Fuel 115 (2014) 490–499

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Performance and emissions of an automotive diesel engine using a tire pyrolysis liquid blend

Juan Daniel Martínez [a,b], José Rodríguez-Fernández [c,*], Jesús Sánchez-Valdepeñas [c], Ramón Murillo [a], Tomás García [a]

[a] Instituto de Carboquímica, ICB-CSIC, Miguel Luesma Castán 4, 50018 Zaragoza, Spain
[b] Grupo de Investigaciones Ambientales, Instituto de Energía, Materiales y Medio Ambiente, Universidad Pontificia Bolivariana, Circular 1 No. 70-01, Bloque 11, Piso 2, Medellín, Colombia
[c] Grupo de Combustibles y Motores, Escuela Técnica Superior de Ingenieros Industriales, Universidad de Castilla La-Mancha, Avda. Camilo José Cela s/n, 13071 Ciudad Real, Spain

HIGHLIGHTS

- Tire pyrolysis liquid – TPL can be used in low content for diesel fuel blends.
- We compare a TPL blend and a pure diesel fuel in an automotive engine.
- Engine performance with TPL improves by increasing the engine load.
- Emissions with TPL are higher, but may be reduced by refining the production process.

ARTICLE INFO

Article history:
Received 28 May 2013
Received in revised form 2 July 2013
Accepted 17 July 2013
Available online 1 August 2013

Keywords:
Waste tire pyrolysis
Tire pyrolysis liquid
Tire fuel
Diesel engine
Emissions

ABSTRACT

A tire pyrolysis liquid (TPL) fuel produced in a continuous auger reactor on pilot scale was blended at 5 vol.% (5TPL) with commercial diesel fuel (100D) and tested in a 4-cylinder, 4-stroke, turbocharged, intercooled, 2.0 L Nissan diesel automotive engine (model M1D) with common-rail injection system. The engine performance and exhaust emissions were obtained for both the 5TPL blend and the commercial diesel fuel. Experiments were conducted in four operating modes that simulate the New European Driving Cycle (NEDC). Both brake specific fuel consumption and brake thermal efficiency seemed to be deteriorated by the composition and the properties of the TPL blend at low engine load, while at higher engine load the values of these parameters were almost equal for both fuels. Total hydrocarbon (THC) emissions followed the same pattern than that of the specific fuel consumption since they were higher for 5TPL at low engine load but similar for both fuels when the engine load increased. NO_x emissions were higher for 5TPL than those for 100D in three operating modes (U10, EU8 and EU16), while no significant differences were found in the other mode (U9). In addition, 5TPL led to higher smoke opacity respect to those found for 100D in all operating modes. Combustion duration was slightly longer for 5TPL than 100D. This work could be considered as a contribution for strengthening and encouraging the waste tire pyrolysis for the production of liquid fuels which could be used in automotive engines in very limited concentrations.

1. Introduction

About 1.5 billion tires are sold worldwide each year giving as result around 20 million tons [1]. Besides this huge amount, waste tires are non-biodegradable materials and their thermo-mechanical properties make them difficult to be directly reused or recycled without mechanical or thermal pre-treatment. Therefore, waste tires represent a serious pollution problem in terms of waste disposal. Rubber from tire has a high heating value (35–40 MJ/kg) and this energy may be recovered by means of waste-to-energy processes which encompass thermo-chemical treatments such as combustion, gasification and pyrolysis for power and heat generation and/or fuel production. In addition, waste tires are a valuable source of renewable energy (part of the rubber contained has a biogenic origin) and therefore they are within the scope of the 2009/28/CE Directive on the promotion of renewable energy.

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 [2]. However, due to the lack of product standardization and available markets, legislative barriers (pyrolysis is considered as incineration in the EU) and

* Corresponding author. Tel.: +34 926 295 300x6472; fax: +34 926 295 361.
E-mail address: Jose.RFernandez@uclm.es (J. Rodríguez-Fernández).

0016-2361/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.07.051

sometimes poor public acceptance, the practical applicability of the products obtained from waste tire pyrolysis has been rather limited. Pyrolysis plays a major role for waste tire valorization and is currently considered to be more attractive than other thermo-chemical processes because of its minor environmental impact and the material recovery [2]. These materials include the carbon black added in tire manufacture, which is trapped in the char fraction, and a liquid fraction (tire pyrolysis liquid – TPL) which comprises a mixture of unrefined oil compounds with a remarkable heating value (40–44 MJ/kg), comparable properties to those of petroleum diesel [3–5] and complete miscibility with petroleum diesel [6]. As consequence, when the TPL is used as fuel, it recycles raw materials from unconventional sources, minimizes the usage of natural resources, mitigates CO_2 emissions and reduces dependency on fossil fuels. For all these reasons, pyrolysis is gaining major interest as a prominent and sustainable process to tackle the waste disposal problem related to used tires as well as for the production of alternative liquid fuels.

Just a limited number of studies using TPL/diesel blends in stationary diesel engines are found in literature [7–9]. These works show different results of the effect of different blends on both diesel engine performance and emissions and this is ascribed to the different properties of TPL as well as differences in engine technologies and operational conditions. For instance, Murugan et al. [7] using a direct injection diesel engine, observed an increase in NO_x, THC and CO emissions as TPL increased in the blend. They attributed this behavior to the aromatic content, higher viscosity and lower volatility of the TPL. Ilkilic and Aydin [8] also using a direct injection diesel engine observed that TPL produced higher CO, THC, SO_2 and smoke emissions than conventional diesel fuel. The authors explained these differences based on the poor atomization and low cetane number of the TPL. Likewise, Doğan et al. [9] studied the effect of different blends on both performance and exhaust emissions using a direct injection unmodified diesel engine at full load and at four different engine speeds (1400, 2000, 2600 and 3200 rpm). In that work, TPL was previously improved by refining and desulphurization processes. The authors did not find major effects on the engine output power and the brake thermal efficiency with respect to those of diesel fuel 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.

However, all the reports found in the literature use non-automotive diesel engines (single-cylinder, air-cooled, naturally-aspirated, low injection pressure, mechanical injection systems) and therefore their results cannot be properly extended to other engines. For instance, in common rail fuel injection systems, there is no major influence of the fuel physical properties on the injection advance [10] and for this reason differences in performance, emissions and combustion process are mainly owed to the chemical composition of the fuel. Besides, the high TPL content of the blends tested in those reports is not realistic in the current automotive fuel context. Hence, the work presented herein explores the possibility of using TPL obtained in a continuous auger reactor on pilot scale for very limited diesel fuel substitution in automotive diesel engines without any engine modifications or substantial redesigns. Such blends could be initially used in captive fleets besides to serve for showing the trend of both emissions and engine performance and therefore, after a refinement process (distillation under vacuum and desulphurization as proposed in [11]), extending the TPL usage to higher blends or even to other sectors. To the best of authors' knowledge, this is one of the first studies investigating the effect of a TPL blend on an automotive diesel engine performance and emissions, using operating modes that reproduce real driving conditions.

2. Materials and methods

2.1. TPL production

The TPL is 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 [12,13]. 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 5 NL/min. The waste tire mass flow rate was 6.7 ± 0.1 kg/h and the residence time of the feedstock inside the reactor was 3 min. These conditions were selected as those maximizing both the liquid yield and the tire rubber conversion. As consequence, yields to liquid, solid and gas were 42.6 ± 0.1, 40.5 ± 0.3 and 16.9 ± 0.3 wt.% respectively. Process details can be found elsewhere [13].

2.2. Fuel properties

The diesel fuel (100D) used as reference and for blending was purchased from Cepsa Corporation (Spain) and it is characteristic of the current diesel fuels sold in Spanish gas stations (it has a renewable methyl ester fraction of 5.8 vol.%, approximately). This fuel meets all the requirements established in the EN-590 Standard. Key properties of the pure TPL and its blends with 100D have been previously reported [5] and are showed in Table 1. Among all properties it is worth noting that TPL density (917 kg/m^3) is higher than that of 100D (845 kg/m^3) whilst kinematic viscosity is slightly lower for TPL than that for 100D. The lower heating value (LHV) on mass basis for TPL is slightly lower (around 4.2%) than that for 100D. However, the LHV on volume basis, which is a better parameter to determine the fuel consumption and user's economy in diesel vehicles, is higher for TPL (37.13 MJ/L) than that for 100D (35.74 MJ/L). Regarding elemental composition, carbon and hydrogen contents for TPL compare well with those for 100D, while the sulfur (0.83 wt.%) and nitrogen (0.79 wt.%) contents for TPL are remarkably higher than those for 100D.

Apart from 100D, one blend with low TPL content (5 vol.% TPL and 95 vol.% 100D, named here as 5TPL) was tested in order to keep some critical properties of the blend within the range set in the European standard EN 590 (cold filter plugging point, water content and total acid number) and to be realistic in the current automotive context. Although other aspects such as density and sulfur content did not fulfill the limits established in the standard (even at this low TPL content), the experiments with this blend are considered as crucial to show the trend of both emissions and engine performance and also to reveal the scope of some upgrading process for the fuel.

2.3. Engine and test procedure

The experimental work was carried out in a 4-cylinder, 4-stroke, turbocharged, intercooled, 2.0 L Nissan diesel engine (model M1D), equipped with a common-rail injection system and a variable geometry turbine (VGT). The engine utilizes a cooled exhaust gas recirculation (EGR) system for NO_x reduction, and the flow mass rate of the refrigerant in the EGR cooler is externally managed for a more accurate temperature control. The engine is equipped with an oxidation catalyst (DOC) and a regenerative wall-flow type diesel particle filter (DPF), although the latter was by-passed in the tests (see Fig. 1) in order to measure opacity, particulate matter and particle size distributions (the evaluation of the performance of the DPF is not an objective of these tests). The engine was