' for engine dynamometer operation, according to ISO 8178-4, approved by the current EU guidelines that forms the legislative base for emissions standards [16]. Emissions test plan adapted to Diesel engine Perkins AD 3-152 is shown in Table 2. Each running step was held for 10 min until exhaust emissions were stabilized and maintained while each parameter was measured and recorded, during the last 3 min of each running step.

A first test was run with straight Diesel fuel at the beginning, followed by the waste oil methyl ester test run, in order to compare exhaust emissions and BSFC with the two fuels. Engine tests were run on the same engine and same day, in order to have almost the same atmospheric conditions within the three repetitions of each test.

To gain knowledge about the implications of the results, several statistical tests were performed. This process statistically compared each of the tested parameters between used olive oil methyl ester and Diesel fuel.

Table 2
Test plan for emissions test

Step number	Engine speed ±1%[a] (equivalence in rpm)	Load% ±2%[a] (equivalence in Nm)
1	Rated (2390)	100 (530)
2	Rated (2390)	75 (370)
3	Rated (2390)	50 (247)
4	Rated (2390)	10 (80)
5	Medium (1330)	100 (560)
6	Medium (1330)	75 (420)
7	Medium (1330)	50 (281)
8	Low idle (600)	–

[a] Allowed accuracy.

3. Results and discussion

3.1. Emissions tests

Results concerning percent changes in emissions of the Perkins engine fueled with used olive oil methyl ester compared to Diesel fuel are shown in Fig. 1. The graph show percent changes as the ordinate and the step number of the emissions test plan as the abscissa. These data show a significant reduction in CO (up to 58.9%), CO_2 (up to 8.6%, excepting step no. 2, which presented a 7.4% increase), NO (up to 37.5%) and NO_x (up to 32%) for used olive oil methyl ester compared to Diesel fuel. Results showed also a significant reduction in SO_2 (up to 57.7%), because biodiesel contains little sulfur compared to Diesel fuel, as found by Chang et al. [8] and Scharmer [10]. A reduction in SO_2 emissions decreases the acid rain risk. However, NO_2 increased up to 81%, excepting step no. 4, where presented a slight reduction. Reduction in CO_2 emissions has an immediate and positive impact on greenhouse gas emissions reduction.

In contrast to previous investigations with biodiesel from used frying oil [8,10,14], it is important to notice the NO_x ($NO + NO_2$) emissions reduction. Although, it was observed a high increase in NO_2 emissions compared to NO reduction. This is due to the bigger absolute values of NO emissions compared to those of NO_2. Also, NO_x emissions are determined by oxygen concentration, combustion temperature and time. While oxygen concentration increases up to 17.6%, however, combustion temperature (stack temp. in Fig. 2) remained almost constant. This could be the explanation for the lower exhaust NO_x levels; however, more research is needed. In this sense, it is important not to forget that this is the first time for biodiesel from waste olive oil to be tested so results can differ from those using used frying oils from other origins. NO production is favored by high temperatures and by high excess oxygen concentrations. Unfortunately, a reduction of flame temperature to prevent NO formation decreases the efficiency of energy conversion, as calculated by the Carnot equation [13]. Low-excess-air firing is effective in reducing NO_x emissions

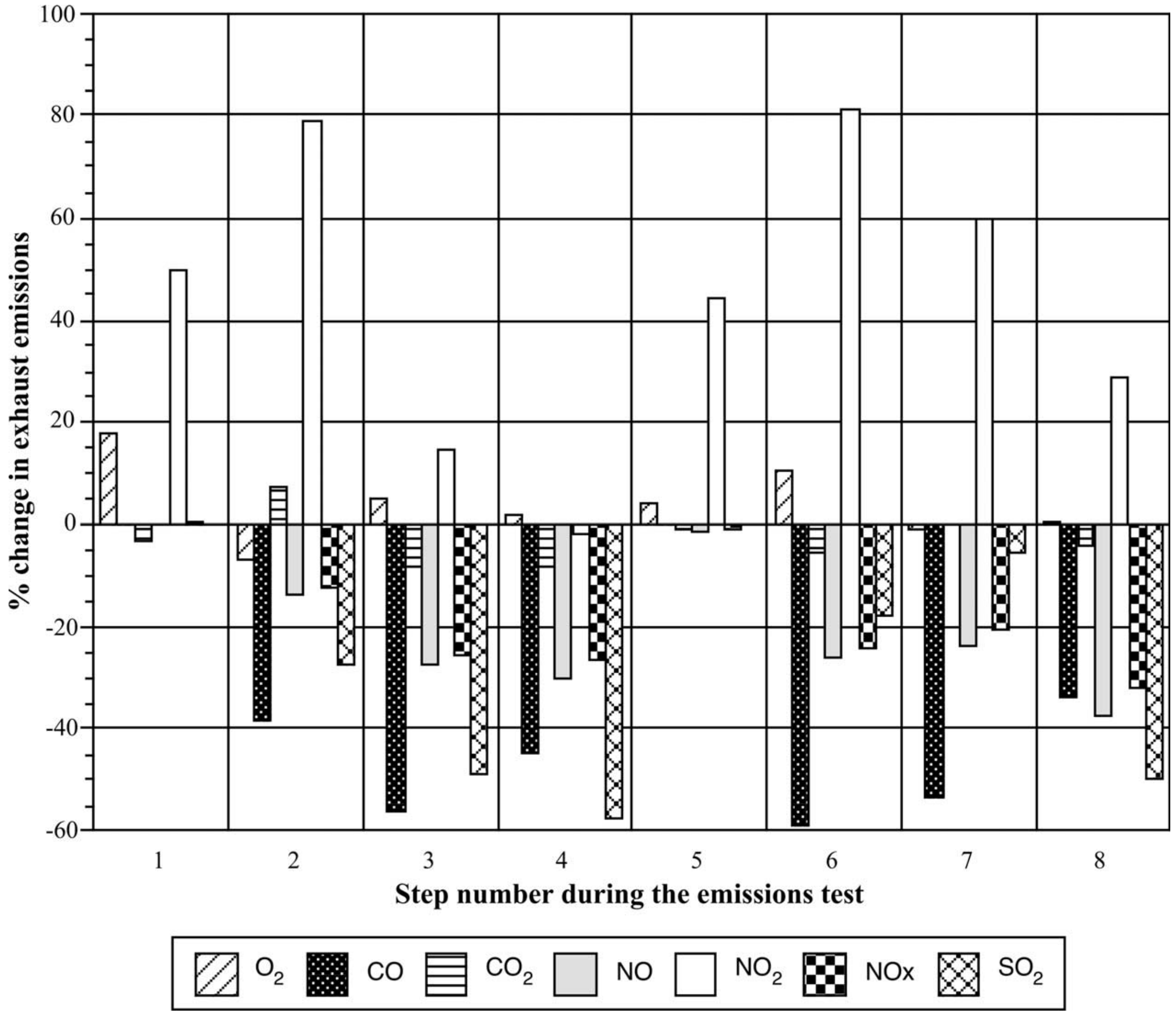

Fig. 1. Percent changes in exhaust emissions of a Perkins engine fueled with used olive oil methyl ester compared to Diesel fuel. No data were collected in steps no. 1 and 5 for SO_2 emissions. Percent change in NO_x ($NO + NO_2$) indicates a decrease in NO_x emissions using waste olive oil methyl ester instead of Diesel fuel, while NO_2 presents a generalized significant increase compared to NO reduction. This is due to the bigger absolute values of NO emissions compared to those of NO_2.

during the combustion. However, incomplete fuel burnout with the emission of hydrocarbons, soot, and CO appear.

In addition, statistical analysis using the Kolmogorov and Smirnov method showed that data are sampled from populations that follow Gaussian distributions. Also, the unpaired *t*-test showed that emissions differences between biodiesel from used olive oil and Diesel fuel were not significant, except results concerning CO and NO_2 which were considered significant and very significant, respectively.

At this point, it is important to notice that the Perkins Diesel engine used is old and rather different from new 'state of the art' engines that have much lower emissions. For this reason, this work not includes the actual exhaust emissions values, because our main target was to give a broad indication of the benefits of the approach adopted in this paper.

3.2. Effect of used olive oil methyl ester on BSFC and combustion efficiency

As shown in Fig. 1, the oxygen concentration increased up to 17.6%, thus providing more oxygen for combustion. Combustion efficiency did not drop during testing and remained almost constant using either used olive oil methyl ester or Diesel fuel. The engine was efficient with both used olive oil methyl ester and Diesel fuel.

Results revealed a slight increase in BSFC, lower than 8.5%, as shown in Fig. 2. However, this little increase may be tolerated due to the exhaust emission benefits. In addition, statistical analysis showed no significant BSFC and combustion efficiency differences between biodiesel from used olive oil and Diesel fuel. Engine performance of used olive oil methyl ester was similar to Diesel fuel and no changes in operation were noticed. However, the exhaust

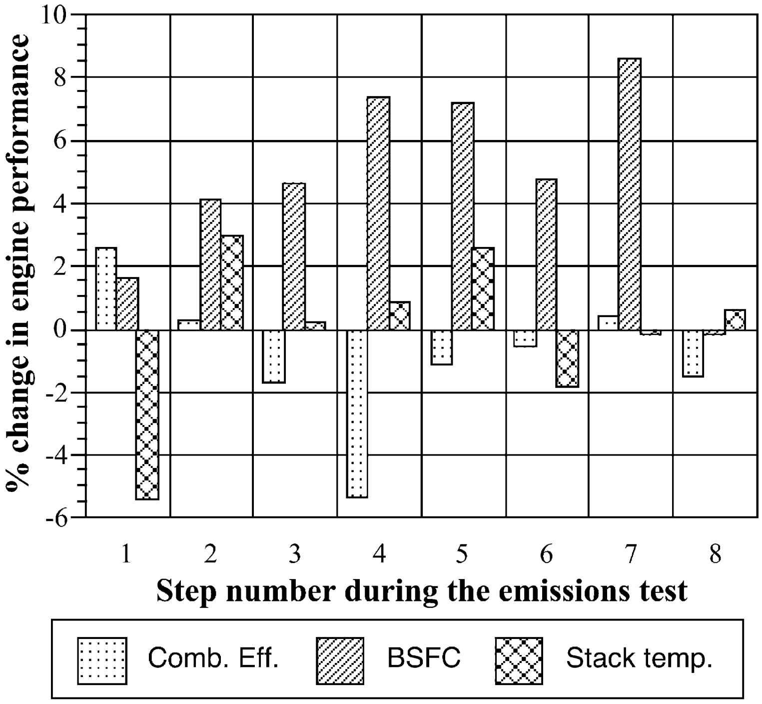

Fig. 2. Percent changes in combustion efficiency and BSFC of a Perkins engine fueled with used olive oil methyl ester compared to Diesel fuel.

gases had a slightly different odor, and a slight fried food smell was detected.

Smoke emissions were visually observed and appeared extremely low. We can conclude from this field trial that used olive oil methyl ester can provide an alternative to Diesel fuel from fossil origin that significantly decreases most of the regulated exhaust emissions. To prove the quality of this fuel, however, a long term engine test is required.

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