Fuel 216 (2018) 890–897

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Performance and emissions of long-chain alcohols as drop-in fuels for heavy duty compression ignition engines

Josefine Preuß*, Karin Munch, Ingemar Denbratt

Chalmers University of Technology, Gothenburg, Sweden

ARTICLE INFO

Keywords:
n-Octanol and 2-ethylhexanol
n-Decanol and 2-propylheptanol
Hydrotreated vegetable oil and rapeseed methyl ester
Drop-in fuel
Diesel engine combustion and emissions
Particle size and mass analysis

ABSTRACT

The experimental research reported in this paper evaluates the potential of blends consisting of different biomass derived alcohols and vegetable oils as possible drop-in components in fossil Diesel fuel to overcome the need for modifications in engine hardware or calibration settings. Two C_8-alcohols (*n*-octanol and its isomer 2-ethylhexanol) and two C_{10}-alcohols (*n*-decanol and its isomer 2-propylheptanol) were blended with hydrotreated vegetable oil (HVO), rapeseed methyl ester (RME) and fossil Diesel. The blends were prepared to mimic the properties of standard Diesel fuel, in particular the cetane number was held constant. The percentage of fossil Diesel in the blends was 0%, 10% or 20%. The impact of the fuel composition on performance and emissions in a Volvo D13 single cylinder heavy duty research engine operated with standard engine settings was analyzed.

Experiments revealed that the engine performance with the different blend compositions resembled that with standard Diesel with regard to the indicated thermal efficiency. Owing to the lower heating value of the fuel blends, the specific fuel consumption of the blends was about 6% higher than that of Diesel. Emissions were found to be similar among all alcohol-HVO blends. Compared to Diesel emissions, a reduction of carbon monoxide was measured for the blends. The yields of HC and NOx did not vary significantly for the different fuel blends. Soot emissions were substantially lower compared to those obtained with neat Diesel fuel. The lowest soot emissions were achieved with the fully renewable fuel composition, which did not contain any aromatic structures. Evaluation of the particle size distribution showed that the number of particles in agglomeration mode was substantially higher for standard Diesel fuel than for the blends. Alcohol-HVO-blends particle sizes were mainly in the nucleation mode range. Overall, the obtained results indicate that blends mainly containing long-chain alcohols could be a potential replacement for fossil Diesel fuel.

1. Introduction

Counteracting global warming caused by increased greenhouse gas emissions is one of the world's greatest challenges. The transport sector contributes 23% to the global emissions and road traffic accounts for two thirds of this [1]. The introduction of increasingly strict emission legislation has prompted research into alternative solutions to secure future energy supplies.

Fuels from biomass are considered part of the solution to secure a fossil free energy supply in the future while also helping to fulfill more stringent regulations on exhaust gas emissions. In 2020, 10% of the transport fuels in the European Union should be from a renewable origin [2]. Fueling a car with a compression ignition engine with 100% biodiesel (B100), HVO or 95% ethanol with ignition improver (ED95) has been successfully applied for selected trucks and busses. Standard Diesel fuel accounts a share of renewable fatty acid methylesters (FAME) of maximal 7% (EU Fuel Quality Directive). Diesel engines provide an efficient combustion technology. Unfortunately, high nitrogen oxide (NOx) emissions and soot are emitted due to the diffusion controlled combustion. Previous research on fuels based on alcohol as well as vegetable oils has shown that they can be used to reduce soot, carbon monoxide (CO) and unburned hydrocarbon (HC) emissions in Diesel engines. However, a disadvantage is the need for engine modifications [3–5].

Moreover the availability of the feedstock is of great concern. First generation biofuels compete with food production. Therefore, second generation biofuels, for instance, bioethanol from lignocellulose, are more favored. Further requirements for biofuels are the production efficiency regarding mainly costs and climate impact, land and infrastructure use, distribution and storage as well as health and safety

Abbreviations: COV, coefficient of variation; D, Diesel; Dec, *n*-decanol; EH, 2-ethylhexanol; HVO, hydrotreated vegetable oil; IMEP, indicated mean effective pressure; LHV, lower heating value; Oc, *n*-octanol; PH, 2-propylheptanol; RoHR, rate of heat release; RME, rapeseed methyl ester

* Corresponding author.
E-mail address: josefine.preuss@chalmers.se (J. Preuß).

https://doi.org/10.1016/j.fuel.2017.11.122
Received 16 June 2017; Received in revised form 28 September 2017; Accepted 28 November 2017
0016-2361/

Table 1
Fuel properties [6–10].

	Unit	Diesel	*n*-octanol	2-ethyl-hexanol	2-propyl-heptanol	*n*-decanol	HVO	RME
Abbreviation		D	Oc	EH	PH	Dec	HVO	R
Formula			$C_8H_{18}O$	$C_8H_{18}O$	$C_{10}H_{22}O$	$C_{10}H_{22}O$	$C_{13,3}H_{28,5}$	$C_{21}H_{38}O_2$
Density	kg/m^3	830	827	832	832	829	779.9	888.3
Cetane number (CN)	–	52	34	23.2	33.3	48.2	87.80	53.4
Aromatic content	vol.%	5.2	–	–	–	–	–	–
Flash point	°C	74	80	75	100	82	94	154
Lower heating value (LHV)	MJ/kg	42.9	38.4	38.4[1]	38.9[2]	38.9	44.1	37.3
Oxygen content (Ox)	%	–	12.3	12.3	10.3	10.3	–	10
Boiling point	°C	180–350	195	184	218	221.5	< 330	317–346
Viscosity Kin. (40 °C)	mm^2/s	3.0	5.5	5.2	17.7 (20 °C)	8.5	2–4	4.5
Vapor pressure (25 °C)	mbar	< 1.2	0.19	~0.266	0.21	0.011	0.087	NA
Latent heat of evaporation	kJ/kg	250	545	389	NA	310	NA	NA

[1] Value taken from *n*-octanol.
[2] Value taken from *n*-decanol.

regulations. Alternative fuel solutions from different renewable origins and fuel mixtures are gaining increasing attention [6,11,12].

To fulfill the conditions of sustainable production and suitability for standard engine settings, fuels in the present work were selected based on the producibility from renewable material as well as the physical properties compared to standard Diesel. The main criteria were the cetane number (CN), lower heating value, density, boiling point and oxygen content. Table 1 lists the neat components and most relevant properties.

The C_8- and C_{10}-alcohols have Diesel-like densities and boiling points lying within the range of those for Diesel. The CN was lower for the alcohol blends than for Diesel. Compared to shorter chain alcohols like methanol and ethanol, longer chain alcohols have the advantage of a higher CN. Moreover, the lower heating value (LHV) is higher in comparison to the LHV of the commercially available fuel component ethanol (26.8 MJ/kg) [4]. The energy output per kilogram fuel increases with increasing chain length. However, with longer chain length, the molar percentage of oxygen decreases. Several researchers have shown that adding alcohols to standard Diesel fuel can help to reduce NOx and soot emissions. The reduction in soot emissions can partly be attributed to the higher oxygen content in the fuel [4,6,13–16]. The kinematic viscosity of all four alcohols is elevated compared to Diesel, which can cause difficulties within the fuel injection and spray formation.

In this paper, only fuels that can be generated from renewable resources were selected for study. It is possible to produce *n*-octanol and *n*-decanol either in a metabolic reaction with E. coli or by biochemical conversion from platform chemicals. For *n*-octanol, a lab-scale production process is available [17–19]. The respective isomers 2-ethylhexanol and 2-propylheptanol can be obtained from sustainably produced ethanol from cellulosic biomass [20].

HVO is an aliphatic paraffinic hydrocarbon. It contains no aromatic structures and is free of sulfur. Properties of HVO resemble those of standard Diesel except HVO has a lower density and the CN is higher than for Diesel. HVO used in Sweden is mainly produced from oil from vegetable or animal wastes or raw tall oil. Worldwide, it is commonly produced from soy bean oil [21]. In a hydro treatment process, vegetable oils are converted to HVO. The CN as well as cold start properties vary with the manufacturing process and can be adjusted [10]. Previous studies have shown a decrease in specific fuel consumption when the share of HVO reaches 30% in a Diesel blend. With neat HVO, a considerable reduction of HC, CO and particulate emissions can be achieved in heavy duty engines [5,7]. The main restriction against using HVO is its low lubricity. Therefore, previous studies have suggested a maximum share of 50% HVO in the blend [22].

RME consists of saturated and unsaturated fatty acids and can be produced by extraction of the oil from rapeseeds, followed by a refining and transesterification reaction. RME is available in today's infrastructure, reduces well-to-wheel CO_2 emissions and promises a decrease in CO, HC and particulates whilst maintaining Diesel-like properties, apart from the density. NOx emissions vary with engine design and manufacturer [23–25]. All components used had a flash temperature above 74 °C under atmospheric conditions, which is beneficial for transport and storage. Moreover, all components were immiscible with water and had low susceptibility to microbial growth. Therefore, they were expected to be stable during long term storage.

Several researchers have investigated blends with Diesel and longer chain alcohols like butanol or pentanol [12,26,27]. However, there have been only a limited number of publications on *n*-octanol or alcohols with longer chain lengths. Heuser et al. (2014) have tested *n*-octanol as a neat component in a single cylinder research engine. HC- and CO-emissions were increased compared to Diesel, but particulate emissions were decreased significantly, maintaining a constant NOx level [28,29]. Zhang et al. (2015) have evaluated the performance of 30% 2-ethylhexanol blended with Diesel. Use of this blend resulted in a decrease in particulate emissions and CO but a slight increase in HC at higher loads, maintaining a constant NOx level [6]. Both the latter studies highlight the potential of the C8-alcohols to reduce engine out emissions while retaining engine performance.

Research conducted on alternative fuels has mainly focused on engine performance parameters, including thermal efficiency, cylinder pressure and heat release. Emissions evaluation usually concentrates on NOx, HC, CO and particulate mass. As a response to more stringent emissions legislation, the Euro VI standard for heavy duty Diesel engines has introduced limitations not only for the particle mass but also for the particle number. Particulates cause adverse health effects and contribute especially in urban areas to air pollution.

With the use of renewable fuel alternatives, the nature (e.g., size, form, composition) of the emitted particles has also changed. Procedures for capturing particles are usually based on the Particle Measurement Programme (PMP), which establishes standard particle size distribution measurement and analysis methods. A particle size of 23 nm was set as the cut-off size for the particle number counter, mainly due to restrictions in measurement technology. Particles are normally divided into modes according to their diameter. Nucleation mode particles are formed by the nucleation of volatile particles and have a size range of 3–30 nm. Particles above this range are referred to as agglomerated particles. Particles in the nucleation mode cover 0.1–10% of the particle mass. The rest are represented by particles in the agglomeration mode [30–35]. There has been only a limited amount of research published on the particle size distribution of alternative fuels.

In this paper, the engine performance and emissions, including the particle size distribution of several renewable alcohol based blends in a heavy duty Diesel engine will be evaluated. Fuel blends were designed to overcome their individual drawbacks and to generate a fuel with Diesel-like properties. The content of renewables accounted for the