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Potential for using a tire pyrolysis liquid-diesel fuel blend in a light duty engine under transient operation

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HIGHLIGHTS

- For first time, a 5TPL has been tested in a current diesel engine by using NEDC.
- 5TPL proved its ability to be used as fuel in current automotive diesel engines.
- The properties of TPL to improve both gaseous and PM emissions were identified.
- Unregulated gaseous emissions has been included as novel result.

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ABSTRACT

A tire pyrolysis liquid (TPL) has been blended in 5 vol.% with commercial diesel fuel (5TPL) and tested in a light-duty diesel Euro 4 engine (with all technologies for meeting Euro 5) under transient operation by means of Road Load Simulation (RLS) and simulating the New European Driving Cycle (NEDC). Commercial diesel fuel has also been tested for comparative purposes. In order to characterize engine operation, parameters such as relative fuel/air ratio, exhaust gas recirculation (EGR) valve opening and coolant temperature have been registered. Regulated (THC, NO_x, CO) and unregulated gaseous emissions (CH_4, C_2H_4, C_3H_6 and SO_2), smoke opacity and particulate matter (PM) emissions have been monitored for both fuels (5TPL and diesel fuels) during the tests. The EGR valve opening has resulted to be slightly higher for 5TPL than that for diesel fuel. Although the EGR valve opening has some influence on the gaseous emissions, both properties and composition of the 5TPL also showed an important effect. In this regard, these results have demonstrated the potential usage of the TPL for being blended with commercial diesel fuel for light-duty diesel engines without constructive modifications although some properties of TPL should be improved if the blending percent is intended to be increased. Thus, the reduction of sulfur content seems to be one of the major issues to be overcome if both lower THC and PM emissions, and marginal sulfur poisoning of the catalyst are wished.

1. Introduction

Production of renewable fuels and waste disposal are two of the main concerns facing the world today because both the environmental and energy concerns derived from petroleum-based fuels and the population growth worldwide. Nowadays, about 1.5 billion tires are sold worldwide each year [1], whereas European Union (27 countries) (EU27) plus Turkey and the United States of America (USA), generate annually around 300 million of wastes tires [1,2]. Thanks to the landfill directive (1999/31/EC), only 4% of the waste tires generated in Europe are tipped in landfills or have unknown destination while the remaining 96% is managed for recycling, recovery, reuse and retreading [1]. The material recovery practice, which accounts for the 40% of the waste tires generated in Europe, just considers the tire grinding. Although different applications can be found for each rubber size [3], these practices cannot cope with the large number of ground rubber generated. For example, currently in Spain there are 13 granulation plants with a processing capacity of around 100,000 t/year [4]. Although this treatment produces three different size granulated products, none of them are total or considerably consumed and therefore there is an excess of production of about 60,000 t/year of these granulated products [4].

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One way for obtaining liquid fuels from wastes is by means of waste-to-energy processes such as pyrolysis. Waste tire pyrolysis has been studied for several years and a notable number of projects with a broad range of technologies and scales can be found in literature as recently reviewed elsewhere [5–7]. Nevertheless, the practical applicability of the products obtained from this process has been rather limited. As stated by Antoniou and Zabaniotou, any thermal treatment of wastes with or without recovery of the heat generated is classified as incineration in EU, and for this reason the main barrier facing waste tire pyrolysis is related to the unclear process definition in the legislation. Pyrolysis is not incineration but an energy and material recovery process and should be differentiate from incineration in order to be socially acceptable [6]. Moreover, waste tires are a valuable source of renewable energy because part of the rubber contained has a biogenic origin, i.e. the natural rubber which comes from the *Hevea* tree, and therefore their use for energy purposes is promoted by the 2009/28/EC directive regarding the promotion of renewable energies.

Waste tire pyrolysis is receiving renewed interest and attention and it is currently considered to be more attractive than other thermo-chemical processes because of its minor environmental impact and the material recovery [5,6]. Likewise, waste tire pyrolysis enables the production of a liquid fuel (herein named TPL: tire pyrolysis liquid) with a remarkable heating value (40–44 MJ/kg), comparable properties to those of petroleum diesel [8–10] and complete miscibility with diesel fuel [11]. These facts, as well as the current dependence on fossil fuels, their rapid depletion and the impact of their emissions on the environment, together with the disposal problem of the waste tires, makes quite attractive the TPL usage as fuel in current light duty vehicles. In this way, TPL would help to minimize the usage of natural resources, to mitigate CO_2 emissions and to reduce dependency on fossil fuels.

TPL has been blended with commercial diesel fuel (D) and fueled in stationary diesel engines [12–15] in order to assess the effect of different TPL/D blends on gas emissions. Since all these works have been conducted in non-automotive diesel engines (single-cylinder, air-cooled, naturally-aspirated, low injection pressure, mechanical injection systems) the results cannot be properly extended to other engines. In addition, these works have shown different results regarding emissions and engine performance. Despite differences on the TPL properties, these differences on the results (emissions and engine performance) can also be ascribed to the operational conditions since they have not followed the same testing procedure. For instance, Murugan et al. [12] performed the experiments by varying the brake power keeping constant the engine speed (1500 rpm). They observed an increase in NO_x, THC and CO emissions as TPL increased in the blend. Ilkilic and Aydin [13] only varied the engine speed and observed that TPL produces higher CO, THC, SO_2 and smoke emissions than conventional diesel fuel. Doğan et al. [14] also studied the effect of different TPL/D blends by using a refined and desulfurized TPL and by varying only the engine speed. No major effects on the engine output power and the brake thermal efficiency with respect to those of D were found when TPL was blended up to 50 vol.%. The authors concluded that smoke opacity, CO and THC emissions decreased while NO_x increased as TPL content increased in the blend, but the results were very sensitive to the operating modes tested. Frigo et al. [15] used different loads (50%, 75% and 100%) and engine speeds (2000, 2500 and 3000 rpm). At 3000 rpm they observed a reduction on both THC and NO_x emissions whereas CO emissions increased as TPL increased in the blend. The results showed that engine performance (output engine torque, engine power and specific fuel consumption) do not change significantly up to 20 vol.% of TPL.

On the other hand, the authors' previous work [16] showed the performance and emissions of 5TPL/95D blend by using an automotive diesel engine under fixed operating modes (U10, U9, EU8 and EU16). As these conditions are considered as steady-state conditions, the results found in that work should be handled carefully. When comparing the results obtained under steady and transient conditions, different trends can be found because in the latter there are many other variables that play an important role on the performance engine and exhaust emissions. In Europe, the assessment of fuels for automotive diesel engines follows the New European Driving Cycle (NEDC) which simulates real driving conditions in order to assess the emission levels and the fuel economy. In real driving conditions, engines mainly work at transient conditions and different parameters of the engine related with its control (turbo-lag, EGR valve response, injection timing, etc.) could change the trends in comparison to those obtained under steady state operation [17]. Transient operation is the most common operation of an automotive engine and hence its optimization at these operational conditions is one of the most challenging tasks that new fuels need to address [18]. Moreover, by applying a transient cycle for the testing of new vehicles or engines, the complete engine operating range is tested and not just the maximum or some specific power or torque operating points [19]. As showed elsewhere [20], this type of operation clearly affect the accessibility of oxygen during the combustion process (due to the turbocharger lag), which significantly affect the exhaust emissions produced by the engine. This important issue is a fact of key importance because nowadays diesel engines are mostly turbocharged [19].

In addition, there are several factors related to the engine tuning that were taken into account for deciding to study the potential of fuel under transient operation. These facts are the following: (a) currently, the certification of engines and vehicles (light or heavy duty) is mandatory under transient conditions, (b) under NEDC tests, engine start is included and it is considered the most critical transient process of engines, (c) Original Engine Manufacturers (OEM) demand not only the knowledge of specific emissions but even modal emissions from transient tests in order to design control strategies for minimizing emissions at each part of the certification cycle, and finally, and (d) the temperature of post-treatment devices varies along the test cycle. At steady state conditions this pattern does not occur because they are ran at warm constant conditions.

Although Original Engine Manufacturers (OEM) are very restrictive regarding the use of non-conventional fuels, blending low contents of these fuels with commercial automotive diesel fuel serves to estimate its potential usage since (i) it shows the trend of both emissions and engine durability and (ii) it reveals the necessity of some upgrading process for the fuel. In this way, the addition of 5 vol.% of TPL is considered as a realistic proportion to be used in the current automotive context. This is because, in addition to suppose a non-negligible saving of fossil fuel, a minor but revealing difference in the engine performance and emissions is expected.

Therefore, by all the reasons cited above, is because this work deals with the potential usage of TPL in a light duty diesel engine under critical transient operation.

2. Materials and methods

2.1. TPL production

The TPL was the result of more than 500 kg of granulated waste tires pyrolyzed in a continuous auger reactor plant of 150 kW_{th} of nominal capacity described in detail elsewhere [21,22]. This experimental campaign was conducted in thirteen experiments which gave as result 100 h of continuous operation without any significant technical problem. The reaction temperature and pressure were 550 °C and 1 bar, respectively. N_2 was used as carrier gas at