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Particulate number and NO_x trade-off comparisons between HVO and mineral diesel in HD applications

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ABSTRACT

The increase in worldwide greenhouse gas emissions and costs for fossil fuels are forcing fuel suppliers and engine manufacturers to consider more sustainable alternatives for powering internal combustion engines. One very promising equivalent to mineral diesel fuel is hydrotreated vegetable oil (HVO) as it is highly paraffinic and offers similar combustion characteristics. This fuel offer the potential of not requiring further engine hardware modification together with correspondingly lower exhaust gas emissions and better fuel consumption than mineral diesel.

In this paper the spray and combustion characteristics of HVO and its blends are investigated and compared with mineral diesel (European standard). Evidence of the reported reductions in NO_x emissions has proven contradictory with some researchers reporting large reductions, whilst others measured no differences.

This paper reports the results from comparison of three different experimental tests methods using diesel/HVO binary fuel blends. The macroscopic spray characteristics have been investigated and quantified using a constant volume spray vessel. Engine performance and exhaust emissions have also been characterised using a HD diesel engine in its original configuration (mineral diesel fuel-ready) and then in a recalibrated configuration optimised for HVO fuel.

The results show that the engine injection control and also the fuel quality can influence the formation of NO_x and particulate matter significantly. In-particular a potential pilot injection proved highly influential upon whether NO_x emissions were reduced or not. When optimising the fuel injection, a reduction in NO_x emissions of up to 18% or reductions of PN of up to 42–66% were achieved with simultaneous savings in fuel consumption of 4.3%.

1. Introduction

Hydrotreated vegetable oil (HVO) is a highly paraffinic diesel-like biofuel, with the chemical structure $C_n H_{2n+2}$, processed from vegetable oil by adding hydrogen in a catalytic reaction. Hydrotreated fuels are also called "renewable diesel fuels" and the term biodiesel is usually avoided since this is more conventionally used for fatty acid methyl esters (FAME) produced by transesterfication [1]. HVOs are mixtures of paraffinic hydrocarbons without sulphur or aromatic contents. They are characterised by a higher cetane number (CN) and lower density than conventional mineral diesel. It has been reported that no engine modification or additional service of the engine is necessary and up to 30% of HVO can be added into European diesel fuel (EN590), and even more into American diesel fuel (ASTM D975) to still meet legislative fuel standards. Even pure HVO fuel is already being utilised for public transport, such as city buses [1]. In California, Sweden and Finland it is commercially available for other users also.

As shown in Fig. 1, in the first step, the triglyceride is hydrogenated and broken down into mono-glycerides, di-glycerides and carboxylic acids. These intermediates are then formed into *n*- and *iso*-alkanes by either hydrogenation (with no carbon removal) or decarboxylation and decarbonylation (both removing a carbon from the initial intermediate) [2]. The by-products are water, carbon monoxide, carbon dioxide as well as naphtha, which is a group of liquid hydrocarbons which could be used for heating and energy requirements. The CO and CO_2 can react further to produce methane, another useful by-product. In the presence of a zeolite catalyst [3], reaction temperatures and pressures are between 300 and 360 °C and 50–180 bar pressure, respectively. The composition of the products to their desired state is dependent on the above reaction temperatures.

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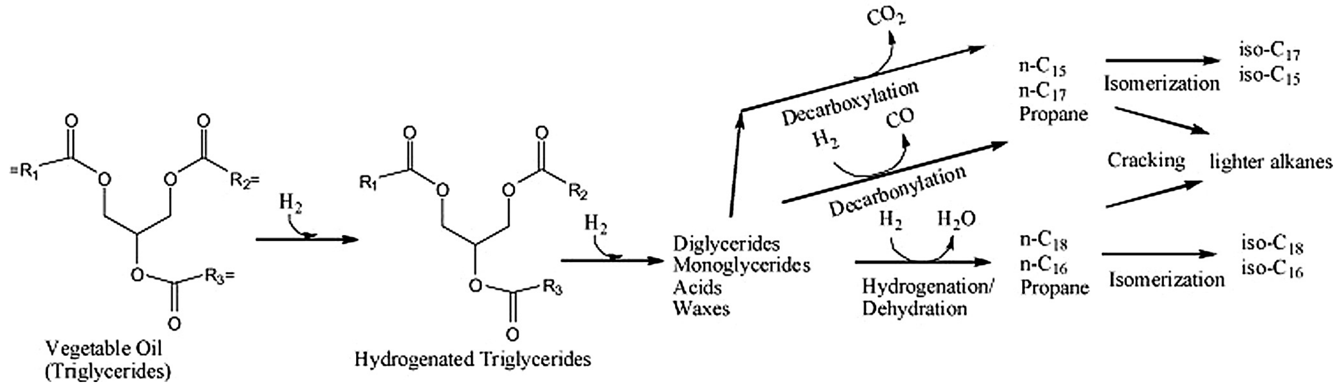

Fig. 1. Production process of hydrotreated vegetable oil (HVO) [2].

The first commercial scale HVO plant with a 170,000 ton/year capacity was built in the summer 2007 at Neste Oil's Porvoo oil refinery in Finland [1]. Two years later, Neste started a second plant with the same capacity. In 2010 and 2011 two large scale plants in Rotterdam and Singapore with an annual capacity of 800,000 ton were commissioned. Currently HVO plants are mainly integrated into oil refinery plants, but companies have started developing larger stand-alone units around the world for large-scale production [4]. The costs of producing HVO are in some studies is stipulated to be about 50% the transesterfication processing costs [5]. Kalnes, et al. however, stated that the overall economics will depend on feedstock costs and by-product revenues [6]. Sunde, et al. reported in their studies that HVO made from waste or by-products outperforms FAMEs (fatty acid methyl ester) and BtL (biomass-to-liquid) in respect to costs and environmental life cycle impacts [5]. However, feedstock availability and logistics are currently limiting factors and other raw materials must be used. HVO has lower viscosities, lower cloud points and therefore better storage and cold flow properties than FAMEs. Also the relatively high heating value and CN makes HVO a very high-quality fuel for potential utilisation in the transportation sector. Compared to conventional biodiesel the natural lubricity of HVO is poorer and additives have to be used to increase lubrication properties [7].

Some researchers have tested HVO on different engines to gain an understanding of its combustion and exhaust formation behaviour. Kuronen et al. tested neat HVO on two heavy duty engines and two city buses and compared the results with EN 590 diesel fuel [8]. For HVO, the particulate mass (PM) was reduced between 28 and 46%, NO_x was reduced by 7–14% and THC and CO emissions decreased by 0–48% and 5–78%, respectively. In a later study, they used a 6 cylinder 8.4 litre DI engine at several speeds and loads and carried out an injection timing sweep [1]. They found that by retarding the injection, the smoke- NO_x trade-off shifts towards higher smoke numbers and lower NO_x values. Also, retarding the injection resulted in higher bsfc (brake specific fuel consumption), but much lower NO_x emissions. They concluded that a clear reduction in NO_x and smoke emissions as well as fuel consumption (mass-based), but higher volumetric fuel consumption was due to the lower fuel density. Pflaum, et al. investigated emission formation of neat HVO and mineral diesel in a CI 2 litre four cylinder test engine and on a chassis dynamometer test [9]. Their results revealed that HVO has the potential to reduce PM, THC and CO emissions up to 50% as it is free of aromatic compounds. The NO_x emissions, however, only showed a slight reduction compared to fossil diesel. Rantanen et al. tested several HVO blends (5, 15, 20 and 85 vol%) and compared them with conventional diesel [10]. They pointed out that both regulated and non-regulated emissions decreased with increasing HVO ratios. However, a clear reduction of NO_x was not observed. Similar results have been found by Kim et al. testing HVO and *iso*-HVO in a light duty diesel engine and no significant differences in NO_x are observed when HVO blend ratio was increased [11]. A study has been carried out by Toyota investigating the effect of single and multi-injection with HVO and EN590 diesel and they found out that with a single injection NO_x emissions are reduced up to about 10% with HVO, while with a pilot injection no significant reductions are found [12]. The conclusion was that with a pilot injection, the start of the main fuel ignition is very similar with HVO and mineral diesel and the heat release curves were identical.

Very few papers related to spray characteristics have been published. Hulkkonen et al. compared the macroscopic spray characteristics of HVO and mineral diesel [13]. An injector with two different nozzle diameters of 0.08 and 0.12 mm in a common rail fuel system with rail pressures of 450, 1000 and 1980 bar were used. They concluded that neither the type of fuel, nor the orifice diameter had an effect on the spray penetration. They further found out that the cone angle of HVO is greater than that of diesel, probably due to lower viscosity of HVO. The spray angle also increased with a larger orifice diameter, but diminished with higher injection pressures. Finally they concluded that the macroscopic spray characteristics of HVO are similar to GtL (gas-to-liquid). The effect of pure HVO on macroscopic spray parameters in a DI engine were studied by Sugiyama et al. [12]. Their results revealed that the Sauter mean diameter, spray penetration and spray angle were similar for conventional diesel and HVO. Chen et al. investigated the microscopic and macroscopic spray behaviour of HVO and other biofuels and concluded that HVO has a much smaller SMD than diesel and that the effect of injection pressure on spray angle was not obvious for all tested fuels [14]. Overall, the amount of research conducted on HVO is small despite HVO being a very promising future fuel. In reviewing the literature, it was concluded that the results of HVO, such as exhaust emission and spray characteristics are heavily dependent on the B0 benchmark fuel and the injection conditions used in the study. Whilst almost all studies the properties of the benchmark fuel were all within the EN590 limits, the differences in viscosity, CN and aromatics content all varied significantly and thus affected the results accordingly. In this work, the macroscopic spray characteristics, engine test bench performance and injection recalibration has been carried out with neat HVO and its blends benchmarked with the same reference fuel. The B0 fuel for blending and referencing was supplied by a well-known fuel supplier specially used for referencing purposes. The novelty of this study is the holistic investigation of spray and combustion analysis for a heavy-duty application using HVO and its blends.

2. Experimental setup and procedure

2.1. Constant volume vessel

A medium pressure, high temperature combustion vessel was used to investigate the spray and combustion characteristics using a high-speed direct photography technique. The vessel is made of Inconel alloy and is resistant against corrosion and oxidation and suited for extreme