AN EXPERIMENTAL STUDY ON THE USE OF PYROLYSIS OIL IN DIESEL ENGINES FOR CHP APPLICATIONS

Bert van de Beld, Elmar Holle, Jan Florijn
BTG Biomass Technology Group BV
7500 AV Enschede, the Netherlands

ABSTRACT: The EC has set a target to increase the share of combined heat and power (CHP) in the European energy supply. The fuelling of pyrolysis oil in conventional diesel engines is challenging, but it could be an interesting option for CHP-units in the capacity range of 50 – 1,000 kW_e. This application has been studied experimentally using a small, 1-cylinder test engine. Main modification of the engine concerns the fuel injection system, which has been completely reconstructed from stainless steel. Subsequently a number of experiments have been carried out to determine engine performance and flue gas emissions. The engine was operated at 1,800 rpm and air preheating to 150 °C was required to achieve complete combustion of the pyrolysis oil. Finally, a successful run of 12 hours was carried out.

Keywords: pyrolysis oil, combined heat and power (CHP), engine.

1 INTRODUCTION

The EC has set a target to increase the share of combined heat and power (CHP) in the European energy supply. One of the objectives is to develop energy systems for remote regions with a special emphasis on the integration of renewable energy. So far, the implementation of small-scale (50 to 1000 kW_e), direct biomass-to-electricity CHP-systems has been rather limited. The main reasons include:

- Relatively high investment costs for small-scale systems
- High running costs
- Poor reliability and availability
- Low acceptance by end-users

The factors causing intrinsic problems with biomass based units on relative small scale are manifold, but include:

- The presence of contaminants in the biomass
- The limited availability of uniform biomass
- The non-uniform appearance of biomass
- Its general low energetic density (especially in terms of GJ/m^3), requiring huge volumes of biomass stocks to be stored near the electricity production unit.

The use of liquid biofuels may be more suitable for this purpose and may overcome the abovementioned issues.

Bioliquids are defined here as liquid fuels produced from biomass and used for energy purposes other than transport. Their energy purposes include electricity production, heating and cooling. Converting biomass into bioliquids increases the acceptance by end-users, as they are uniform and easier to use. The Bioliquids-CHP (www.bioliquids-chp.eu) project was set up to break down the technical barriers preventing the use of bioliquids in engines and turbines.

2 DESCRIPTION OF THE PROJECT

2.1 Project objectives

The aim of the overall Bioliquids-CHP project is to adapt engines/turbines to enable operation on a variety of bioliquids, including pyrolysis liquids.

On the one hand, the project will modify the design of a diesel engine and a micro gas turbine so that these can run efficiently on bioliquids such as biodiesel, vegetable oil and pyrolysis oil. On the other hand, bioliquids will be upgraded and blended in order to facilitate their use in engines and turbines. Eventually, the most economic and reliable engine/turbine-bioliquids combinations will be developed in order to make the system attractive. In addition, the project will develop methods and techniques to control exhaust emissions (NO_x, CO, particulates). The outline of the project is given schematically in Figure 1.

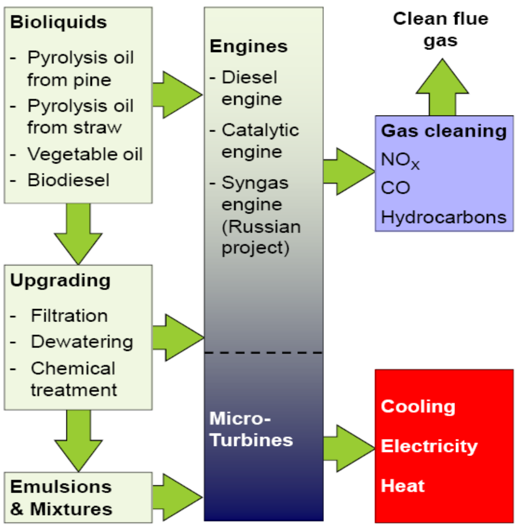

Figure 1: Outline of the BioLiquids - CHP project

2.2 The use of bioliquids in diesel engines

This paper focuses on the modification of a conventional diesel engine and its testing with pyrolysis oil. Results with other bioliquids will be published in due course. Of all fuels to be tested, pyrolysis oil will be the most difficult one. Prior research effort on the use of pyrolysis oil in engines is rather limited, but some relevant articles can be found. A good overview paper has been published by Chiaramonti et al. [1].

The technical modifications proposed in this work are meant to enable fuelling of pyrolysis oil. The properties of pyrolysis oil are quite different from diesel, and the most important ones for application in a diesel engine are:

- Pyrolysis oil is acidic, typical pH ~2.5 - 3. All piping and devices in contact with pyrolysis oil should be corrosion resistant;
- Pyrolysis oil contains typically 20-28 wt% water, lubrication is poor and small particles (< 20 µm) might be present. This may cause severe abrasive wear, in particular in the injector;
- The viscosity of pyrolysis oil is higher than that of diesel fuel, and strongly depends on water content and temperature. Reducing the water content will cause a significant increase in viscosity;
- Pyrolysis oil is sensitive to re-polymerisation if its temperature rises above 50-60 °C. Re-polymerisation may result in small particles in the oil and increase in viscosity;
- Pyrolysis oil is more difficult to ignite, and higher temperatures will be required to achieve complete combustion. An important indicator is the Cetane Number (CN). However, the actual CN for pyrolysis oil is highly unclear and values between 5 and 25 are reported. In addition, it is known that the ignition delay for pyrolysis oil is higher than that of diesel;
- The Heating Value of pyrolysis oil is significantly lower than that of diesel (approx. ½ the value on a volumetric basis). Obviously, for the same energy input twice the volume of fuel needs to be injected;
- Direct mixing of pyrolysis oil with mineral diesel or biodiesel is not possible as pyrolysis oil is not miscible with these liquids.

3 OIL PROPERTIES

To enable pyrolysis oil fuelling in a conventional diesel engine either the pyrolysis oil properties can be improved, the engine modified or both. In the Bioliquids-CHP project research is also carried out on radically changing the oil properties by e.g. esterification, hydrotreatment, blending and emulsification. In the near future these fuels will also be tested in the engine.

The pyrolysis oil has been produced from pine wood by BTG in its own pilot plant. In Table I some properties of the pyrolysis oil are given.

Table I: Overview of pyrolysis oil properties

		Pyrolysis oil
C (as received)	wt%	45.5
H	wt%	5.8
N	wt%	< 0.1
O	wt%	48.8
Water content	wt%	25.4
LHV	MJ/kg	16.4
	MJ/L	19.2
Density	kg/L	1.17
Solids content	wt%	0.016
Ash Content	wt%	0.040
MCRT	wt%	15.1
pH		2.6
Viscosity (40 °C)	cSt	13

After production, the crude pyrolysis oil has been centrifuged to reduce solids content. The influence of removing water on the fuel quality has been studied. Obviously, by removing some water the heating value of the pyrolysis oil will increase. Disadvantageously, the oil viscosity and the sensitivity to re-polymerisation increase. Re-polymerisation and/or aging will also result in a higher viscosity upon storage. Oil viscosity is an extremely important parameter for diesel engine operation and in particular the fuel atomization.

In Figure 2 the kinematic viscosity of pyrolysis oil is plotted as a function of the oil water content and for different temperatures. Decreasing the water content will result in a strong increase in viscosity which can -to some extent- be compensated by a higher oil temperature.

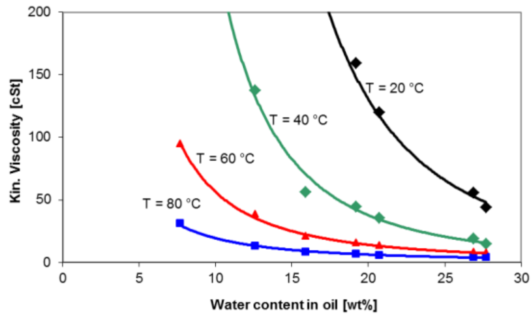

Figure 2: Kinematic viscosity of pyrolysis oil as a function of the water content in the oil and for different temperatures.

For diesel engine operation the kinematic viscosity of the fuel upon fuelling should be typically in the range of 13 – 20 cSt. In case of heavy fuel oil (HFO) preheating to temperatures well above 100 °C is applied to reach a sufficient low viscosity. This approach is not suitable for pyrolysis oil as significant re-polymerization will already take place at temperatures below 100 °C, and around 100 °C all water will be evaporated resulting in even higher viscosities. In Figure 3 the relative change in kinematic viscosity of pyrolysis oil is shown for different storage temperatures. Keeping the oil at 80 °C for just one day will already result in an increase in viscosity of roughly 35%. At 20 °C this would take approximately 1 year, which is comparable with the observations of Oasmaa et al. [4]. To compensate for such an increase in viscosity a further increase in fuel temperature of 4-5 °C will be needed to obtain the required viscosity prior to injection. Partly dewatered pyrolysis oil does show a much stronger sensitivity to aging; removing 50% of the water from the oil resulted in roughly doubling the viscosity change rate. For the tests presented in this paper, no water has been removed from the oil.

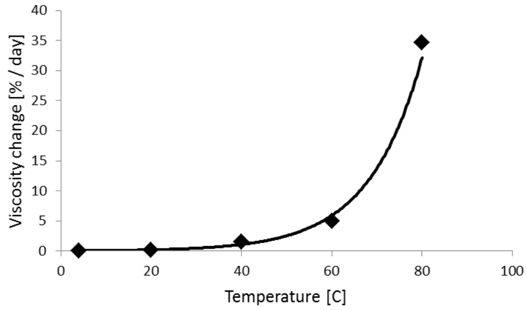

Figure 3: Relative change in kinematic viscosity [%/day] as a function of the storage temperature (pine derived pyrolysis oil).

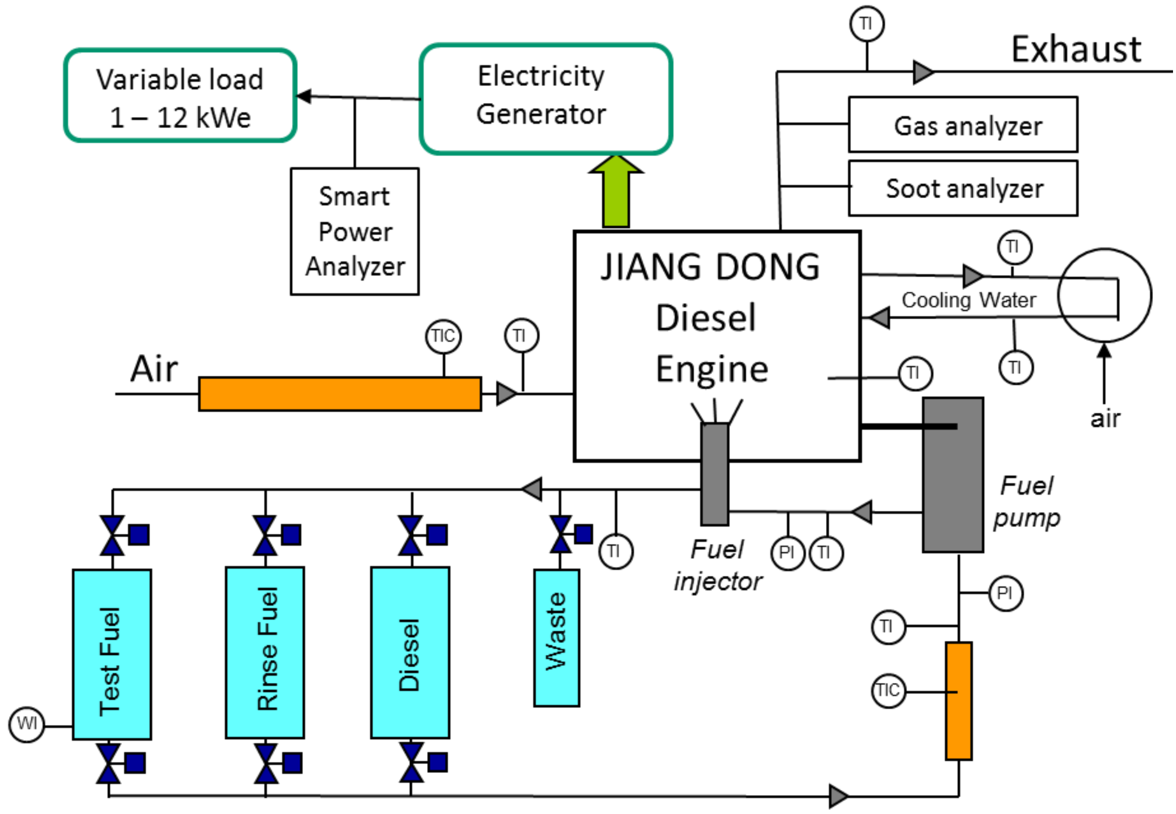

Figure 4: Schematic drawing of the engine test set-up

4 ENGINE TEST SET-UP

The main objective of the work described here is to modify a conventional diesel engine to such extent that pyrolysis oil fuelling is possible.

4.1 Test engine

The basis of the test set-up is a one-cylinder, 20 kWe diesel engine, which has the advantage that only a single fuel injection system has to be replaced. The original engine characteristics are given in Table II.

Table II: Engine characteristics

JIANG DONG Engine	
Model	ZH1130
Piston displacement	1,592 ml
Compression ratio	17.6
Output	23.5 kW (at 2,200 rpm)
Injection pressure	200 – 250 bar
Fuel Consumption	240 g/kWe (diesel)
Generator	MECC ALTE – T20FS-160
Max output generator	10 kWe

A schematic drawing of the set-up is given in Figure 4. The core of the setup is the diesel engine, which has been adapted to enable the feeding of different fuels. A number of measuring devices have been added to monitor its performance. Three fuel vessels are installed containing engine start-up fuel (typical mineral diesel), rinsing fluid (e.g. ethanol) and the test fuels respectively. A fourth vessel is required to collect fuel during switching between vessels. Normally, a few percent of BERAID 3455 is added to the ethanol rinse fluid to improve ignition and lubrication behavior. If needed or desired the fuel can be preheated to temperatures up to about 100 °C. The incoming air can be controlled at temperatures between 20 and 200 °C. A generator is connected to the engine to convert the mechanical power into electricity. Up to 6 electrical heaters (0-2 kW_e each) can be switched on to vary the load on the engine in steps of 1 kW_e up to a maximum of 12 kW_e.

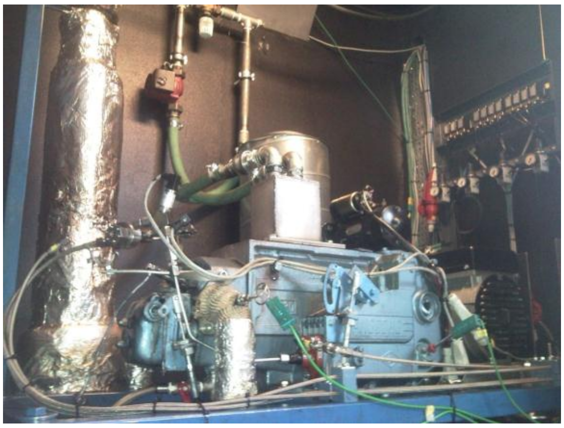

Figure 5: Engine test set-up

The original fuel pump and injector have been replaced by a complete, dedicated stainless steel fuel injection system. Both parts have been constructed in-house, because suitable suppliers for such parts could not be identified. To obtain sufficient resistance against abrasive wear a surface treatment has been applied to the most critical elements. In Figure 5 a picture is shown of the engine test set-up.

4.2 Analysis

At several positions in the set-up temperatures and pressures can be measured and logged. A fast response, pressure indicator and oscilloscope (Picoscope, Picotech) is installed to measure fuel injection pressure. The fuel storage tank is placed on a mass balance (Sartorius), and based on these measurements the actual fuel consumption is calculated. Two analysers have been installed (Rocar-Tech), one measuring the gas components (CO, NOx, CO_2, O_2 and HC), and the second one measuring soot/particles and the rotational speed of the engine. The actual power output and frequency are measured with a smart power analyser (Carlo Gavazzi/WM3-96).

5 RESULTS

Initial tests with the engine set-up have been carried out with diesel fuel to check all controls and measurements, and to characterize the engine with the original fuel. In this first series of tests the number of changes to the engine have been limited. The original piston was installed (compression ratio ~17) as well as the original fuel injector. The fuel pump was already replaced by the new stainless steel version. The engine was typically running at about 1,800 rpm. To overcome difficulties with pyrolysis oil ignition the incoming air can be preheated to achieve higher temperatures in the cylinder at the moment of fuel injection. In Figure 6[A-E] several properties are plotted as a function of the air inlet temperature for fuelling diesel and pyrolysis oil. In Figure 6[D] the fuel consumption is given; if the temperature is sufficient at the moment of fuel injection there will be hardly any change in fuel consumption if the

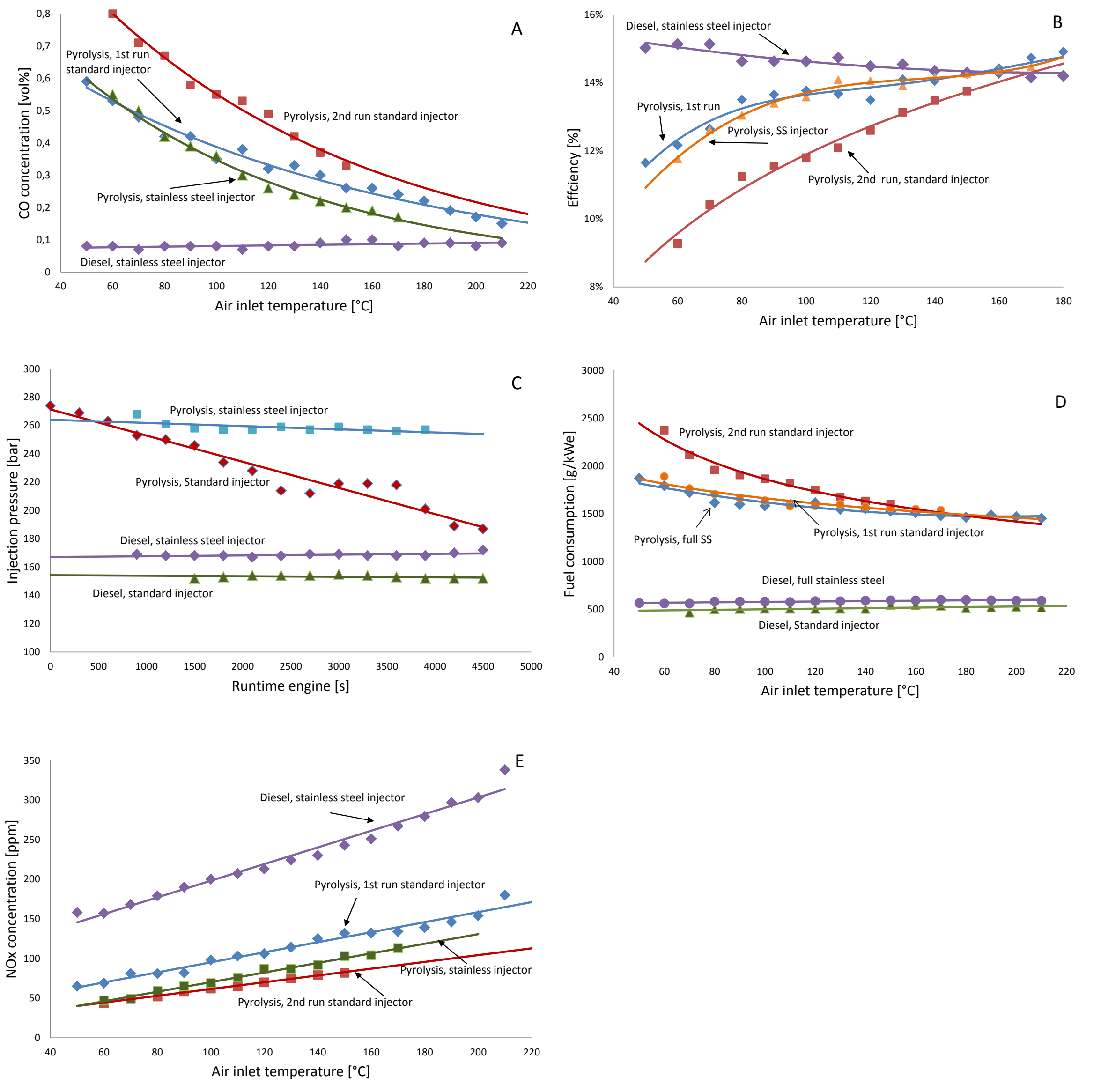

Figure 6[A-E]: Performance of the diesel engine at a load of 3 kWe as a function of the air inlet temperature for diesel and pyrolysis oil using a standard injector and a new stainless steel injector. In figure 6C the injector pressure is given as a function of the runtime of the engine

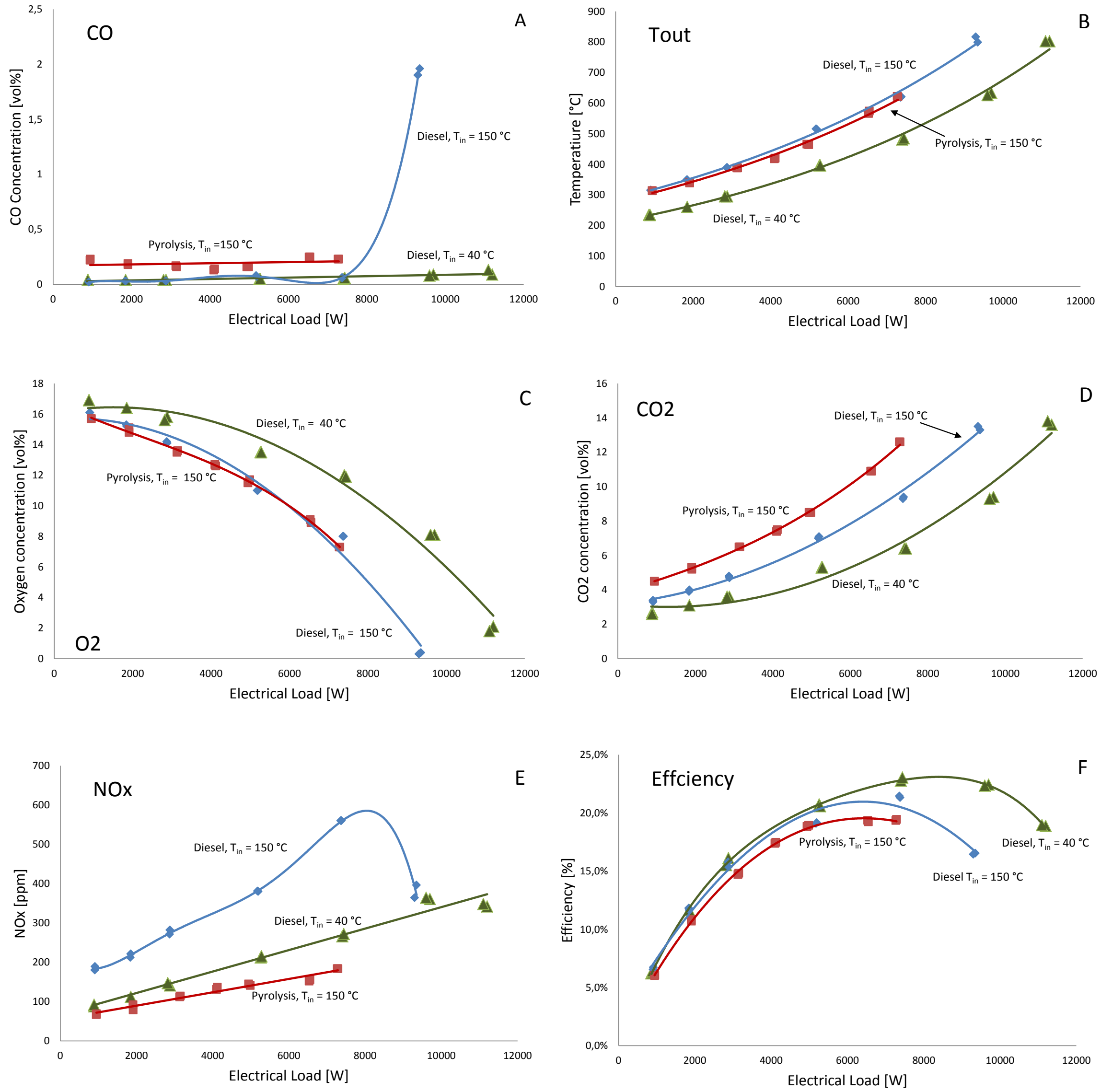

Figure 7^{A-F}:Engine performance and flue gas emissions as a function of the electrical load for diesel and pyrolysis oil at different air inlet temperatures.

air inlet temperature is further increased. If the temperature is too low, additional fuel will be required to give the same output. As expected, for diesel hardly any influence is observed by changing the air inlet temperature. For pyrolysis oil it is concluded that an inlet temperature of about 150 °C is required to reach complete conversion. The 1st run on pyrolysis oil with the standard injector and the new stainless steel injector gave nearly the same results. However after the first run significant wear on the standard injector could be observed. Originally, the holes in the injector have a diameter of about 330 µm; after 1 hr of operation the diameter of the holes grew to about 400 µm. It means a 20 % increase in diameter, but even 48% on surface basis. It results in poor atomization of the oil, increasing emissions and fuel consumption. This can be clearly observed when comparing the fuel consumption in Figure 6^B between the 1st and 2nd run on pyrolysis oil with the standard injector. The stainless steel injector performs much better, which can be seen in Fig 6^C, where the injection pressure remains constant for more than 1 hour of operation.

In Figure 7^{A-F} engine performance is given as a function of the electrical load for pyrolysis oil and diesel. Diesel performance has been measured at normal air inlet temperature and at 150 °C to enable a good comparison with pyrolysis oil fuelling. With increasing air inlet temperatures less air is introduced into the cylinder, and consequently less oxygen is available for combustion. This is clearly observed in Figure 7^C where the oxygen content in the flue gas is already close to zero at a load of 10 kW. As a result the CO content suddenly increases and NO_x decreases.
Increasing the air inlet temperature will result in a similar increase in flue gas outlet temperature (see Figure 7^B). The NO_x emissions will normally increase with increasing temperatures. However, fuelling pyrolysis oil instead of diesel resulted in lower NO_x emissions for low and high air preheat temperatures.
The overall efficiency from fuel to electricity is given in Figure 7^F. At low capacities the efficiencies are

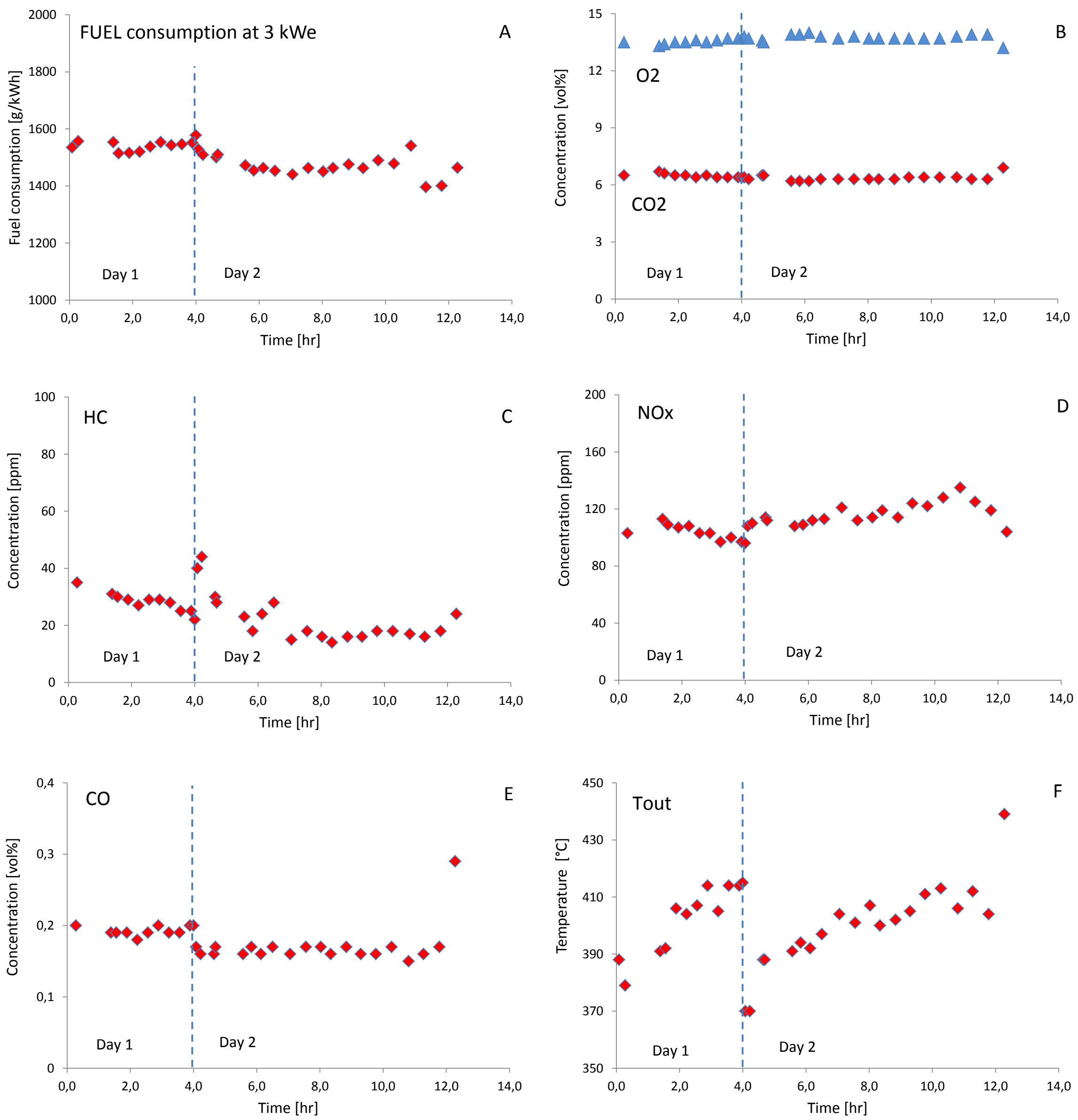

Figure 8[A-F]: Engine performance as a function of the time on stream for pyrolysis oil fuelling. Engine load = 3 kW_e. Air inlet temperature = 150 °C.

comparable for the three different cases. At higher load a clear deviation occurs. Probably this is due to a lack of oxygen and consequently less efficient combustion. In Figure 7[D] the CO_2 concentration in the flue gas is shown. At higher air inlet temperatures less gas is introduced into the cylinder but at the same load approximately the same absolute amount of CO_2 is produced resulting in a higher CO_2 content in the flue gas. For pyrolysis oil the CO_2 content is even higher because the fuel itself already contains significant oxygen yielding more CO_2 per GJ of fuel converted.

The performance of the engine has not been optimized for the new fuel injection system. The overall electrical efficiency is considered rather low for a diesel engine, but there is significant room for further improvement.

In Figure 8[A-F] the results are shown for a semi-continuous run with pyrolysis oil at an electrical load of 3 kW_e. On the first day the engine was operated for 4 hours, and subsequently the fuel injector was inspected. No visual damage was observed on both the injector needle and injector body. The size of the injector holes did not change during the 4 hours test run. On day 2, the operation was continued with the same injector and under the same operating conditions. In our experience, the CO-content in the flue gas is a good indicator for atomization and combustion of pyrolysis oil. In Figure 8[E] the CO content is plotted as a function of the runtime. Till 12 hrs of operation hardly any change was observed indicating that fuel injection system was functioning properly. Suddenly at around 12½ hours CO went up rapidly, and the engine was stopped. Inspection learned that the tip of the injector was broken off, and proper atomization is impossible. The reason for the broken tip has not been fully clarified yet, and requires some further investigation.

6 CONCLUSIONS

A standard diesel engine has been modified to enable the fuelling of pyrolysis oil. The fuel pump and fuel injector have been constructed in-house from stainless steel to withstand corrosion. To achieve sufficient fast ignition and combustion of the pyrolysis oil the incoming air is preheated to 150 °C. A successful, continuous run of 12 hours could be carried out without a notable change on performance and emissions. In comparison to mineral diesel fuel wood-derived pyrolysis oil resulted in higher CO and lower NO_x emissions. The timing of ignition has not been modified yet, but is probably desired to further improve performance and reduce emissions.

Some new injector bodies are currently under construction where both improvements are made to the material and the construction techniques.

7 REFERENCES

[1] Chiaramonti, Oasmaa and Solontausta, Renewable and sustainable Energy Reviews, 11, 2007, pp. 1056-1086.

[2] Alan Shihadeh, Simone Hochgreb, Diesel engine combustion of biomass pyrolysis oils, Energy& Fuels, 2000, 14, pp. 260-274.

[3] Galen J. Suppes, Ying Rui, Eric Regehr, SAE Technical paper series 971686, Hydrophilic diesel fuels-ignition delay times of several different blends.

[4] Anja Oasmaa and Gordner Peacocke, Properties and fuel use of biomass derived fast pyrolysis liquids – A guide, VTT publication 731, 2010.

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