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Performance, emission and combustion characteristics of a IDI engine running on waste plastic oil

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ABSTRACT

An interesting alternative to fossil fuel for Diesel engines is the use of Diesel-like oil from plastic wastes: such a solution yields the double advantage of recovering the valuable energy content of wastes, as well as of mitigating the disposal problem of the very large amount of plastic wastes produced by both domestic and industrial activities.

The present paper describes the experimental campaign carried out on a current production indirect injection, naturally aspirated diesel engine, running on standard Commercial Diesel Oil (CDO) and on a Waste Plastic Oil (WPO) derived from the pyrolysis of plastics. Tests have been carried out at both full and partial load, while in-cylinder pressure traces have been measured in order to analyze the combustion phase.

The results of the experimental campaign showed a slight reduction of engine performance for the WPO, basically due to a lower volumetric fuel rating, but better brake specific fuel consumption and brake fuel conversion efficiency (differences up to 8%). In-cylinder pressure traces, measured at the same load, revealed some difference in the first part of the combustion process, in particular at high speeds, where for WPO heat release is smoother. Engine soot emissions are always lower running on WPO, with difference up to 50% at full load.

1. Introduction

Diesel engines are the most widespread power generation units, thanks to their high fuel conversion efficiency, reliability and robustness. Typically, they run on fossil fuels, but the interest in the use of alternative energy sources has been strongly increasing in the last years, in order to address the concerns about the future petroleum availability and the associated volatility of fossil fuels price.

An interesting proposition is the production of Diesel-like oil from wastes: such a solution yields the double advantage of recovering the valuable energy content of wastes, as well as of mitigating the disposal problem. The typical wastes yielding high heating values, so that can be conveniently converted into engine fuel are: waste cooking oil (WCO), waste lubricating oil (WLO), and waste plastics (WP) [10]. The conversion of WP appears the most promising option because of their huge availability: it has been reported that each year more than 100 millions tons of plastics are produced worldwide [11]. Furthermore, plastics are one of the main industrial wastes [12]. The conversion of WP is usually done by pyrolysis, transforming the plastic polymers into their basic monomers or hydrocarbon; this practice is considered as tertiary (or chemical) recycling [3]. Despite the number of studies and projects on the conversion of WP into fuel [17], very few of them include a detailed investigation about combustion on high-speed diesel engines [10].

Some remarkable exceptions are represented by the works done by Soloiu et al., by Mani et al., and a few others. The first group of researchers tested different blends of waste plastic oil and heavy oil (type A) on a Yanmar single cylinder Diesel engine (about 1 L of displacement), equipped with a low pressure (about 200 bar) direct injection system. They found that the higher viscosity of WP blends increases injection duration, in comparison to heavy oil (Soloiu et al. [14]). As a result, with WP blends in-cylinder pressure rises more gradually and peak pressures are lower. As far as engine performance are concerned, they found that thermal efficiency of the polymer fuels is almost identical to that of heavy oil, so concluding that the thermal recycling of plastic waste is suitable for engine application. These results were confirmed in a

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further investigation (Soloiu et al. [15]), using water-polymer fuel emulsions on the same engine. Finally, a comprehensive analysis on combustion and emissions was presented by the same author in an SAE technical paper in 2010 (Soloiu et al. [16]).

Mani et al. carried out a comprehensive experimental campaign on a single cylinder Kikloskar Direct Injection research engine with a total displacement of about 600 cc and rated power of 4.4 kW at 1500 rpm. They fueled the engine without any modification using both pure Waste Plastic Oil and blends of WPO and Diesel Oil (Mani et al. [9] and Mani et al. [8]). They found that the maximum heat release rate with WPO is higher than with Diesel, because the engine running on WPO is affected by a longer ignition delay, causing also higher in-cylinder pressure peaks. However, smoke for WPO decreases significantly (up to 40–50%) and even the tested blends yield lower soot emissions; conversely, NOx exhaust concentration was found higher. Mani et al. also demonstrated that engine performance and emissions of the engine running on WPO can be further optimized adjusting the injection timing (Mani and Nagarajan [6]) and EGR (Mani et al. [7]).

Kumar et al. [4] investigated the performance of waste plastic oil blends on a Comet VCT-10 engine (4-stroke, CI, Direct Injection, 2-cylinder, total displacement 1.1 L). They concluded that brake thermal efficiency at full load is lower to that of Diesel fuel due to the lower heating value of their WPO.

Güngör et al. [1] tested a plastic oil produced from waste polyethylene on a Mitsubishi 4D34-2A engine (4-stroke, CI, Direct Injection, 4-cylinder, total displacement 3.9 L) rated at 89 kW at 3200 rpm. They found that fuel properties of the blends are comparable with those of Diesel fuel within the EN-590 Diesel Fuel Standard. The power output of the engine was slightly increased by using WPO blends, while CO emissions were reduced by 20.6%. However an increase of NOx was also observed.

Finally, Lee et al. [5] used oil from the scrap-tire thermal mechanical pyrolysis on a single cylinder small engine (0.2 L, DI, rated at 3 kW at 3600 rpm), concluding that the maximum engine power dropped around 17% with a 20% blend and more than 50% with a 40% blend.

The present paper describes the experimental campaign carried out on a current production indirect injection (IDI), naturally aspirated diesel engine. Thanks to their robustness, reliability and low cost, IDI diesel engines are widely used in the agriculture and construction machinery field, as well as in many other industrial applications such as electric generators and motor pumps. In this project the engine runs on standard Commercial Diesel Oil (CDO) and on a Waste Plastic Oil (WPO) derived from the pyrolysis of plastics. The alternative fuel production process is described in details in Section 2.

The engine used for tests was chosen on the basis of the following considerations. First of all, a current production engine was preferred to a research engine in order to get more straightforward information about the applicability to real cases. Furthermore, it was considered that indirect injection with a mechanical fuel metering system is much less demanding and more robust than a high pressure direct injection system, so that the engine can easily tolerate unconventional fuels. Moreover, while some technical papers have been recently published on DI Diesel engines running on WPO, no experimental work on IDI engines fueled by WPO has been still proposed, according to the authors' knowledge. Finally, many small capacity industrial engines adopt a mechanical injection system, and it's relatively simple to operate these power plants with alternative fuels, since rules and constraints are much less stringent than in the automotive field.

Experimental tests were carried out at a dynamometer bench, measuring engine performance and soot emissions in many operating conditions. Particular attention was paid to the combustion process, measuring and analyzing the in-cylinder pressure traces.

2. Fuel production and properties

The oil used for the test was produced and provided by DEMONT S.r.l. (www.demont.it). A schematic of the production process is reported in Fig. 1. As visible, the plastic material is conveyed, through a dedicated loading system, to the extruder. Here the plastic material is melted and heated up to 300 °C and then delivered to the reactor where temperature is maintained between 400 °C and 450 °C. A portion of reacting polymer is continuously mixed with the inlet polymer in order to create an intimate contact between the catalyst and the fresh feed and to enhance heat transport. The depolymerization process (thermocatalitic cracking) occurs into the reactor, where a special Zeolite powder developed ad hoc for the process is used as catalyst. In the reactor, polymer chains are cracked by the effect of temperature and very short molecules are obtained. The obtained fuel leaves the reactor from its top in a vapor state while a solid carbon residue builds up with the exhausted catalyst and inert materials that usually are included into the inlet polymers. The fuel leaving the reduction ambient of the reactor finds oxygen and a small amount of it is entrained in the hydrocarbon molecules. The solid carbon material is discharged every few hours to maintain the carbon concentration into the reactor under a critical value. Then it is processed in an evaporation section to recover a portion of fuel product and to concentrate the solid residue. The gaseous fuel stream is condensed in a dedicated water condenser. The extracted oil is finally stored in a tank. The non-condensable gas fraction made of light hydrocarbons is extracted by means of an ejector and burnt in a thermal-oxidizer to produce thermal energy.

The raw material processed into the plant is recycled plastic recovered from municipal waste and/or industrial by-products mixture, mainly composed by polyethylene (HDPE and LDPE), polypropylene (PP), polybutadiene (PBD) and polystyrene (PS). The percentage of LD + HD is included in the range 75–85%, while PP percentage can vary between 15% and 25%.

The final product is a liquid free sulphur fuel made of hydrocarbon from C6 to C30 (see Fig. 2), having a lower heating value (LHV) and a density slightly lower than Diesel Oil. The main properties of the fuel are reported in Table 1 while its distillation curve is shown in Fig. 3.

In addition to fuel oil, the system generates also a light gas mainly composed by methane and ethane and a solid residue rich in carbon (90%) having a lower heating value (LHV) around 20 MJ/kg. The mass balance of the process is shown in Fig. 4: for every kg of raw plastic, about 0.70–0.85 kg of fuel are obtained depending on type and concentration of inlet polymers. One kg of plastic is so converted into a fuel mass containing about 33 MJ by using 0.85 kW h (about 3 MJ). This energy consumption is made up of 3 main contribution, as visible in the diagram of Fig. 5. The fuel obtained from 1 kg of plastic can be then burnt in an internal combustion engine producing up to 11 MJ of mechanical energy (considering a global efficiency of the engine equal to 33% at full load), with a positive energy balance of the process of about 8 MJ for each kg of plastic processed.

3. Experimental setup

The engine used in the test is a 1.4 L Lombardini-Kohler engine, whose main characteristics are shown in Table 2. The experiments have been performed at the University of Modena and Reggio Emilia facility (Fig. 6), featuring an Apicom FRV 400 eddy-current brake, and the Apicom Horus software for system control and data acquisition. Besides the standard pressure and temperature transducers, the laboratory instruments also include a flow meter for measuring fuel consumption and a light absorption opacimeter