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Multiple response optimization to reduce exhaust emissions and fuel consumption of a diesel engine fueled with olive pomace oil methyl ester/diesel fuel blends

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In this work, with the aim of selecting the optimal operating conditions of a diesel engine (with regard to load and biodiesel blend) besides reducing both main exhaust emissions and *BSFC* (brake-specific fuel consumption) a methodology based on multiple response optimization has been proposed. *BSFC* and emissions (NO_x, SO_2 and CO) using three different load conditions (50%, 75% and 100%) using similar olive pomace methyl esters/diesel blends have been evaluated. Engine testing was followed by the design of the global desirability function in terms of both engine load and biodiesel blends. Eventually, a direct correlation between emissions and load was found. Finally, to ensure minimum values of *BSFC* under three levels of emissions reduction (10%, 20% and 40%) optimum engine operating ranges, in terms of load rate and biodiesel blends, are studied.

1. Introduction

Nowadays, environmental concerns and the eventual depletion of oil reserves have caught the attention of researchers to find renewable alternatives, like liquid biofuels, to conventional fossil fuels. First, the effect of the use of straight vegetable oils as alternative biofuel for direct injection diesel engines was tested. Results were not enthusiastic, as percentages above 8% of crude vegetable oil blended with diesel fuel led to engine problems such as carbon deposits inside the combustion chamber, piston ring sticking, injection tips cooking and polymerization [1]. To overcome this problem, scientists changed the chemical structure of vegetable oils through transesterification, thus providing a new fuel named biodiesel [2,3]. When diesel engine was fueled with biodiesel, results were encouraging. In fact, the use of biodiesel mixed with diesel fuel to run diesel engines has been accepted worldwide, although different authors have reported a slight power decrease and a *BSFC* (brake-specific fuel consumption) increase, exception made with blends containing below 20% biodiesel [4,5]. With mixtures above 20% of biodiesel blended with diesel fuel, brake-power behaves inversely proportional to the amount of biodiesel in the blend, while *BSFC* increases with the addition of biodiesel to blends [6,7].

Several authors have reported a decrease in CO, CO_2, HC and SO_2 emissions, with no influence on NO_x emissions, when the presence of biodiesel in the blend increases [8,9]. NO_x emissions can even be reduced when the amount of biodiesel added to diesel fuel is below 10% [4,5].

The influence of the use of biodiesel on engine behavior and exhaust emissions at different speed and full load, or in stationary engines, that work at constant speed and different load has been checked. Stationary engines, usually used to generate electricity [10], show a direct influence over the local pollution derived from combustion gases, as emissions proportionally increase to the engine load. For this reason, under certain conditions, the addition of biodiesel to diesel fuel can be a tool to reduce local pollution in stationary engines, thus meeting electric demand besides a reduction of major pollutant emissions [11–13].

Previous works contributed to increase the knowledge about the implications of the use of biodiesel in compression ignition engines, being engine performance and exhaust emissions usually analyzed as independent parameters. However, both characteristics must be analyzed together to select the best approach from both points of view. In this sense, the desirability function offers a

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Acronyms

BSFC	Brake-specific fuel consumption
CO	Carbon monoxide
CO_2	Carbon dioxide
CN	Cetane number
D	Desirability function
FAME	Fatty acids methyl ester
HC	Hydrocarbon
N	engine power
NO_x	Nitrogen oxide
OPO	Olive-pomace oil
OPME	Olive–pomace oil methyl ester
SO_2	Sulfur dioxide

suitable solution to simultaneously optimize different parameters. In fact, this method is commonly used in industry for the optimization of multiple response processes. This methodology is based on the quality of a product or process and depends on multiple characteristics quality; if one of them is placed outside the desired limits, it is completely unacceptable. For this purpose, the method finds operation conditions that provide the most desirable response values [14,15]. To the best of our knowledge, this function has not been applied to find out the optimal operation condition that provides the least *BSFC* and exhaust emissions of a diesel engine fueled with alternative fuels, i.e. biodiesel, at constant speed and different load.

Olive oil consists in a highly valuable oil that is mainly produced in Mediterranean countries, namely Spain, Greece, Italy, Tunisia, Portugal, Syria and Lebanon. Oil extraction is usually accomplished through cold pressing, which provides oil and olive cake as residue. The cake still includes olive-pomace oil, a low-value edible oil that may be extracted using a solvent. As it shows a more neutral flavor than virgin olive oil, experts categorize it as undesirable and cannot be described as olive oil. However, it depicts the same fatty acid composition as regular olive oil. So, another uses such as its recycling for biodiesel production must be taken into consideration.

For the previous reasons, the aim of this study is to evaluate *BSFC* and exhaust emissions of a diesel engine, working under constant speed and different loads, running on both pure olive–pomace oil methyl ester and 50% biodiesel blended with diesel fuel. Results are compared to the use of diesel fuel. For this purpose, the effect of biodiesel content in the blend besides engine load on *BSFC* and exhaust emission are studied. To meet a compromise between the minimum values of *BSFC* and exhaust emissions, the Derringer desirability function approach is applied.

2. Materials and methods

2.1. Fuels description

OPO (Olive-pomace oil) was provided by KOIPE (SOS Cuétara, Madrid, Spain). Oil transesterification to produce biodiesel was performed at 60 °C using a solution of 1.2% KOH and 20% methanol (wt alcohol/wt oil), during 40 min of vigorous stirring. Subsequently, reaction was stopped and settled to decant. Ester phase was washed using distillated water and eventually dried [16,17]. Some properties of both OPME (olive–pomace oil methyl ester) and No. 2 diesel fuel were calculated following EN 14214 and EN 590 standards, respectively, and are presented in Table 1. Engine tests were performed using pure OPME, No. 2 diesel fuel and their blend (50% v/v, OPME50).

2.2. Equipment

Fuel tests were performed in a 2500 cm^3, three cylinder, four–stroke, water–cooled, 18.5:1 compression ratio, direct injection Perkins diesel engine. The maximum torque and engine power were 162.8 Nm at 1300 rpm and 34 kW at 2250 rpm (DIN 6270–A), respectively. The engine dynamometer was a Froment XT200 electric testing device (UK), with maximum engine power of 136 kW and ±1.44 kW of accuracy at maximum speed, as described by Dorado et al. [9,18]. The fuel was measured using a Froment Electronic Fuel Flow Monitor (FM502, UK), placed in the fuel line between the tank and the engine fuel filter. The return fuel from the engine was circulated back into the engine supply line, as described by Dorado et al. [18]. A portable Testo 350-S exhaust emission monitor measured NO_x, SO_2 and CO emissions at different loads.

2.3. Engine performance tests

BSFC curves were analyzed at a constant speed of 1800 rpm and different loads. During the engine operation, *BSFC* was measured using pure OPME, followed by OPME50 and a final test using fossil diesel fuel. The load percentages taken into consideration during the test were 50%, 75% and 100% of the maximum load. The range from 0 to 50% load was not analyzed provided that in this range the stationary engine is not efficient. Both *BSFC* and engine power (*N*) were corrected to atmospheric conditions, following the SAE standard J1349 (revised August 2004).

2.4. Emission tests

For each working condition, the engine was run for 10 min, until it stabilized. Each parameter was measured and recorded, during the last 3 min.

2.5. Statistical analysis

Statgraphics© centurion XVI (StatPoint Technologies, Warrenton–Virginia, USA) was the software employed to build and analyze response surfaces, allowing the design of multiple response optimization, thus leading to achieve the optimum values.

3. Results and discussion

3.1. Engine performance and emission tests

As expected, the production of exhaust emissions was directly proportional to the engine load for all evaluated fuels, while the lowest value of *BSFC* was achieved around 75% load, as can be observed from Figs. 1–4. Consequently, the optimal efficiency area (corresponding to minimum *BSFC*) during the engine operating conditions did not correspond to the lowest emissions values. As may be seen from Fig. 4, no SO_2 emissions were emitted when OPME was used, due to the free-sulphur nature of OPO.

BSFC slightly increased with the concentration of biodiesel in the mixture. Whereas CO and SO_2 emissions showed the opposite trend. The increase in *BSFC* when biodiesel and its mixtures are used is related to biodiesel higher density and lower *LHV* (Low Heating Value) compared to diesel fuel. In other words, considering the same volumetric flow of fuel supplied by the injection pump, the mass flow during the operation of the engine at the same speed is increased. CO emission reduction is due to the oxygen content of biodiesel, which promotes more complete combustion [19].

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