

Investigation of Combustion and Emission Performance of Hydrogenated Vegetable Oil (HVO) Diesel

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ABSTRACT

Hydrogenated Vegetable Oil (HVO) diesel fuels have the potential to provide a reduced carbon footprint for diesel engines and reduce exhaust emissions. Therefore, it is a strong candidate for transport and diesel powered machines including electricity generators and other off-road machines. In this research, a waste cooking oil derived HVO diesel was investigated for its combustion and emission performance including ignition delays, size segregated particulate number emissions and gaseous emissions. The results were compared to the standard petroleum diesel. A EURO5 emission compliant three litre, direct injection, intercooled IVECO diesel engine equipped with EGR was used which has a maximum power output of 96kW. The engine was equipped with an integrated DOC and DPF aftertreatment system. Both the upstream and downstream of the aftertreatment emissions were measured. The tests were conducted at different RPM and loads at steady state conditions. A DMS500 particle size measurement instrument was used for measuring particles between 5 nm and 1000nm. The engine was instrumented with a number of thermocouples so that the engine conditions were closely monitored. Gaseous emissions were measured using a HORIBA 7100 series gas analyzer. The results showed that HVO reduced particulate numbers significantly at the upstream of the aftertreatment system. The particle number emissions were not much different between HVO and standard diesel at the downstream of the aftertreatment system due to the low particle number concentrations.

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INTRODUCTION

The wide application of modern diesel engines inevitably consumes the limited fossil derived diesel fuel and contributes to the air pollution. The research by Kavalov, B. and Peteves, S.D., [1] showed that the increasing automotive diesel consumption in the EU can lead to problems such as potential energy supply risk, higher diesel fuel costs and most importantly air quality issues. The exposure to diesel exhaust can cause asthmatic diseases and damage to the lung function [2]. Therefore, finding solutions to relieve the heavy reliance on petroleum diesel and reduce the pollutants' emissions can be necessary.

Hydrogenated vegetable oil (HVO) can either be derived from waste cooking oil or animal fats and thus can be deemed as renewable energy resources. In the process of refining HVO, oxygen is removed by the hydrogen added at the isomerization stage, leaving the HVO free of aromatics, which contributes to Polycyclic Aromatic Hydrocarbons (PAH) emissions [3,4]. A previous study by Sugiyama, K., et al, [5] showed that HVO with zero aromatics would produce lower hydrocarbon and PM emissions than petroleum diesel. Another researcher, E Zervas [6] reports on the PM emissions from aliphatic fuels compared to diesel, and there doesn't tend to be much difference at low loads indicating there is little difference between the total particle number and the distribution of the sizes. This is because the reduced sulphur content, such as in aliphatic fuels, should decrease

the particle number, since sulphur is key in the nucleation mode. Therefore, the control of the nucleation-mode must come from another source. Zervas [6] denotes this to carbon condensation.

For diesel engines, the most concerned emissions are NO_x and particulate emissions. The advantage of HVO fuel lies on its potential on particle and THC emissions. From the research of Bhardwaj, O.P., et al.in 2013 [7], the pure HVO can reduce up to 50% of particle emissions in comparison with fossil diesel. HVO also achieves the lowest soot accumulate rate on the diesel particle filter (DPF) when compared with the FAME fuel or diesel fuel. [8] However, studies of HVO's performance on NO_x doesn't show a very significant advantage in comparison with diesel. From Mizushima, N et al [9], NO_x emissions from HVO fuel are almost the same as diesel fuel. Millo, F et al, in 2013[10], also reported the similar level of NO_x for the blended HVO B30 fuel with diesel fuel. The results showed a similar outcome: the HVO B30 fuel reduces the CO and HC emissions significantly, but the NO_x emission was nearly the same.

This paper presents the particulate and gaseous emissions from a HVO diesel fuel derived from waste cooling oil. The combustion performance (ignition delay and engine power) was also investigated. The results were compared to standard diesel fuel. The efficiency of diesel particle filter (DPF) on particle removal was determined.

EXPERIMENTAL

Test Engine and Control System

An IVECO 3.0 L direct injection diesel engine compliant with Euro 5 emission legislation and fitted with a turbocharger and an intercooler and EGR system was used, [Table 1](#) shows the specifications of the engine.

Table 1. Specifications of the test engine.

Parameters	Values
Engine type	Diesel 4 stroke
Total displacement; liter	3
Number of cylinder	4 in line
Injection type	Direct & High pressure common rail
Injection pressure; bar	1600
Injection sequence	1-3-4-2
Bore; mm	88
Stroke; mm	94
Maximum power;	96 kW@3100-3500rpm
Maximum torque;	300 Nm@1300-3100rpm
Aftertreatment system	DOC+DPF (closed wall-flow type filter)
EGR	Yes

The engine is connected to a 100kW AC dynamometer. The engine and dynamometer were controlled via a software system -DSG system, which is used to control the engine rpm and engine throttle position, and to monitor and log the experiment data, including engine rpm, engine torque, engine emissions, and temperatures at specific locations of the engine.

In-Cylinder Pressure and Crank Angle Measurement

An AVL in-cylinder pressure transducer and crank angle measurement system was installed to the engine to acquire the pressure data from one of the cylinders. It consists of the pressure transducer, AVL amplifier, and AVL software. The pressure transducer is connected to one combustion cylinder of the engine on one side, and inputs the signals to the amplifier. The AVL amplifier receives two types of signals from the experiment engine: one is the pressure signal from the cylinder; the other is the crank angle signal from the crank angle encoder. Thus, the AVL acquires the data both in combustion cylinder pressure and crank angle degree. During the measurement, the amplifier receives signals from the engine and

passes them to the AVL Indicom software via one Ethernet cable connected between the amplifier and computer. The software will normally record 100 combustion cycles' data.

AVL system provides the combustion PV (Pressure-Volume) diagram, combustion P-crank angle diagram, ignition delay, and heat release.

Fuels

The standard Ultra Low Sulphur Diesel (ULSD) complying with EN590 and HVO diesel (Neste Renewable Diesel) supplied by NESTE which meets EN 15940:2016 for paraffinic diesel fuels were used for testing. Some selected properties for both fuels are shown in [table 2](#).

Table 2. Selected fuel properties

Property	Ultra Low Sulphur Diesel	HVO
Kinematic viscosity at 40°C; mm ² /s	~2.7	2.8
Density at 15°C; kg/m ³	~0.84	0.78
Cetane number	>51	78.8
NCV; MJ/kg	44	44
Sulphur; mg/kg	<10	<1
Water; mg/kg	<100	34
Flash point; °C	66	84
Cloud point; °C		-31
Aromatics; wt%		0.3
Hydrogen; wt%		15.2

Emissions Measurement

The Horiba MEXA 7100 gas analyzers were used to measure the concentration of CO, CO₂, O₂, THC, NO, NOx and air to fuel ratio. It was controlled by the DSG system during the experiment, and the data was logged by the DSG system.

DMS 500 was used to measure the particle size distribution of the engine exhaust gas. It was controlled by an independent computer and logged its' own data with that computer during the experiment.

No DPF regeneration event was observed during the measurements.

The Whole System Set Up and Test Conditions

[Figure 1](#) shows the whole system set up for the engine, dynamometer, and measurements systems.

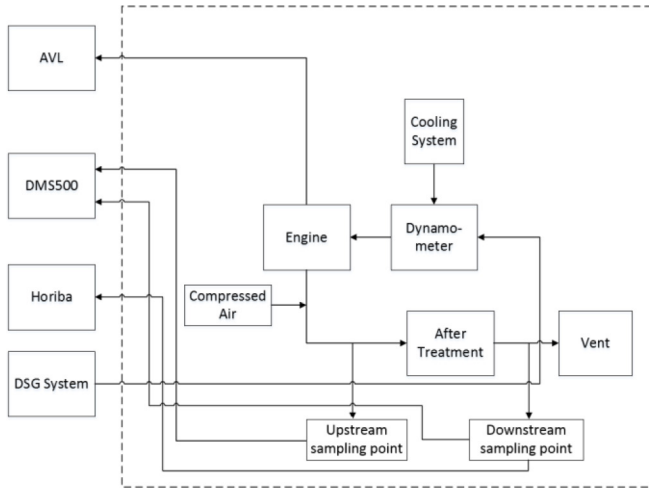


Figure 1. Schematic view of engine and testing system set up

The Horiba MEXA 7100 and DMS 500 were connected to both the upstream and downstream of the engine exhaust aftertreatment system. To optimize the accuracy of experiment data, the engine was tested at 9 selected stable condition stages. The selected engine working condition was based on bench marking experiment and is shown in the table 3 below. The diesel fuel experiments were taken first as the baseline. Then the engine was purged with pure HVO fuel before the HVO fuel tests. Approximately 10 litres of HVO fuel was used to purge the fuel system.

Table 3. Engine rpm, throttle position and power parameters

Stage of experiment	Engine rpm	Throttle position (%)	Engine power (kW)	Exhaust temperature - Post DPF (°C)
1	1000	30	6	176
2	1000	40	14	265
3	1000	50	17	353
4	1600	40	7	377
5	1600	50	17	344
6	1600	60	29	391
7	1900	50	15	398
8	1900	60	25	391
9	1900	70	39	413

RESULTS AND DISCUSSIONS

Comparison of Particle Size Distribution between Diesel and HVO at the Downstream of DPF

Both HVO fuel and diesel fuel were measured for their particle size distribution from the upstream and downstream of the engine exhaust aftertreatment system using DMS 500. The instrument measuring frequency was set to 2 Hz, and for each engine working condition,

the data logging time was 5 minutes. The average readings were taken and reported. Error bars (one standard deviation) were calculated and found to be in a range of 1×10^3 to 2×10^4 p/cm³.

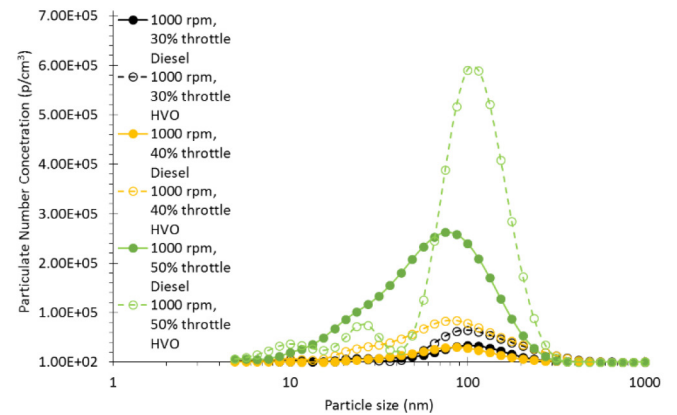


Figure 2. Particle size distribution from downstream of the aftertreatment system at 1000 rpm engine working condition.

Figure 2 shows the particle size distribution from downstream of the aftertreatment system (DPF) at the 1000 rpm engine working condition. The particles generated from HVO fuel and diesel fuel were very close at 30% and 40% throttle positions. However, the HVO fuel produced more large particles (~ 100 nm) and less nano particles (10 nm) when the throttle increased to 50%. The nano particles are known to pose more hazards to human health since they can penetrate and deposit to the lungs and alveolar membrane.

When the engine rpm increased to 1600 and 1900, from Figure 3 and Figure 4, it can be found that the particle size distribution and number concentrations from HVO fuel and diesel fuel are very similar. All of them were close to the detection limit of the instrument ($10^{-3} \sim 10^{-4}$ p/cm³). Despite the diesel fuel showing a slightly lower PN emission at 1600 rpm, 40% throttle engine condition, the PN performance from the two types of fuels was nearly the same at the 1900 rpm engine working condition.

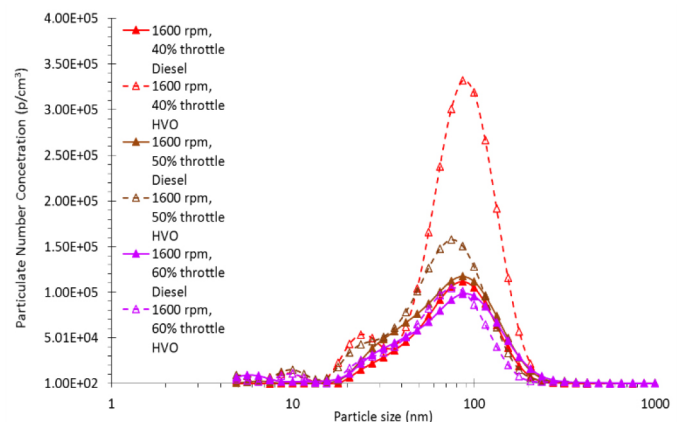


Figure 3. Particle size distribution from downstream of the aftertreatment system at 1600 rpm engine working condition