Fuel 96 (2012) 524–534

Contents lists available at SciVerse ScienceDirect

Fuel

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

Heat release analysis of combustion in heavy-duty turbocharged diesel engine operating on blends of diesel fuel with cottonseed or sunflower oils and their bio-diesel

D.C. Rakopoulos *

Internal Combustion Engines Laboratory, Department of Thermal Engineering, School of Mechanical Engineering, National Technical University of Athens, Zografou Campus, 9 Heroon Polytechniou St., 15780 Athens, Greece

A R T I C L E I N F O

Article history:
Received 6 November 2011
Received in revised form 17 December 2011
Accepted 29 December 2011
Available online 14 January 2012

Keywords:
Heavy-duty DI diesel
Turbocharged
Vegetable oil
Bio-diesel
Emissions

A B S T R A C T

The present work evaluates the effects of using blends of diesel fuel with cottonseed or sunflower oils and their (methyl ester) bio-diesel in proportions of 10% and 20% (by vol.), on the combustion and emissions behavior of a fully instrumented, six-cylinder, turbocharged and after-cooled, heavy-duty, direct injection (DI), 'Mercedes-Benz' diesel engine. Combustion chamber and fuel injection pressure diagrams are obtained at two speeds and three loads. A heat release analysis of the experimentally obtained cylinder pressure diagrams is developed and used. Plots of histories in the combustion chamber of the heat release rate and temperatures, and the variation of interesting quantities such as maximum cylinder pressures and their rates, maximum cylinder temperatures and ignition delays reveal some interesting features, which shed light into the combustion mechanism and emissions formation when using these bio-fuels. The analysis results, together with the differing physical and chemical properties of these bio-fuels against those for the diesel fuel, which constitutes the 'baseline' fuel, aid the correct interpretation of the basic regulated emissions of smoke and nitrogen oxides measured at the engine exhaust.

1. Introduction

For meeting stringent imposed emissions regulations, engineers who are working in the automotive industry or belong to the research community, have focused their interest either on the domain of engine- [1–6] or fuel-related techniques, such as alternative gaseous fuels of renewable nature or oxygenated fuels that can mitigate particulate emissions [5–11].

In various countries, considerable attention has been paid in the development of alternative fuel sources, with emphasis on bio-fuels that possess the advantage of being renewable, biodegradable and non-toxic [12–14]. Bio-fuels are receiving increasing public and scientific attention, driven by factors such as uncertainties related to oil price, greenhouse gas emission, and the need for increased energy security and diversity. The share of bio-fuels in the automotive fuel market is expected to grow rapidly in the next decade. In 2003 the European Directive 2003/30/EC established the necessary legal framework for their introduction in the automotive fuels market. The same Directive has set the aim of replacing 5.75% of conventional fuels used in road transportation with bio-fuels by 2010. In 2009, the new European regulation (Directive 2009/28/EC) introduced new targets for the European Union (EU) member states (among those Greece), stating that each state shall ensure that the share of energy from renewable sources in all forms of transport in 2020 is at least 10% of the corresponding final energy consumption [14,15]. In the USA, the environmental protection agency renewable fuel standard version 2 (EPA-RFS2) and the Californian low-carbon fuel standard are driving the US market [12].

The most promising bio-fuels for fossil liquid fuels substitution are vegetable oils, their derived bio-diesels and bio-alcohols. Bio-ethanol is the primary alternative at present to gasoline for spark-ignition engines, while for diesel engines vegetable oils and their derived bio-diesels are favored, as well as bio-ethanol mixed in small proportions with diesel fuel [16–18]. Further, other bio-fuels, being regarded as next generation bio-fuels, such as bio-butanol, biomass-derived hydrocarbon fuels and hydrogen, are under the microscope of research at present [13,18,19].

The advantages of vegetable oils as diesel fuel are the minimal sulfur and aromatic content, and the higher flash point and lubricity. Their disadvantages include the very high viscosity, the higher pour point, and the lower cetane number, calorific value and volatility. Their major problem is associated with highly increased viscosity, 10–20 times greater than normal diesel fuel. To solve the problem associated with their very high viscosity, the following methods are adopted: mixing in small blending ratios with diesel

* Tel.: +30 210 7723530; fax: +30 210 7723531.
E-mail address: dimracop@central.ntua.gr

0016-2361/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.fuel.2011.12.063

fuel, micro-emulsification with methanol or ethanol, preheating, cracking, and conversion into bio-diesels mainly via the transesterification process [20–22].

The advantages of bio-diesels as diesel fuel are the minimal sulfur and aromatic content, and the higher flash point, lubricity and cetane number. Their disadvantages include the higher viscosity (though much lower than the vegetable oils one), the higher pour point, and the lower calorific value and volatility. Furthermore, they are hygroscopic and have lower oxidation stability.

For all the above reasons, it is generally accepted that blends of diesel fuel, with up to 20% vegetable oils and bio-diesels, can be used in existing diesel engines without modifications. Experimental works on diesel engines concerning the use of diesel fuel blends with vegetable oils have been reported for example in [23–29] and with bio-diesels in [30–37].

Works originating from the present laboratory studied and compared, performance- and emissions-wise, blends of diesel fuel with vegetable oils and bio-diesels of various origins, fueling a single-cylinder, high-speed, direct injection (HSDI), naturally aspirated, Ricardo/Cussons 'Hydra', standard experimental diesel engine [14]. Those investigations were extended for the case of neat cottonseed oil and its neat methyl ester [38], followed by a study dealing with their heat release and statistical analyses [39]. Moreover, related works have been carried out by the same laboratory on the engine concerning the present investigation, i.e. a six-cylinder, water-cooled, turbocharged and after-cooled, heavy-duty, direct injection (HDDI), 'Mercedes-Benz' bus diesel engine used by the Athens Urban Transport Organization (AUTO) in its mini-bus fleet, fueled with blends of diesel fuel with various vegetable oils [40], bio-diesels [41], ethanol [42], or *n*-butanol [43]. The interpretation of the experimental measurements was based solely on the differences of properties between the fuels tested.

The present work is a continuation of the above investigations [40,41] when using cottonseed or sunflower oils and their derived (methyl ester) bio-diesels in blends with diesel fuel in proportions of 10% and 20% (by vol.). Here, the interpretation of the observed engine behavior performance- and emissions-wise is based on more fundamental grounds, by following an experimental heat release analysis for studying the relevant combustion mechanisms, along the lines of related work originating from this laboratory and published for the cottonseed oil and its bio-diesel in neat forms for a HSDI diesel engine [39]. As known, a very important means to analyze combustion characteristics in engines is the calculation and analysis of heat release rates according to actual measurements of pressures in the combustion chamber [17,39,44–46].

The experimental cylinder pressure (indicator) diagrams acquired from the present bus diesel engine are directly processed in connection with the pertinent application of the energy and state equations. Attention is paid to the experimental work related to the specially developed, high-speed data (signal) acquisition and processing system. A companion diagram of the fuel injection pressure assists towards this side. Such heavy-duty turbocharged engines are more difficult to handle experimentally concerning heat release analysis, unlike the corresponding studies concerning light-duty diesel engines [39]. The results of the analysis for the maximum pressures and their rates, cylinder temperatures and ignition delays reveal some interesting features of the combustion mechanism associated with the use of these bio-fuels, which when combined with the differing physical and chemical properties of these bio-fuels against those for the 'baseline' diesel fuel, aid the interpretation of the basic regulated emissions of smoke and nitrogen oxides measured at the engine exhaust.

Table 1
Engine and injection system basic data.

Engine model and type	'Mercedes-Benz', OM 366 LA, six-cylinder, in-line, four-stroke, compression ignition, direct injection, water-cooled, turbocharged, after-cooled
Speed range	800–2600 rpm
Engine total displacement	5958 cm^3
Bore/stroke	97.5 mm/133 mm
Connecting rod length	230 mm
Compression ratio	18:1
Firing order	1–5–3–6–2–4
Maximum power	177 kW @ 2600 rpm
Maximum torque	840 Nm @ 1250–1500 rpm
Inlet valve opening	15° crank angle before Top Dead Center
Inlet valve closure	25° crank angle after Bottom Dead Center
Exhaust valve opening	68° crank angle before Bottom Dead Center
Exhaust valve closure	12° crank angle after Top Dead Center
Fuel pump	'Bosch' PE-S series, in-line, six-cylinder, with 'Bosch' variable-speed mechanical governor
Injector body and nozzle	'Bosch', with five injector nozzle holes and opening pressure of 250 bar
Turbocharger	'Garrett' TBP 418-1
After-cooler	Air-to-air

2. Description of the engine and test facility

Facilities to monitor and control engine variables are installed on a test-bed, 'Mercedes-Benz' OM 366 LA, six-cylinder, heavy-duty, direct injection, four-stroke, water-cooled diesel engine. The engine is turbocharged with a 'Garrett' TBP 418-1 turbocharger and an air-to-air after-cooler after the turbocharger compressor. It is widely used to power medium trucks and mini-buses, as in the present case of the Athens Urban Transport Organization (AUTO) sub-fleet. It is coupled in the laboratory to a 'Schenck' U1-40 hydraulic brake (dynamometer), which is a variable fill brake with the loading accomplished via the brake lever that controls the amount of water swirling inside the machine. The basic data for the engine and injection system are shown in Table 1. The static injection timing of these engines is reduced up to a value of 5° CA (degrees Crank Angle) before Top Dead Center (TDC) at high loads, for the purpose of reducing nitrogen oxides emissions to meet the Euro II emission standards [1]. Fig. 1 provides a full schematic arrangement of the engine test bed, instrumentation and data logging system.

A custom made tank and flow metering system is used for fuel consumption measurements of the various blend samples as follows. A glass burette of known volume is used with the time measured for its complete evacuation of the fuel sample feeding the engine. A system of pipes and valves aids the quick drain of a fuel sample, including the return-fuel from the pump and injector, and the refill of metering system with the new fuel sample.

The exhaust gas analysis system consists of a group of analyzers for measuring soot (smoke), nitrogen oxides (NO_x), carbon monoxide (CO) and total unburned hydrocarbons (HC). For the present work the first two emitted pollutants are used. The smoke level in the exhaust gas is measured with a 'Bosch' RTT-100 opacimeter, the readings of which are provided as smoke opacity in% Hartridge units, or equivalent smoke (soot) density (milligrams of soot per cubic meter of exhaust gases), with accuracy ±0.1% of full scale output (fso). The nitrogen oxides concentration in ppm (parts per million, by vol.) in the exhaust is measured with a 'Signal' Series-4000 chemiluminescent analyzer (CLA), with accuracy ±5 ppm; it is fitted with a thermostatically controlled heated line.

For measuring the pressure in one of the cylinders, a 'Kistler' miniature piezoelectric transducer is used, mounted to the cylinder