Fuel 140 (2015) 541–554

Contents lists available at ScienceDirect

Fuel

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

Investigation of the effects of renewable diesel fuels on engine performance, combustion, and emissions

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HIGHLIGHTS

- Renewable diesel fuels were tested in compression-ignition engines.
- Renewable diesel fuels are non-oxygenated hydrocarbon fuels.
- Lower fuel consumption and combustion pressure are observed for renewable diesel.
- Lower soot and NO_x emissions are obtained for renewable diesel.

ARTICLE INFO

Article history:
Received 12 July 2014
Received in revised form 19 September 2014
Accepted 20 September 2014
Available online 11 October 2014

Keywords:
Biofuels
Renewable diesel
Diesel engines
Combustion
Emissions

ABSTRACT

A study was undertaken to investigate renewable fuels in a compression-ignition internal combustion engine. The focus of this study was the effect of newly developed renewable fuels on engine performance, combustion, and emissions. Eight fuels were investigated, and they include diesel, jet fuel, a traditional biodiesel (fatty acid methyl ester: FAME), and five next generation biofuels. These five fuels were derived using a two-step process: hydrolysis of the oil into fatty acids (if necessary) and then a thermo-catalytic process to remove the oxygen via a decarboxylation reaction. The fuels included a fed batch deoxygenation of canola derived fatty acids (DCFA), a fed batch deoxygenation of canola derived fatty acids with varying amounts of H_2 used during the deoxygenation process (DCFAH), a continuous deoxygenation of canola derived fatty acids (CDCFA), fed batch deoxygenation of lauric acid (DLA), and a third reaction to isomerize the products of the deoxygenated canola derived fatty acid alkanes (IPCF). Diesel, jet fuel, and biodiesel (FAME) have been used as benchmarks for comparing with the newer renewable fuels. The results of the experiments show slightly lower mechanical efficiency but better brake specific fuel consumption for the new renewable fuels. Results from combustion show shorter ignition delays for most of the renewable (deoxygenated) fuels with the exception of fed batch deoxygenation of lauric acid. Combustion results also show lower peak in-cylinder pressures, reduced rate of increase in cylinder pressure, and lower heat release rates for the renewable fuels. Emission results show an increase in hydrocarbon emissions for renewable deoxygenated fuels, but a general decrease in all other emissions including NO_x, greenhouse gases, and soot. Results also demonstrate that isomers of the alkanes resulting from the deoxygenation of the canola derived fatty acids could be a potential replacement to conventional fossil diesel and biodiesel based on the experiments in this work.

1. Introduction

The rising cost as a result of depleting fossil reserves as well as problems relating to greenhouse gas emissions have been the most important drivers for seeking out new sources of energy [1]. Stringent emissions standards such as the newly proposed tier 3 standards by the Environmental Protection Agency (EPA) indicate that fuels that burn cleaner and have lower sulfur content will be favored [2]. A variety of alternative sources of energy, ranging from wind, solar, nuclear, etc., already exist but several challenges such as capital, portability, inefficiency, storage, and further environmental degradation make these sources of energy inadequate and in some cases non-viable.

For internal combustion (IC) engines, liquid biofuels have emerged as viable alternatives to fossil fuels. Biofuels are fuels

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http://dx.doi.org/10.1016/j.fuel.2014.09.061
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typically made from renewable sources such as animal feedstock, plants, and biomass. Biofuel production and consumption has increased in recent years partly as a result of government support in the form of tax credits, mostly because they have been found to effectively supplement current fossil fuels [3]. Biodiesel is a type of biofuel made from the trans-esterification process and involves reaction of a feed stock, usually oil or fatty acids from oil, with an alcohol in the presence of a catalyst [4]. The end product of the trans-esterification process is a fatty acid methyl ester (FAME), also called biodiesel. Biodiesel has several benefits over conventional fossil diesel; it is renewable, non-toxic, has greater lubricity, generally lower emissions and most of all has similar properties to convention fossil diesel [5].

Many studies have investigated the influence of biodiesel on engine performance, combustion and emissions [6–16]. From these studies, fuel physical and chemical properties play a significant role in the results obtained. Biodiesel has a higher cetane number when compared to diesel and as such it has a shorter ignition delay [17,18]. Other properties such as fuel penetration, atomization and droplet size are also important for the combustion of the fuel and ultimately its emissions [19]. The general consensus is that biodiesel results in a slight increase in brake specific fuel consumption and higher brake thermal efficiency than diesel [6,7]. Biodiesel generally produces lower hydrocarbon and carbon monoxide emissions; however, NO_x emissions are typically higher than diesel [6,7,12,13]. Biodiesel has some disadvantages such as higher production cost, restriction on feedstock use, lower energy density (due to oxygen content), higher viscosity, stability, and higher freezing point amongst others [4,5]. An attempt to resolve some of the disadvantages of biodiesel, with cost and chemical composition as the main focus, has led to the production of renewable diesel fuels.

Renewable diesel is a non-oxygenated fuel produced from a thermo-catalytic process that involves the conversion of feed stock or fatty acids into straight chain n-alkanes through deoxygenation [20]. These straight chain alkanes can then be further processed to meet specification standards of the desired fossil fuel. The production process of renewable diesel production is flexible enough to allow for the production of a wide variety of hydrocarbon fuels that can meet most fossil fuel standards.

In this work, renewable diesel is made from the deoxygenation of triglycerides or fatty acids [20–25]. The production process typically occurs in a reactor under high temperature and high pressure in the presence of a catalyst. Hydrolysis is the first step of the process and involves splitting the fatty acids in the oil from the glycerol backbone by heating the oil under high pressure in the presence of water [20]. Upon separation from water, the fatty acids then undergo deoxygenation via a thermo-catalytic process by which oxygen is removed from fatty acids. There are several pathways involved in this process depending on how oxygen is removed. The decarboxylation pathway removes oxygen as carbon dioxide while the decarbonylation pathway involves the removal of oxygen as carbon monoxide. The preference is usually for the decarboxylation pathway as carbon dioxide is less harmful to man and to the catalyst used. Depending upon the degree of saturation of the fatty acid, and the mole fraction of hydrogen in the gas phase, the final product from this deoxygenation process is a straight chain n-alkane, with one less carbon than the corresponding fatty acid. This alkane may then be reformed into an isomer via hydroreforming or an aromatic via dehydrocyclization depending on the desired characteristics of the final fuel (e.g., cloud point, freeze point, flash point, octane or Cetane rating, etc.). The absence of double bonds and oxygen are some of the advantages of renewable diesel over conventional biodiesel as it allows for an increase in the energy content of the fuel. Other advantages are lower viscosity, absence of sulfur (which reduces the efficiency of exhaust catalyst), and ease of customization, *i.e.*, renewable diesel can easily be tailored to meet other fuel requirements etc. Based on estimated cetane number values, it is expected that most of the renewable fuels may have higher cetane numbers than either diesel or biodiesel [26].

The objective of this work is to determine how these newly developed renewable fuels perform compared to fossil fuels (diesel and jet fuels) in a compression-ignition engine. The experiments focus on engine performance, combustion and emissions, and also serve to compare a first generation biofuels (biodiesel, *i.e.*, fatty acid methyl ester) with the second generation renewable fuels.

2. Experimental setup

The experiments were conducted in a 10 horse power (hp) single cylinder air-cooled compression-ignition engine with a bore of 86 mm, a stroke of 72 mm, a displacement of 418 cc, and a compression ratio of 19:1. The engine was coupled to a Go-Power water brake dynamometer. The engine specifications are listed in Table 1 and the schematic of the experimental setup is given in Fig. 1. In-cylinder combustion pressure was measured using a Kistler 6052A pressure sensor; a Hall effect sensor and a Hengstler 0521097 shaft encoder were used in combination to determine the engine's top dead center (TDC) position as well as the engine crank angles. A M5100 series pressure transducer was used to measure dynamometer load. Air mass flow rate into the engine was measured with a Bosch air mass flow sensor. Fuel mass flow rate into the engine was obtained by measuring the mass of the fuel during engine operation with an OHAUS GT2100 Scale. Atmospheric pressure was measured using a SSI tech pressure transducer with intake and exhaust temperature measured with *K*-type thermocouples. The voltages from each sensor were sampled by a NI PCI-MIO-16E-4 data acquisition board before data collation by a custom Labview program. Further analysis of data was done using Matlab and Microsoft Excel. Gaseous emissions were measured with an Infrared Industries FGA 4000XDS gas analyzer. Smoke opacity measurement was taken at the end of the exhaust tail pipe with a Wager 6500 full flow smoke meter. The exhaust tail pipe ends with a T junction to allow for an increase in the light path length of the smoke meter, allowing the measurement of low smoke conditions under low load conditions. Two glass panels were placed on either end of the T junction to prevent exhaust gas from been deposited on both the transmitter and receiver ends of the smoke meter sensor. The glass panels were cleaned and the smoke meter was background corrected before any data collection occurs. A schematic of the smoke meter setup is shown in Fig. 2. Sensor specifications and accuracy are given in Tables 2–4.

Eight different fuels were used during the course of the experiments. Five of the fuels were renewable diesel fuels derived from

Table 1
Engine specifications.

Type of engine	Single cylinder, vertical, direct injection 4 stroke
Compression ratio	19:1
Bore × stroke	86 mm × 72 mm
Method of loading	Water brake dynamometer
Method of starting	Electric start
Method of cooling	Air cooled
Type of ignition	Compression ignition
Rated power	7.46 kW
Rated speed	3600 rpm
Initial injection	17.0 Crank angle degrees before TDC
Displacement	418 cc
Fuel consumption at rated power	340 g/kW h