

Large-Bore Compression-Ignition Engines: High NO_x Reduction Achieved at Low Load with Hydro-Treated Vegetable Oil

Matteo Imperato, Aki Tilli, Teemu Sarjovaara, Martti Larmi
Aalto University School of Engineering, Finland

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ABSTRACT

The objective of this paper is to analyze the performance and the combustion of a large-bore medium-speed engine running with hydro-treated vegetable oil (HVO) at low engine load. This fuel has a paraffinic chemical structure and high cetane number (CN). 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, where the conditions before and after the machine, the valve timing and the injection parameters are fully adjustable. Several in-cylinder conditions before the combustion have been tested. The results are promising and show the benefits of HVO compared to diesel fuel. In fact, it has been possible to reduce nitrogen oxides (NO_x) emission over 50% running with HVO and opportunely tuned valve timing.

INTRODUCTION

The emission limits for diesel engines for ships are becoming stricter and stricter. In 2016 a new regulation, which reduces nitrogen oxides (NO_x) emission by 80% [1], will come into effect. The development of new solutions and technologies for reducing emissions is therefore mandatory in order to fulfill the stringent demands of the law.

In this concern the combined use of advanced techniques for emissions 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, 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 that running with HVO results in lower exhaust emissions 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 NO_x and soot at the same time due to its lack of complex chemical aromatics.

In this paper the main target is to reduce the NO_x 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. The study is carried out at low load.

A useful way to lower NO_x 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 a lower temperature. The Miller technique has already been tested with EVE [7] and the results have shown that a high reduction of pollutants can be achieved by only advancing the intake valve closing (IVC).

In addition to the Miller cycle, a certain quantity of exhaust gas residuals in the combustion chamber is tested. Some inert gases in the combustion chamber subtract part of the heat produced during the combustion process and confound the zones at high temperature, reducing the NO_x formation [8]. Since EVE does not have any exhaust gas recirculation (EGR) 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 briefly opening the exhaust valves around the bottom dead center (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 a reduction

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 EGR can bring to increased 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 engine like EVE.

CHARACTERISTICS OF HVO

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. The end product is a clean paraffinic diesel fuel similar to fuels produced by biomass, coal or natural gas gasification and Fischer-Tropsch (FT) 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 excellent quality compared with conventional diesel fuel and with conventional biodiesel. Regardless of the feedstock, all paraffinic diesel fuels or components have many benefits. Firstly, they can be used as is or as blends in existing diesel engines and they enable the development of engines with improved efficiency. Secondly, the fuels are sulfur-free and low aromatic content. Moreover, they are more biodegradable, less toxic not as harmful to aquatic organisms as conventional diesel and with good storage stability [12, 13].

With no aromatics or sulfur, consisting of paraffins, the fuels burn very cleanly and as such diminish emissions, especially soot, compared to standard diesel. The physical properties of paraffinic diesel (low density, bulk modulus, viscosity and distillation temperatures) lead to wide fuel spray angles, smaller Sauter mean diameter, early evaporation and thus short liquid penetration, good mixing and less spray-wall interactions. 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, synthetic diesel FT and typical EN 590 standard-fulfilling diesel are reported in Table 1. The density of HVO is lower than that of diesel and the CN is much higher. The heating value of HVO on a mass basis is slightly higher but on a volume basis is lower, therefore to inject the same "potential energy" into the engine, slightly longer durations are needed for HVO. Viscosities of standard diesel are slightly lower than with HVO on average.

Table 1 - Typical properties of HVO compared with synthetic diesel and average European EN 590-standard fuel. [12]

	HVO	FT diesel, typical	EN 590, average
Density at 15C (kg/m ³)	775-785	770-785	835
Viscosity at 40C (mm ² /s)	3.0 - 3.5	3.2- 4.5	3.5
Cetane number	80 - 99	73 - 81	53
Heating value (MJ/kg)	44	43	43
Heating value (MJ/lit)	34.5	34	36
Aromatic content (wt-%)	0	0	30

EXPERIMENTAL SETUP

A large-bore single-cylinder medium-speed CI research engine is used in this work. 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 [14]. The EVE has electro-hydraulic valve actuators (EHVA) [15] instead of traditional camshaft mechanism. This system permits a 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.

The EVE engine is presented in Figure 1.

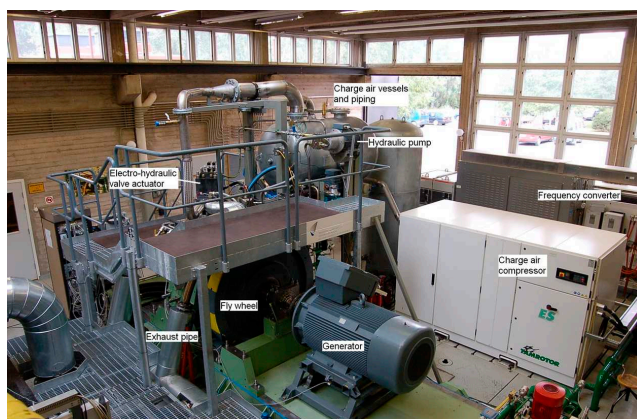


Figure 1 – The EVE engine platform

ENGINE SPECIFICATION

Table 2 reports the engine specification used in this work, regarding engine geometry, engine speed and fuel system set-up.

The EVE is a large-bore engine for ship application. Its cylinder bore is 200 mm and the cylinder volume is 8.796 liters. In this research the engine nominal compression ratio has been 15:1. All runs have been carried out at 900 rpm and the output power has been 25 kW.

The fuel injection system is common rail type. The injection nozzle tip has 9 holes and the diameter of each hole is 0.30 mm. Rail pressure, start of injection (SOI) and injection duration have been unchanged for every test point of this work. This has been chosen in order to focus the attention on the combustion process.

Table 2 - EVE engine specification

Displaced volume (cc)	8796
Stroke (mm)	280
Bore (mm)	200
Connecting Rod (mm)	610
Compression ratio	15:1
Number of valves	4
Engine speed (rpm)	900
Injection nozzle tip (# holes x mm)	9 x 0.30
Rail pressure (bar)	1400
SOI electric (CAD bTDC)	-10.5
Injection duration (ms)	1.80

TEST PROGRAM

In this section an accurate explanation of the test program is provided. All the valve lifts and the chosen strategy for this work are described below.

VALVE TIMING

Several tests are carried out in this work. Using the flexibility of the EVE gas exchange valve system, it is possible to run with very advanced valve profiles.

The starting point has been to define a reference point, whose results have been compared to the outcomes of the other runs. The valve profiles used as references have been quite similar to a standard configuration: the IVC is close to the BDC and the scavenging period is widely positive by 60 CAD.

Miller technique and dilution with hot exhaust gases has been performed further. Firstly extreme Miller rate has been used in the runs: it has been achieved by advancing the IVC up to 70 CAD. In Figure 2 the valve profiles are represented. One can see that the maximum intake valve lift is not achieved when very advanced IVC is set: this happens because the system is not able to reach the maximum set lift in the opening phase before the closing phase starts [15].

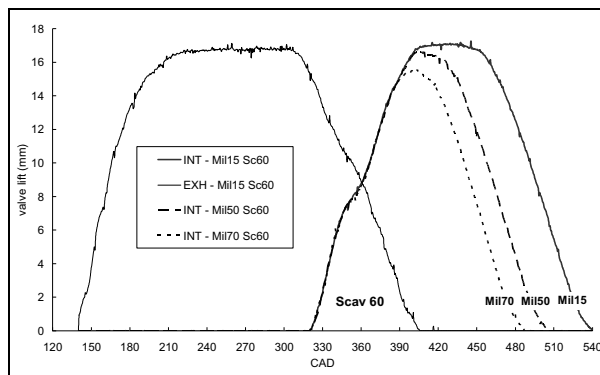


Figure 2 – Valve lift profiles, advanced IVC

Later, the exhaust gas residuals have been increased in the combustion chamber by reducing the scavenging period around the top dead center (TDC). Since the reduction of the scavenging period implies that the duration of the valve opening is reduced, it has been decided not to open the intake valve later than the top dead center (TDC). This avoids that the maximum valve lift becomes too low and very high charge air pressure is needed in order to achieve the desired in-cylinder pressure values. Hence, all the negative scavenging timings have been realized closing earlier the exhaust valve.

Figure 3 and 4 show the valve lift profiles with the two advanced IVC or Miller. In this paper Miller rate is defined as the IVC in crank angle degree (CAD) before the bottom dead center (BDC). With Miller 50 the maximum valve lift is 15 mm, just 2 mm less than the reference timing; lower value is achieved with the most advanced IVC (Miller 70), and the needed charge air pressure is higher.