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Evaluation of sooting tendency of different oxygenated and paraffinic fuels blended with diesel fuel

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HIGHLIGHTS

- Reduction of sooting tendency was observed with alternative diesel fuels blends.
- Sooting tendency can be ordered as follows: Diesel > Biodiesel > Paraffinic fuels > Alcohols.
- Biodiesel- and paraffinic-diesel blends show similar sooting tendencies.
- Sharper decrease of sooting tendency was registered with alcohol-diesel blends.
- Great differences in sooting tendency characterize differences in particle emissions from engines.

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ABSTRACT

In this study a comparative experimental work about the sooting tendency of different fuel blends has been carried out. Three groups of alternative fuels, blended with diesel fuel, were tested: (1) an animal fat biodiesel; (2) two paraffinic fuels: a hydro-treated vegetable oil (HVO) and a gas-to-liquid (GTL) from natural gas and (3) two alcohols: ethanol and butanol. The smoke point of different binary alternative-diesel fuel blends was determined by means of a standardized Smoke Point Lamp. A low sulphur diesel fuel without biodiesel content was used as reference fuel. As sooting tendency parameters, both Threshold Sooting Index (TSI) and Oxygen Extended Sooting Index (OESI) from blends with respect to diesel fuel were compared. Two main trends were obtained. While biodiesel-, HVO- and GTL-diesel fuel blends showed similar exponential decreasing trend in sooting tendency as a function of blending percentage (with an exponential factor between −0.005 and −0.01), alcohol-diesel fuel blends resulted to be more effective suppressors of the soot (around 20 times better).

Comparing the sooting tendency of fuel blends to engine opacity/particle emissions achieved by other authors, when great differences were obtained, as in the case of alcohol blends compared to biodiesel, HVO and GTL, the translation are in good agreement.

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1. Introduction

Standards limits of regulated pollutant emissions produced by diesel engines, mainly nitrogen oxides (NO_x) and particulate matter (number of particles and total mass emitted), are getting increasingly more restrictive. In order to fulfill these stringent regulations, vehicle manufacturers are adopting different solutions, between them the use of alternative fuels [1–4].

Focusing on this latter solution for reducing diesel pollutant emissions, the 2009/30/EC directive of the European Union promotes the use of alternative fuels and renewable energies. In fact, the objective for the year 2020 is to replace the 10% of fossil fuels used in transportation by fuels from renewable sources. Many different alternative fuels have been studied: on one hand, oxygenated fuels like biodiesel from transesterification processes, different alcohols like methanol, ethanol or butanol or even ethers such as dimethyl ether and diethyl ether, and, on the other hand, paraffinic fuels from different origins, either produced by Fischer-Tropsch and/or hydro-treatment processes [4–7].

Due to the similarity of fuel properties, compared to conventional diesel fuel, biodiesel is the most widely alternative fuel used in diesel engines, either pure or blended. As is known, biodiesel is a renewable oxygenated fuel produced by transesterification of vegetable oils or animal fats. Several studies show that the use of biodiesel reduces soot and/or particulate matter emission [8,9]. However, the effect of biodiesel on NO_x depends not only on the fuel composition, but also on the engine operation [10–13].

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Other important oxygenated fuel for diesel engines is ethanol, which can be produced by fermenting sugary, starchy or even lignocellulosic biomass. Traditionally, it has been widely used in spark ignition engines because of its very high octane number, but its oxygen content (3 times higher than biodiesel) and functional group (alcohol instead ester), promoted the study of its behavior on diesel engines [14,15] despite its drawbacks such as its low cetane number, high volatility and low miscibility with diesel fuel. This latter problem implies that only very low ethanol percentages can be blended with diesel and different additives must be used to ensure the stability of blends [16–18]. A strong reduction of particulate matter is obtained when ethanol-diesel blends (despite the low ethanol percentage) are used as fuel.

In order to improve the miscibility of ethanol with diesel, ternary blends of ethanol-biodiesel-diesel have been studied since biodiesel has been proved to be a very good stabilizing agent [19]. Other way would be the use of longer-chain alcohols, e.g. butanol, instead of ethanol, whose miscibility with diesel is better [19]. Nowadays, the biological production of butanol from biomass is potentially encouraging [20]. Butanol has less volatility and higher cetane number and heating value than ethanol. Moreover, although its oxygen content is lower, its higher miscibility with diesel allows increasing the butanol percentage in the blend. As it was expected, a strong reduction of particulate matter is again obtained when butanol-diesel blends are used instead of pure diesel fuel but not a clear trend has been found when ethanol-diesel and butanol-diesel blends were compared [21–23].

Nowadays, the interest for using new renewable non-oxygenated fuels based on paraffinic hydrocarbons as a surrogate fuel in diesel engines is increasing. Between them, it can be cited those produced by Fischer-Tropsch processes at high or low temperature of natural gas (gas-to-liquid GTL) or syngas from the gasification of coal (coal-to-liquid CTL) or the gasification of biomass (biomass-to-liquid BTL) which produce paraffinic fuels. An alternative process for obtaining paraffinic hydrocarbons from renewable sources consists of vegetable oils hydro-treating at controlled temperature. The liquid fuel obtained is usually denominated as HVO (hydrotreated vegetable oil) or green fuel [24]. Although paraffinic fuels do not have molecular oxygen in their composition, their high cetane number combined with the absence of aromatic compounds lead to a cleaner combustion process with significant reduction of particulate matter and hydrocarbons without NO_x increase [25,26]. Therefore, literature agrees in affirming that the use of all of these alternative fuels reduces the smoke/particulate matter emissions, being higher with the increase of the alternative fuel percentage in the blend [27].

Recent studies have shown that the determination of propensity to smoke of these new alternative diesel fuels can be a less complex and fast tool for comparing fuel behavior trends previously to engine testing [28–30]. In this study, a comparative experimental work about the opacity tendency of different binary alternative fuel-diesel blends has been carried out using the smoke point technique. Fuels tested have been the following: an animal fat biodiesel, two paraffinic fuels (a HVO from vegetable oil and a gas-to-liquid (GTL) fuel from natural gas with similar properties than a BTL fuel obtained from biomass gasification) and two alcohols (ethanol and butanol).

2. Experimental setup

The smoke point is defined as the height (in millimeters) of the highest flame produced without smoking when the fuel is burned in a standardized test diffusive lamp with wick. So the higher the flame height, the lesser the sooting tendency of the fuel tested. Fig. 1 shows the flame appearance before, at and after the smoke point in the ASTM D1322 (ISO 3014) standard smoke point lamp used for tests.

Following the procedure specified in the ASTM D1322, prior to fuel tests, the smoke point lamp was calibrated using two of the blends with standardized smoke points: 20% (v/v) toluene – 80% *iso*-octane and 40% toluene – 60% *iso*-octane. After the lamp calibration, each blended fuel was tested three times in order to obtain an average smoke point.

The tendency to smoke of a flame depends on the balance of the required and the available oxygen content in two related processes, soot formation and soot oxidation. In this sense, the molecular composition of the fuel is one of the most important factors, which affects the sooting tendency because an increase in molecular weight requires more oxygen to diffuse into the flame per unity of fuel volume [31]. Therefore, the increased height of the flame should be taken into account. Because of this, an empirical correlation called the Threshold Sooting Index (TSI), which is directly proportional to the ratio of the molecular weight (MW) to smoke point (SP) is usually used (Eq. (1)) [31].

$$TSI = a\left(\frac{MW}{SP}\right) + b \tag{1}$$

Coefficients a and b are constants which depend on the test lamp used. Assigning a TSI = 0 to ethane (less sooty element) and a TSI = 100 to naphthalene, values of 4.3854 and −4.5741 can be obtained for constants a and b, respectively.

However, the molecular weight used in the TSI correlation is not an exact measurement of the volumetric stoichiometric air required by the flame, especially if it is referred to oxygenated fuels, e.g. as biodiesel blends. In this case, Barrientos et al. [29] proposed the use of the Oxygen Extended Sooting Index (OESI), where n, m and p, are the coefficients of carbon, hydrogen and oxygen of a generic fuel ($C_nH_mO_p$), respectively, (Eq. (2)).

$$OESI = a'\left(\frac{n + m/4 - p/2}{SP}\right) + b' \tag{2}$$

Coefficients a' and b' are constants which again depend on the test lamp. As occurred for TSI calculation, an OESI = 0 is assigned to ethane (less sooty element) and an OESI = 100 is assigned to naphthalene. Values 47.32 and −5.72 were obtained for a' and b' constants, respectively.

OESI can be used for both, oxygenated and non-oxygenated fuels. In fact, the variable part of the correlation is almost proportional to molecular weight when non-oxygenated fuels are tested.

Some other sooting indexes can be found in literature, as the Yield Sooting Index (YSI), the Fuel Equivalent Sooting Index (FESI) or the Micropyrolysis Index (MPI) proposed by [32–34], respectively. As these indexes are not based on smoke point measurements, in this study only the TSI and OESI were used to evaluate the sooting tendency.

3. Fuel samples

Three groups of alternative fuels were tested on the smoke point lamp together with a pure low sulphur diesel fuel without biodiesel supplied by Repsol (Spain), which was used as reference fuel for blending:

- Two different paraffinic fuels (alkanes): a hydro-treated vegetable oil (HVO) supplied by NESTE OIL (Finland) and a gas-to-liquid fuel (GTL) obtained from a low temperature Fischer–Tropsch process and derived from natural gas, in this case supplied by SASOL (South Africa).
- A biodiesel obtained from transesterification of animal fats, which was supplied by BDP (Spain).

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