

Diesel Fuel by Scrap-Tyre Thermal-Mechanical Pyrolysis

Stefano Frigo, Roberto Gentili, Maurizia Seggiani, and Monica Puccini
University of Pisa

ABSTRACT

Current energy policies are encouraging the near-term use of fuels derived from civil and industrial waste residues, giving new perspectives for their disposal.

The possibility of using, in Diesel engines, a liquid fuel derived from waste synthetic polymeric matrices, such as scrap tyres, is evaluated in this paper. The fuel is obtained by means of an innovative technology based on a thermo-mechanical cracking process at moderate temperatures and pressures.

A preliminary investigation was carried out on a 440 cm³ single-cylinder Diesel engine for stationary applications using a commercial automotive Diesel fuel (UNI-EN 590:2010) and two mixtures of automotive Diesel fuel and tyre pyrolysis oil (TPO): the first one containing 20% TPO by volume, the other containing 40% TPO. With the first mixture, test bench results in terms of engine torque, power, specific fuel consumption and exhaust emissions are similar to the ones relative to automotive Diesel fuel, whereas the use of the mixture with 40% TPO leads to a general worsening in engine combustion features.

Lubricant oil analysis, made at the end of the tests, proves a certain level of lube oil dilution due to fuel leaking into the oil sump.

The toxicity levels of the exhaust particulate matter were analysed and result to be the same using automotive Diesel fuel and both the mixtures of Diesel fuel and TPO.

No meaningful mechanical inconvenience occurred during the engine tests. Nevertheless, long-time reliability of the injection system, as well as of the entire engine, has to be verified.

CITATION: Frigo, S., Gentili, R., Seggiani, M., and Puccini, M., "Diesel Fuel by Scrap-Tyre Thermal-Mechanical Pyrolysis," *SAE Int. J. Fuels Lubr.* 6(3):2013, doi:10.4271/2013-32-9038.

INTRODUCTION

Each year almost 1 billion tyres for cars, commercial vehicles, trucks, ATVs, etc. are produced worldwide and every year a similar number of tyres is removed from vehicles and becomes waste [1]. Collecting scrap tyres in piles is unacceptable due to risks of fire and because it provides habitat for infection vectors, e.g. mosquitoes. The United States Environmental Protection Agency (EPA) suggests, in order of preference, the following methods to manage scrap tyres: reduce, reuse, recycle, waste-to-energy, disposal in an appropriate facility.

Old tyres recycling can be intended for a wide range of purposes. Among them the most important are [2]:

- Construction bales
- Carbon Products
- Landfill engineering

- Expansion joints
- Stabilisation
- Sound barriers
- Retreading
- Sports/play surfaces
- Tyre Derived Fuel (TDF)

The last one, i.e. the obtainment of fuels from waste tyres, especially by means of a pyrolysis process [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18] (direct combustion can be employed as well), today is becoming more and more attractive, since it is an environmentally friendly and efficient way to take advantage of scrap tyres. The application of pyrolysis, which is a thermal degradation in absence of oxygen, produces fuel gas, oils and a solid residue (char), which contains significant quantities of mineral matter and low-grade carbon black. The oils can be used as fuels or

added to petroleum refinery feedstock, the pyrolysis gas can be used as fuel in the pyrolysis process or for heat generation and the solid residue can be reutilised in tyre production.

The mass fraction of each phase, as well as its chemical-physical characteristics, mainly depends on the type of pyrolysis process (i.e. fixed bed reactor, fluidized bed pyrolysis unit, vacuum pyrolysis reactor, jet bed reactor, etc.) [5, 7, 8], since tyres contain more or less the same basic ingredients, with small variations depending on the different types of tyres. Scrap tyres average composition by mass is reported in Table 1 [1].

Tyre pyrolysis oil (TPO) is mainly constituted of aromatics and aliphatic hydrocarbons, with some properties, such as lower heating value and density, similar to those of automotive Diesel fuel [3, 4], while others, as viscosity, depend on pyrolysis process characteristics. However, TPO use in energy conversion devices may imply some preventative measures that depend on the specific applications. In the case of Diesel engines, TPO, on account of its low cetane number, must be mixed with Diesel fuel or complemented by a cetane improver, for example diethyl ether [17]. Moreover, TPO high sulphur content [8, 9, 12, 15] imposes fuel desulfurization in the case of stringent exhaust SO₂ limits.

Tab. 1. Composition by mass of car and truck tyres in the EU.

Material	Car/utility %	Truck/Lorry %
Rubber/Elastomers ^a	48	45
Carbon black silica ^b	22	22
Metal	15	25
Textile	5	—
Zinc oxide	1	2
Sulphur	1	1
Additives	8	5

^aThe ratio of natural rubber to synthetic rubber in truck tyres is higher than in car tyres.

^bDifferent varieties of carbon black are used for different purposes and may appear in other categories of material.

Nowadays Diesel engines cover a wide application area and power range, from small power generators to marine propulsion, from few kilo-Watts to several mega-Watts. Accordingly, to meet the different needs, many Diesel fuel grades, with different chemical-physical characteristics, are present on the market. As well, TPO has largely variable chemical-physical characteristics and can be employed as fuel in a wide range of engines. Of course, big engines are the most suitable to be fuelled with TPO since they are less fuel-quality demanding and are submitted to less stringent emission regulations. However, it is worth considering TPO employ in small engines, e.g. for small electric generators or for agricultural applications, since it may well lead to a widespread energetic utilisation of scrap tyres.

It is worthwhile to underline that TPO cannot be considered an “alternative fuel”. It only represent a possible “energetic valorisation” of a waste material, since the quantity of TPO that can be produced is insignificant in respect of the amount of fossil fuels consumed all over the world. In the EU, for example, approximately 3.5 million tonnes of passenger car, utility vehicle and truck tyres become waste each year [1]. Considering that the liquid yield, by mass, can reach at maximum 50% [11, 12, 15], approximately 1.75 million tonnes of TPO can be produced per year and represents less than 0.6% of the roughly 300 million tonnes of oil that correspond to the EU energy consumption only for road transportation [19].

PYROLYSIS PROCESS

The tyre pyrolysis oil used in the experimental activity is the liquid fraction of the products obtained with an innovative pyrolysis process for scrap tyres treatment, based on thermal-mechanical cracking at moderate temperatures and pressures.

Material Analysis

Waste automotive tyres were collected and cut into small pieces (size of 1 - 3 mm). Steel wires and fabric fibres were removed. In order to characterize the tyre pieces employed in the pyrolysis experiments, thermogravimetric analysis (TGA) was carried out on dry representative samples using a TGA Q500 (TA Instrument). Elemental analysis was accomplished by means of a CHN-S analyzer (LECO CHN-TruSpec) and the lower heating value was determined using a bomb-calorimeter.

The results of the analyses are reported in Table 2. The amount of volatile matter (65 %) should correspond to the amount of gases and liquids to be obtained in a complete pyrolysis, while the amount of fixed carbon and ash (about 34 %) should coincide with the solid residue after pyrolysis.

Tab. 2. Proximate and ultimate analyses of crushed tyre sample.

Proximate analysis (as received, mass %)	
Moisture	0.7
Volatile matter ^a	65.0
Ash	4.6
Fixed carbon (by difference)	29.7
Ultimate analysis (dry basis, mass %)	
Carbon	83.17
Hydrogen	8.87
Nitrogen	0.33
Sulphur	1.63
Oxygen (by difference)	6.00
High Heating Value (MJ/kg _{dry})	35.75

Pyrolysis Apparatus

The innovative pyrolysis process, developed and patented within the study described in this paper (US patent N. 20100008836), comprises a thermo-mechanic cracking chamber designed as a twin-screw extruder with decreasing section from the entrance to the exit, which realizes a mixing and mechanical pressing of the material. The pressed material inside the extruder doesn't allow oil vapours and gases to flow upstream to the feeding hopper.

Tyre pieces are continuously fed inside the chamber and the holding time is controlled by the revolution speed of an electric motor connected to the extruder through an adaptor. The cracking chamber is externally heated by two independent electrical resistances and the temperatures are controlled by apposite devices. In a first section of the chamber the temperature is set between 300 and 350°C and in the second tubular section, of larger diameter, the temperature reaches about 500°C to complete the pyrolysis. At the end of the extruder, the evolved pyrolysis oil vapours and gases are separated from the solid (carbon black) by gravity and then passed through a water cooled condenser to cool the vapours. The condensed liquid, collected in a tank, is the fuel employed in the engine tests. A part of the non-condensed gases is collected in cylinders for a subsequent analysis and the rest is sent to a torch. The scheme of the pyrolysis apparatus is shown in Figure 1.

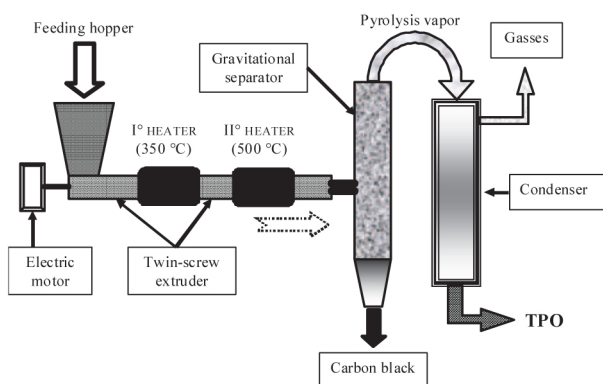


Fig. 1. Schematic of the experimental apparatus for tyre pyrolysis.

The mass fractions of liquid, solid and gas yield depend on crushed tyre flow rates: the solid yield increases, mainly at the expense of gas yield, with increasing the flow rate, while the liquid yield slightly decreases at the highest flow rates. In this investigation the crushed tyre flow rate was set to maximize the TPO production (~ 45 % by mass).

Tyre Pyrolysis Oil

The fuel properties of the pyrolytic oil produced were analyzed with standard methods and results are reported in Table 3 together with the specifications of a commercial European automotive Diesel fuel (UNI-EN 590:2010), hereafter called DF, that was used as reference fuel in engine testing.

Density, viscosity, heating value and flash point of TPO are comparable to those of DF, but sulphur content is significantly higher and precludes TPO use in road vehicles. However TPO could be used in stationary and marine Diesel engines, which are less fuel-quality demanding, mainly due to less stringent requirements as regards both emissions and fuel injection features [20, 21, 22, 23]. Indeed, marine engines can accept fuels with a minimum cetane index (CI) = 35 and with sulphur content up to 2% [ISO-8217:2010].

Tab. 3. Properties of the TPO compared with the specifications of an European automotive Diesel fuel (UNI-EN 590:2010).

Property	unit	TPO	UNI-EN 590:2010
Cetane number (CN)			> 51.0
Cetane index (CI)	-	27	> 46
Density at 15°C	kg/L	0.903	Min = 0.820 Max = 0.845
Distillation ^a			
Initial Boiling Point	°C	73	report
Final Boiling Point	°C	150	370
Viscosity at 40°C	cSt	2.90	Min = 2.0 Max = 4.5
Flash point	°C	58	> 55
Particulate	mg/kg	4800	
Ash	mass %	0.0061	< 0.01
Sulphur	mass %	0.97	< 0.001
Karl Fischer water	ppm	326	< 200
PAH	mass %	7.8	< 8
Lower heating value	MJ/kg	41.96	> 41

^a the distillation at atmosphere pressure showed decomposition at 150°C.

The cetane number (CN) of TPO was estimated by means of the CI, calculated as a function of the density and the volatility of the fuel with the following equation [ASTM standard D976]:

$$CI = 454.74 - 1641.416 \cdot D + 774.74 \cdot D^2 - 0.544 \cdot T_{50} + 97.803 \cdot [\log_{10}(T_{50})]^2$$

where D is the fuel density at 15 °C (kg/L) and T₅₀ is the temperature (°C) corresponding to 50% point in the distillation curve. The TPO T₅₀ resulted roughly 240 °C, which leads to a CI equal to 27, considerably lower than the minimum CI required for DF. Yet, CI fairly matches CN only