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Regeneration of diesel particulate filters: Effect of renewable fuels

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ABSTRACT

Current trends in diesel transport anticipate that in the upcoming future a range of renewable fuels will be necessary to comply with emission and sustainability legislations. Exhaust after-treatment devices such as diesel particulate filters –DPFs– will have to operate satisfactorily with this pool of biofuels. In particular, DPF regeneration is crucial to cut the fuel penalty and guarantee an acceptable lifetime for this device. In the present work, an automotive diesel engine was run with fossil fuel and three renewable fuels: a conventional biodiesel, a fuel manufactured through Fischer-Tropsch –FT– process and a HVO biofuel. The DPF was loaded and regenerated through an active process with fuel post-injections. Additionally, soot samples were investigated with thermo-gravimetry (TGA) and calorimetry (DSC) to confirm whether these techniques obtain relevant information for explaining DPF behavior. Both methods proved that biodiesel leads to a more economical regeneration being the biodiesel soot, more reactive than the other samples, the main reason. DPF regenerations with paraffinic fuels (FT-derived and HVO) did not reveal strong differences compared to diesel, though TGA and DSC results suggested that soot from paraffinic biofuels is more reactive than that from diesel. The exhaust gas temperature and composition are behind this apparent discrepancy.

1. Introduction

The increase on the sale and use of diesel vehicles in Europe [1] and the effect of their emissions on human health [2,3] and the environment [4–6] have forced EU institutions to act. On one hand, transport emission legislation [7,8], recently set tighter limits on particulate matter/NO_x and will adopt a more demanding driving cycle (WLTP - Worldwide Harmonized Light Vehicles Test Procedure) and tougher ambient conditions in the future. On the other hand, a broad diesel fuel mix combining fossil fuels, synthetic paraffinic diesel and oxygenated biofuels [9,10], is being promoted in the transport sector to both tackle the GHG emissions (mainly CO_2) and increase the renewable energy share up to 10% by 2020 [11].

Under this regulatory framework, manufacturers have introduced advanced injection strategies and efficient aftertreatment techniques, and they will have to adapt their diesel vehicles to run on multiple fuels. A typical approach consists in running with high EGR ratios [12] to reduce NO_x formation at the expense of increasing emission of particulate matter, which is afterwards trapped and removed in a diesel particle filter – DPF [13]. Euro 6 Standard, with a further 55% reduction of NO_x with respect to Euro 5 limits, obliges to depurate this scheme by including a NO_x after-treatment system [14–17].

Different DPF configurations are available [18,19], but wall-flow type filters are the most widely used. Wall-flow filters are honeycomb monoliths with parallel channels plugged alternately at each end to force the exhaust gas through the porous filter wall where soot is retained. Therefore, backpressure increases in the exhaust line penalizing the fuel consumption [20,21], but the high filtering efficiency (about 90%) makes these filters essential for complying with emission standards. When the backpressure reaches a threshold, fuel post-injections are launched to increase the exhaust temperature and oxidize the soot collected (filter regeneration) [22]. Apart from temperature, other factors such as the exhaust gas (composition, flow rate) and the physicochemical properties of soot affect the regeneration process [23–26]. Indeed the properties of soot modify its reactivity in a remarkable way [27,28]. The term 'reactivity' is used hereinafter to refer to the soot ability to be oxidized at higher rates and/or under a lower temperature environment, which leads to a more efficient regeneration.

The production routes, properties and performance/emissions of engines and vehicles fueled with alternative and renewable diesel fuels have been broadly studied [9,29–31]. Briefly, biodiesel

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Nomenclature

A	total particle surface
BET	break-even temperature
BTL	biomass to liquid
CFPP	cold filter plugging point
DPF	diesel particulate filter
DSC	differential scanning calorimetry
ECU	electronic control unit
EGR	exhaust gas recirculation
FT	Fischer-Tropsch
GHG	greenhouse gas
$HRRT_{max}$	temperature for the maximum heat release rate
HVO	hydrotreated vegetable oil
LTFT	low temperature Fischer – Tropsch
m	total particle mass
$MLRT_{max}$	temperature for the maximum mass loss rate
NEDC	new European driving cycle
R	particle radius
SMPS	scanning mobility particle sizer
TDC	top dead center
TEM	transmission electron microscopy
TGA	thermogravimetric analyzer
V	particle volume
WLTP	worldwide harmonized light vehicles test procedure
XRD	X – ray diffraction
ρ	particle density
φ	particle concentration

(obtained from oils through transesterification reaction) and synthetic paraffinic fuels (hydrogenation of bio oils and Fischer-Tropsch process are typical routes) lead to similar engine efficiency, fuel economy that scales inversely with the heating value and a benefit in pollutant emissions, though the effect of biodiesel on NO_x is controversial and depends markedly on its composition. However, the effect of these future fuels on the performance of advanced after-treatment technologies such as DPFs is a recent issue that will raise the concern of manufacturers.

One research line involves the study of the soot oxidation process and its effect on filter regenerations. Some works characterized commercial soot surrogates [32,33], but this approach is invalid when the effect of fuel on soot reactivity is to be assessed. Others used analytical techniques (TEM [26,34–37], XRD [26,36,38–40] or Raman spectroscopy [26,39,41–44]) to study real soot generated running engines with different fuels. Generally, the fuel used modifies the characteristics (structure, primary particle size, graphitization) of soot generated [26,28,45]. This may affect the soot reactivity and therefore oxidation rate in the DPF. As a rule, a more disordered soot nanostructure presents more distance between graphene layers and a higher number of active sites where oxidants, such as O_2 or NO_2, can be adsorbed initiating the soot oxidation [27,39]. The presence of oxygenated moieties on the soot surface [26] affect the soot reactivity as well, as the oxygen contained in these groups may participate in the carbon oxidation reactions. A higher concentration of oxygenated groups has been reported for biodiesel soot, which may be behind its higher reactivity (compared to fossil diesel soot) [24,26,27].

Temperature-programmed oxidation and thermal analysis techniques [24,26,28,39,46], mainly TGA and DSC, under oxidant atmospheres have been used to directly evaluate soot reactivity in laboratory, but without a validation in a diesel DPF. Finally, few researchers have carried out engine tests to evaluate soot reactivity through the DPF pressure drop trace during regeneration, once the DPF was previously loaded with soot [24,26,47]. Some authors [24,48], showed that biodiesel or alternative fuels enhanced the regeneration process, while others [25,26,47] concluded that biodiesel did not improve the regeneration process because engine calibration (ECU) was not adapted for fuels other than conventional diesel.

In the present work, a Euro 5 diesel engine fitted with a DPF has been used to carry out load and regeneration processes in the filter with four different fuels, including three renewable fuels. Temperature and pressure drop in the filter were monitored to evaluate soot reactivity. Furthermore, soot samples collected during the loading process were analyzed in laboratory with TGA and DSC to confirm whether the trends obtained in laboratory match those in the DPF. The information obtained is relevant to improve the performance of modern after-treatment systems under new biofuels.

2. Experimental setup

Engine tests were carried out in a 4-cylinder, 4-stroke, turbocharged, intercooled, common-rail, 2.0 L Nissan diesel engine (model M1D), fulfilling Euro 5 Standard. Ambient temperature was fixed at 21–23 °C. The engine is equipped with cooled exhaust gas recirculation (EGR), and its temperature was externally controlled. As after-treatment devices, a diesel oxidation catalyst –DOC– and a regenerative wall-flow type diesel particulate filter –DPF– (see filter characteristics in Table 1) are fitted in the engine exhaust system. The main specifications of the engine are given in Table 2. The engine was coupled to an asynchronous electric brake Schenck Dynas III LI250, equipped with speed and torque sensors that allow measuring and controlling the engine speed and effective torque, respectively. The INCA PC software and the ETAS ES 591.1 were used for the communication and management of the electronic control unit (ECU). This allows defining the injection process (timing, pressure, strategy) as well as measuring and recording temperature and pressure in different locations of the engine (temperature upstream of the turbine, temperature and pressure upstream and downstream of the DPF, oil temperature and ambient pressure, among others).

NO_x emissions were measured using a chemiluminescence Topaze 32 M analyzer able to distinguish between NO and NO_2. Furthermore, oxygen concentration was determined with a non-dispersive infrared analyzer MIR2M. Particulate matter (PM) was collected using a partial-flow dilution micro tunnel (Horiba DLS 2300). This equipment sucks a portion of the exhaust gas through a heated probe into the tunnel where it is diluted with filtered ambient air, as required by emission directives, at a dilution ratio of 10:1. Particulate matter is then collected on Whatman GF/F glass microfiber filters (47 mm diameter, 0.7 μm pore side). To obtain the

Table 1
DPF characteristics.

Material	Silicon Carbide (SiC)
Dimensions	Width (190 mm)/Length (240 mm)
Configuration	16/200
Catalyst	Coated with Pt (0.0032 g/cm^3)
Volume	4.1 L
Channel width	1.39 mm
Specific filtering surface	758.91 m^2/m^3