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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) (Naima and Liazid, 2013). 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 (Raja and Mural, 2011). Furthermore, plastics are one of the main industrial wastes (Singhabhandhu and Tezuka, 2010). 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 (Hodek, 1991). Despite the number of studies and projects on the conversion of WP into fuel (Wong et al., 2015), very few of them include a detailed investigation about combustion on high-speed diesel engines (Naima and Liazid, 2013).

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 liter 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. (2000)). 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 further investigation (Soloiu et al. (2004)), 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. (2010)).

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. (2009) and Mani et al. (2011)). 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 & Nagarajan (2009)) and EGR (Mani et al. (2010)).

Kumar and al. (2013) 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 liter). 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. (2015) 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 liter) 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. (2015) used oil from the scrap-tire thermal mechanical pyrolysis on a single cylinder small engine (0.2 liter, 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, motor pumps, etc. 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 the *Fuel production and properties* section below.

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 Figure 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 Figure 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 Figure 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 Figure 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 kWh (about 3 MJ). This energy consumption is made up of 3 main contribution, as visible in the diagram of Figure 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 liter 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 (Figure 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 for soot emissions. A high frequency indicating system has been specifically designed in order to record in-cylinder pressure traces; the system is made up of a piezoelectric transducer, installed in the pre-chamber of cylinder #1 in place of the glow plug, a charge amplifier and an optical encoder. Pressure and phase signals are processed by means of the NI CompactCrio hardware and the Alma Automotive software (Obi). A sketch of the experimental setup, with some further detail, is shown in Figure 7.

The experimental protocol consists of three different types of tests, each one repeated running the engine first on Commercial Diesel Oil (CDO) and then on Waste Plastic Oil (WPO):

1. **Full load**: the engine runs at full load, at 9 different speeds, from 1200 to 3000 rpm by 200 rpm steps; a closed loop control was used to set the brake rotational speed;

2. **Constant rpm:** in this case the engine is running at only 2 speeds (1500 and 3000 rpm) and 6 different values of torque (from 10 to 55/60 Nm by 10 Nm step) corresponding to BMEP values between 0.9 and 5.5 bar; these are the most typical conditions occurring when the engine is coupled to an electric generator, a quite common application for small IDI Diesel engines; 2 closed loop controls was used to set both engine torque and brake rotational speed; at each operating point the in-cylinder pressure trace has been recorded and analyzed;

3. **Maps**: the last type of test consists of an automatic cycle, sweeping the whole engine operating field; 42 stationary points have been investigated (6 values of torque from 10 to 60 Nm, by 10 Nm, and 7 engine speeds, from 1200 to 3000 rpm, by 300 rpm); also in this case both engine torque and brake rotational speed are controlled in closed loop.

The maximum care has been devoted to keep the testing conditions as uniform as possible: in particular, the fuel and the engine lubrication oil temperatures are almost identical for all the cases. Finally, each relevant measure is repeated at least twice, at different times, in order to reduce the uncertainty of the results.

4. Results and discussion

4.1 Full load

In this test, engine performance was assessed in terms of brake power, torque, specific fuel consumption, thermal efficiency and soot emissions, running the engine on both WPO and CDO. The performance parameters are plotted as a function of engine speed in Figures 8-12.

Starting the analysis from figure 10, it is observed that the volumetric fuel consumption is lower with WPO, the maximum measured difference being about 8%. This outcome is quite unexpected, since the engine is equipped with a fully mechanical injection system that is supposed to deliver about the same volume of fuel, at each cycle. This result may be ascribed to the different physical properties of WPO and CDO, in particular density and viscosity, that affect the volumetric efficiency of the mechanical pump (these properties have an influence on the leakage rate through the clearance between plunger and liner). Furthermore, it should be observed that the difference in terms of mass fuel consumption are larger because of the lower density of the WPO.

The lower WPO flow rate, in conjunction with the lower heating value, has a direct influence on the delivered torque and power, with differences between the two fuels varying between 5 and 10% (Figures 8 and 9). On average, the difference in terms of torque is less than the difference in terms of fuel rate and lower heating value, meaning that there is a compensation somewhere.

The specific fuel consumption (Figure 11), using WPO was found to decrease at low and mid speeds and slightly increase at high speeds, except at 3000 rpm. However, the percent differences are quite small (2-3% with a maximum value of 4% at 1400 rpm).

Fuel conversion efficiency, or global efficiency, is defined here as the ratio of brake power to the product of fuel mass flow rate and the fuel lower heating value. The global efficiency plot, Figure 12, clearly demonstrates the WPO superiority (differences up to 8%), in particular at low and mid speeds. An explanation for the higher global efficiency may be a more complete combustion, due to the slightly higher air-fuel ratio (less injected fuel, same air). The entity of the difference between WPO and CDO may be affected by the uncertainties about Diesel LHV (+/- 2%), however the outcome does not change.

Finally, it was found that WPO enables a significant decrease of soot emissions (Figures 13 and 14): experiments show that the average reduction of opacity is about 30% (the maximum difference being 50%), while the benefit decreases up to about 20% (with a maximum value of 45%) considering the specific values (Figure 14). The reasons for the lower level of soot are: 1) the presence of more volatile hydrocarbons, as visible in the distillation curve, enhancing the evaporation rate; 2) the presence of oxygen in the WPO composition, increasing the local air-fuel ratio within the combustion chamber, as well as the higher average air-fuel ratio.

4.2 Constant rpm

In the second set of tests, brake outputs (torque and power) are kept constant running both CDO and WPO. Figure 15 shows the measured volumetric fuel consumption: as the differences are quite small, it can be concluded that fuel consumption does not change significantly passing from a fuel to the other. However, WPO has a lower density, therefore the specific fuel consumption, BSFC, is always lower (Figure 16), and global efficiency higher (Figure 17), confirming the outcome of the previous tests.

As far as soot emissions are concerned, Figure 18, it appears that the benefit of WPO is extended also at partial load conditions: up to 3 bar of BMEP, emissions are very low and almost equivalent but, for higher BMEPs, the exhaust gas opacity of the engine running on WPO is from 10 to 25% lower than the one measured with CDO. The reduced fuel influence on soot at low loads was expected, since the formation rate of soot drops abruptly as the relative air-fuel ratio increases.

Figures 19-22 show the in-cylinder pressure traces, the rates of heat release, the fraction of burnt fuel and the average gas temperature at 1500 and 3000 rpm, full load. The complete set of combustion graphs is presented in Appendix A. In the calculation of combustion velocity from pressure data, the difference between pre-chamber and cylinder pressure is neglected (the transducer is installed in place of the glow plug of cylinder #1, in the pre-chamber, thus the actual cylinder pressure is smaller because of the flow losses across the small channel connecting pre-chamber and cylinder). At each operating condition, 100 consecutive cycles were acquired, and all the data reported in the paper refer to the averaged values. The apparent burnt rate and temperature are calculated assuming a constant specific heat ratio and applying the first principle of thermodynamic (Heywood (1988)). The apparent RoHR is defined as the net rate of energy provided to the charge, that is the difference between the heat released by combustion and the heat rejected through the walls. The negative peak before TDC, due to heat transfer before combustion, is particularly evident in IDI engines because of the high turbulence generated by the pre-chamber geometry.

From Figures 19-22 and from Appendix A it may be observed that, when the engine is fueled with CDO, combustion is slightly faster in the very first part of the process: this trend is clearly visible at 3000 rpm, less at 1500 rpm. This behavior, found also by Mani in similar conditions, is explained by the higher auto-ignition retard of WPO, due to lower Cetane number. However, this characteristic is less relevant for IDI engines, compared to DI, since temperatures at the end of compression are higher (compression ratio of the Lombardini IDI engine is 22.8, while for a DI is generally less than 18). Furthermore the lower is engine speed, the lower is the influence or auto-ignition retard, since the cycle duration is longer and the amount of fuel burning in pre-mixed conditions is more limited. The lower RoHR in the first phase of combustion process is always compensated during the remaining part of the process, so that the total amount of heat released by combustion is about the same.

Figures 23 and 24 show the combustion characteristic angles (10, 50 and 90 % of burnt mass fraction) for both previous engine rotational speeds (1500 and 3000) at different load. At 1500 rpm and low load, the 50% angle corresponding to WPO is larger confirming the lower Cetane number of the alternative fuel. The differences are smaller at 3000 rpm.

Finally, the measured maximum pressure gradient is plotted in Figure 25 at 1500 and 3000 rpm, different loads. It is evident the higher pressure gradient associated to WPO combustion at 1500 rpm. Such a behavior translates into a slight increase of combustion NVH. At 3000 rpm differences are smaller.

4.3 Maps

The BMEP-speed maps shown in figures 26-28 compare CDO and WPO in terms of volumetric fuel consumption, brake specific fuel consumption and opacity. The maps are obtained interpolating 42 stationary operating points using a triangulation function.

The first map, figure 26, shows that volumetric fuel consumption is almost equivalent. Some difference in favor of WPO may be observed in terms of BSFC, figure 27. Here, the less regular patterns of the WPO map may be due to the unavoidable measurement errors.

Finally, the good reduction of soot emissions due to the use of WPO may be appreciated in figure 28.

5. Acknowledgments

6. Conclusion

A current production, indirect injection, naturally aspirated diesel engine, has been tested, without any modification, running on standard Commercial Diesel Oil (CDO) and on a Waste Plastic Oil (WPO) derived from recycled plastic pyrolysis. Engine performance, fuel consumption, soot emissions and in-cylinder pressure were measured. The results obtained from the experiments can be summarized as follows:

- At full load, the volumetric fuel rate is lower with WPO: as a consequence, also the output torque and power are lower, with differences between the two fuels varying between 5 and 10%. The specific fuel consumption was found to decrease using WPO at low and mid speeds and slightly increase at high speeds. The WPO global efficiency is always higher.
- At partial load the outcome of the full load tests is confirmed: independently from the type of fuel, the engine shows about the same performance when the pump delivers the same volume of fuel , but WPO bsfc is always lower due to the lower density; WPO efficiency is still higher.
- The in-cylinder pressure traces show that combustion is quite similar for the 2 fuels even if, when the engine is fueled with CDO, at high speeds, combustion is slightly faster in the first part of the process (higher Cetane number).
- Running on WPO, soot emission are always significantly lower, with a difference up to 50% at full load.

In conclusion, the present experimental campaign shows that Waste Plastic Oil can be successfully used to feed a current production IDI diesel engine; even if further tests are necessary in order to assess the reliably of the engine and the durability of its performance, WPO has demonstrated to be a viable alternative to fossil fuel in Diesel engine.

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