High NOx Reduction Achieved at Low Load Using Very Advanced Valve Timing with Hydro-Treated Vegetable Oil

Matteo Imperato1*, Aki Tilli2, Teemu Sarjovaara3, Martti Larmi4

1Aalto University School of Science and Technology
Puumiehenkuja 5 A
Espoo
Finland
matteo.imperato@aaltouni-versity.fi

2Aalto University School of Science and Technology
Puumiehenkuja 5 A
Espoo
Finland
aki.tilli@aaltouni-versity.fi

3Aalto University School of Science and Technology
Puumiehenkuja 5 A
Espoo
Finland
teeimu.sarjovaara@aaltouni-versity.fi

4Aalto University School of Science and Technology
Puumiehenkuja 5 A
Espoo
Finland
martti.larmi@aaltouni-versity.fi

* corresponding author

ABSTRACT

The objective of this paper is to analyze the performance of a large-bore single-cylinder medium speed compression-ignition (CI) engine running with hydro-treated vegetable oil. This fuel has a paraffinic chemical structure and high Cetane number (CN). These features permit to achieve more complete and cleaner combustion, in many engine operation points. The main benefits are thus lower emission compared to diesel fuel and low soot values. The facility used in this study is a research engine, whose main parameters that affect the performances are fully adjustable. The boundary conditions upstream and downstream the engine are freely controlled by a separated supply air plant and by a throttle valve, located at the end of the exhaust pipe. The injection system is common-rail: rail pressure, injection timing and duration are completely adjustable. The gas exchange valve system consists of electro-hydraulic actuators, used for controlling the intake and exhaust valve timing. Using the flexibility of the engine parameters, several configurations have been tested to realize different in-cylinder conditions before the combustion. In fact, the in-cylinder compression temperature and the exhaust fraction have been changed by modifying the valve timing and the boundary conditions. Instead,
the in-cylinder compression pressure and the injection parameters have been kept unchanged. Two are the loads presented in this paper and they are at medium and at low load: the strategy has been the same for both the loads. The results are promising and show the benefits of hydrotreated vegetable oil (HVO) compared to diesel fuel. In fact, it has been possible to reduce nitrogen oxides (NOx) emission up to 50% running with HVO and opportunely tuned valve timing. However a certain strategy does not bring the same outcomes trend for every tested load and the trade-off between the results has to be drawn out.

**Keywords:** NOx reduction, biofuel, diesel, CI engine, clean combustion, Miller, gas exchange valve, adjustable timing

1. Introduction

The emission limits for diesel engines for ships are becoming stricter and stricter. In 2016 a new regulation, which reduces NOx emission by 80% [1], will become effective. The development of new solutions and techniques for reducing emissions is therefore mandatory in order to fulfill the stringent law demands.

In this concern the combined use of advanced techniques for emission reduction and alternative fuels, like HVO, in compression-ignition (CI) engines can give very promising results and lower emission outcomes, compared to the standard values achieved with diesel.

In this study runs have been carried out with diesel EN590 and a type of HVO, called NExBTL, and produced by Neste Renewable Fuels Oy. HVO has high CN, paraffinic chemical structure and it has no sulfur or aromatic content [2].

The possibility to run CI engines with HVO has been previously studied. Kuronen et al. [3] evaluated the possibility to use HVO as fuel in heavy duty engines. Also Aatola et al. [4] compared the performance of HVO and diesel on heavy duty engine applications and found out that running with HVO results in lower exhaust emissions, regulated and unregulated, and smoke values. In addition, a study by Pflaum et al. [5] presented experimental results achieved with different blends of HVO and diesel fuel; the results showed that HVO can reduce both NOx and soot at the same time due to its lack of complex chemical aromatics.

In this paper several techniques for emission reduction are presented at high load. The main target was to reduce the NOx formation by combining the advantages of HVO chemical structure and physical properties with advanced techniques that can reduce the in-cylinder combustion temperature or increase the charge dilution with exhaust gases. A useful way to lower NOx is using the Miller cycle [6], which consists of reducing the effective compression ratio by changing the gas exchange valve timing. This means that the in-cylinder compression temperature of the charge drops and also the combustion process may happen at lower temperature. The Miller technique had already been tested with EVE [7] and the results showed that a high reduction of pollutants can be achieved only by advancing the intake valve closing (IVC).
In addition to the Miller cycle also high quantity of the exhaust gas residuals in the combustion chamber has been tested. A certain amount of inert gases in the combustion chamber subtracts some heat produced during the combustion process and obstacles the zones at high temperature, reducing the NOx formation [8]. Since EVE has not any gas recirculation external system, the dilution of the charge has been achieved by shortening the gas exchange scavenging period, operating both on intake and exhaust valves, and opening briefly the exhaust valves also around the bottom dead centre (BDC) at the end of the intake stroke: the so called internal exhaust gas recirculation (IEGR).

The combined use of Miller cycle and IEGR has been previously tested in diesel engines. Edwards et al. [9] studied the combined effect of the Miller cycle and the IEGR on heavy duty truck engines finding acceptable levels of in-cylinder temperature. Millo et al. [10] analyzed different strategy of IEGR and found a NOx reduction by 13% and a remarkable improved fuel economy. Osada et al. [11] showed that the exhaust gas recirculation (EGR) can bring to higher fuel economy and reduced NOx, but an excessive EGR rate may increase the soot values in the exhaust gases. No similar studies have been carried out so far in large-bore naval engine like EVE.

2. Experimental
2.1 Research engine
The facility used is a single-cylinder medium-speed CI research engine for ship applications. The Extreme Value Engine (EVE) is in fact capable to operate in several running conditions, due to the high flexibility of the gas exchange valves, fuel and ancillaries systems [12]. The EVE has electro-hydraulic valve actuators (EHVA) [13] instead of traditional camshaft mechanism. This system permits to have high degree of freedom in the gas exchange phase. In fact it is possible to modify the opening and closing timing of the gas exchange valves, their maximum valve lift as well as their opening and closing lift slope. The valve actuators are controlled by pressurized oil (250 bar) that is the same oil used in the lubrication system. The EVE is connected to an electric motor, which also allows running in motored mode. The fuel injection system is common rail type with adjustable rail pressure, injection timing and duration. The engine boundary conditions, such as intake air pressure and temperature as well as exhaust pressure, are controllable by an air supply system and a backpressure throttle valve; this allows running operating points with an infinite configuration of turbochargers. Besides the quantities mentioned so far, all pressures and temperatures of the ancillary systems (LT water, HT water and lubrication oil) are remotely adjustable.
2.2 Measurement equipment
The pressure inside the combustion chamber has been measured via a pressure sensor Kistler 6061B connected to a charge amplifier Kistler 5011. The pressure sensor is installed in the cylinder head, very close to the combustion chamber to minimize any error. In addition to this, a Kistler 7001 pressure sensor in an automatic switching adapter Kistler 741A is installed close to the previous. The automatic switching adapter is used to isolate the pressure sensor from the cylinder pressure during high pressure stage. The influence of thermal shock caused by combustion can thus be avoided and an accurate measurement of lower pressures achieved.

2.3 Experimental procedure
All the test-points are steady-state and the engine operation has been constant. When the set-up is changed, some time is needed for the results stabilization. When the main outcomes e.g. fuel flow, engine power, NOx value are reasonably steady, the engine runs few minutes longer before the measurement is taken. At the beginning of every testing day, a reference test is taken to compare the values with the ones achieved previously and check that all the devices work consistently. With this procedure, a very good repeatability is achieved and the results are very reliable.

2.4 Fuel composition
The fuel used in this study has been a type of HVO, called NExBTL by Neste Renewable Fuels Oy. HVO production is based on hydrotreatment of triglycerides such as vegetable oils and animal fats, whereas with traditional biodiesel (FAME) the process is based on triglyceride esterification with alcohol. The end product is a clean paraffinic diesel fuel similar to fuels produced by biomass, coal or natural gas gasification and Fischer-Tropsch synthesis. Hence, the process combines traditional biodiesel feedstock and the high quality end product of synthetic diesel [2, 3].
Regarding end-use properties, hydrotreated oils show superior quality compared with conventional diesel fuel and especially conventional biodiesel. Regardless of the feedstock, all paraffinic diesel fuels or components have many benefits. Firstly, they can be used as it is or as blends in existing diesel engines and infrastructure and they enable the development of engines with improved engine efficiency. Secondly, the fuels are sulfur-free, with low aromatic content and free of materials compatibility or storage life problems associated with FAME. Moreover, they are more biodegradable, less toxic and not as harmful to aquatic organisms as conventional diesel [14, 15].

With no aromatics or sulfur, consisting of paraffins, the fuels burn very cleanly and as such diminish emissions and especially soot compared to standard diesel. The high CN means better ignition and complete combustion in difficult conditions. This reduces particulate matters (PM), hydrocarbons (HC) and NOx emissions and allows higher EGR rates to diminish NOx emissions [3-5].

Typical properties of HVO, FAME, synthetic diesel and typical EN 590 standard-fulfilling diesel are reported in Table 1. The density of HVO is lower than that of diesel and FAME, and the CN is much higher. Viscosities and distillation ranges of standard diesel and FAME are slightly lower than with HVO on the average. Synthetic diesel chemistry and thus properties are very similar to HVO.

<table>
<thead>
<tr>
<th>Table 1: Typical properties of HVO compared with FAME, synthetic diesel and average European EN 590-standard fuel. [14]</th>
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<tbody>
<tr>
<td>Fuel</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Density at +15°C (kg/m3)</td>
</tr>
<tr>
<td>Viscosity at +40°C (mm²/s)</td>
</tr>
<tr>
<td>Cetane number</td>
</tr>
<tr>
<td>Distillation range (°C)</td>
</tr>
<tr>
<td>Cloud point (°C)</td>
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<tr>
<td>Heating value (MJ/kg)</td>
</tr>
<tr>
<td>Heating value (MJ/l)</td>
</tr>
<tr>
<td>Aromatics content (wt-%)</td>
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3. Test program
Two loads have been run to see the influence of the strategy used along the load: in particular 70 kW (medium load) and 25 kW (low load) as output power have been chosen. The engine speed has been the same at every run point and it has been 900 rpm.

3.1 Valve timing
An extensive test program has been carried out. The main studied object has been the gas exchange valve timing.

The starting valve timing has been chosen with low Miller rate and wide positive scavenging period. With this timing the comparison between diesel and HVO has been
performed; further tests have been run only with HVO. From the reference configuration two advanced Miller rate have been tested by closing earlier the intake valve. They are represented in Fig. 2.

![Figure 2: the advanced Miller timing](image)

With both the advanced timings (Mil50 and Mil70) different scavenging phases have been tested, in order to create different mixture condition before the fuel injection. Beside the positive scavenging (Sc 60), also zero scavenging (Sc 0) and negative scavenging (Sc -30) have been tested. Advancing the intake valve closing (IVC) brings to lower maximum lifts: this may require very high charge air pressure values and quick response of the valve system. To avoid these effects, the negative scavenging is performed so that the intake valve lift is the same of the one with zero scavenging and the exhaust valve is closed much earlier during the exhaust stroke. The tested timings with Mil70 are shown in Fig. 3.

![Figure 3: the three tested scavenging periods](image)
3.2 Strategy
The strategy used has been such as the in-cylinder pressure at the end of the compression stroke has been kept constant with every tested valve timing. The fuel injection parameters are the same in all the runs; only the fuel dosage is different along the engine load. In Tab. 2 the values are reported.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail pressure</td>
<td>bar</td>
<td>1400</td>
</tr>
<tr>
<td>Start of Injection (SOI)</td>
<td>CAD ATDC</td>
<td>-10.5</td>
</tr>
<tr>
<td>Injection dose (at 70 kW)</td>
<td>mg/cycle</td>
<td>670</td>
</tr>
<tr>
<td>Injection dose (at 25 kW)</td>
<td>mg/cycle</td>
<td>365</td>
</tr>
</tbody>
</table>

The boundary conditions, such as intake and exhaust pressure have been drawn out from a 1-D simulation model, which has a mathematical turbocharger, whose action is to transfer part of the exhaust gas energy to the inlet side along a wished efficiency. In this work the turbocharger overall efficiency has been set as 0.75.

4. Results
The main test results are presented in this section. The in-cylinder conditions, considered important in this study, can not be taken from the measurement system: an estimation could be possible but it would give a high rate of uncertainty. For this reason part of the results reported are drawn out from the simulation model.

4.1 Simulation results
The in-cylinder compression temperature and the exhaust gas fraction in the charge have been retrieved by the simulations. Figure 4 shows that the values are not so different with the load: the simulated in-cylinder compression temperature in the reference case is 920 degK for both the load and the exhaust fraction is negligible. The mere Miller usage lowers as expected the in-cylinder compression temperature by 100 degK about. Shortening the scavenging phase brings to increase of both in-cylinder temperature and exhaust gas fraction. The latter does not exceed 5% in any case but the mixture temperature considerably increases: in the case Mil50 Sc-30 at 70 kW load this value is the same as the reference.
4.2 Test results

The attention of the test results has been focused on the fuel consumption and the emission outcomes. Most of the results are reported along the indicated power, since EVE has very high mechanical losses due to its construction and figures along the output power may provide unrealistic values.

Figure 5 presents the measured fuel consumption and NOx emission. One can see that the only fuel conversion brings advantages both in fuel economy and in the NOx production: in fact comparing the two cases with reference timing both ISFC and ISNOx have become lower running with HVO. Advancing the IVC to 50 CAD BBDC, the NOx have dropped in both the loads, especially at 70 kW load; on the other hand the fuel consumption increases by 3-4 g/kWh. Using narrower scavenging has a benefit effect, since the NOx reduction has been by 40-50% compared with the reference value run with diesel. Also the fuel consumption has been lower, although the most advantageous configuration has been negative scavenging (Mil50 Sc-30) at the medium load and zero scavenging (Mil50 Sc0) at low load. Increasing the Miller timing (Mil 70) the outcomes are very different with different scavenging periods. Positive scavenging (Mil70 Sc60) – i.e. the mere application of the Miller technique- has resulted in very high NOx value at 25 kW load, whilst at 70 kW load there has not been further reduction compared with other Miller timing (Mil50 Sc60). Reducing the scavenging period helps very much in the NOx reduction: with negative scavenging (Mil70 Sc-30) the lowest NOx outcomes have been measured in both the loads. The fuel consumption has risen at both the loads as the scavenging has become narrower, and the increase has been 3-4 g/kWh compared with the reference case.
Figure 5: NOx emission and fuel consumption

Figure 6 reports the NOx and the soot measured results. One can see that the soot values have been almost negligible in many tested configuration. The use of HVO reduces the soot and (Mil15 Sc60) and also with very extreme Miller rate the registered FSN is close to 0. The highest soot values have been measured at 25 kW load when very negative scavenging is applied (Mil50 Sc-30 and Mil70 Sc-30), but those results (FSN=0.4) have not been such high as create visible effect from the exhaust chimney.

5. Conclusions

An extensive study with HVO has been carried with EVE, a single-cylinder large-bore medium-speed diesel engine used for research purposes. Two loads, one medium (70 kW) and one low load (25 kW) and different valve timings, modifying IVC and
scavenging periods, have been tested. A starting configuration close to a standard timing has been chosen as reference.

HVO has been compared with diesel EN590 to see the influence on the performance outcomes. The use of HVO brings good advantages in terms of fuel consumption and of NOx. The ISFC reduction is up to 7% and the NOx reduction up to 10%.

Further reduction has been achieved using advanced Miller rate (Mil 50). However, with the most advanced Miller rate (Mil 70) there has not been any further benefit in terms of NOx: at low load, the value has been very high, even greater than the reference configuration.

The advanced Miller timing has given good results combined with negative scavenging period (Mil50 Sc-30 and Mil70 Sc-30): the lowest NOx has been 3.5 g/kWh, obtained at 25 kW load with Mil70 Sc-30; this value is 50% lower than the reference with diesel and almost 1/3 of the NOx figure achieved with positive scavenging (Mil70 Sc60).

The fuel consumption has slightly risen with advanced Miller and negative scavenging (Mil70 Sc-30): the increase of ISFC is by 3-4% at medium load and slightly lower at low load.

One of the main benefits of HVO is that it is possible to run with different conditions of temperature and some exhaust gas fraction in the combustion chamber and the soot produced is remarkably low: in fact the highest value has been FSN=0.4, obtained with 5% exhaust gas fraction in the charge.

6. References


7. ACKNOWLEDGEMENTS

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