Fuel 143 (2015) 351–360

Contents lists available at ScienceDirect

Fuel

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

Combustion analysis of microalgae methyl ester in a common rail direct injection diesel engine

Muhammad Aminul Islam [a,*], M.M. Rahman [a], Kirsten Heimann [b,c,d], Md. Nurun Nabi [a], Z.D. Ristovski [a], Ashley Dowell [e], George Thomas [f], Bo Feng [f], Nicolas von Alvensleben [b], Richard J. Brown [a]

[a] *Biofuel Engine Research Facility and International Laboratory of Air Quality and Health, Queensland University of Technology, Brisbane, Queensland 4001, Australia*
[b] *College of Marine and Environmental Sciences, James Cook University, Townsville, Queensland 4811, Australia*
[c] *Centre for Sustainable Fisheries and Aquaculture, James Cook University, Townsville, Queensland 4811, Australia*
[d] *Centre for Biodiscovery and Molecular Development of Therapeutics, James Cook University, Townsville, Queensland 4811, Australia*
[e] *Southern Cross Plant Science, Southern Cross University, Lismore, NSW 2480, Australia*
[f] *Alternate Fuels Combustion Laboratory, School of Mechanical and Mining Engineering, University of Queensland, Brisbane, QLD 4067, Australia*

HIGHLIGHTS

- Microalgae oil Methyl ester combustion performance is comparable with petroleum diesel.
- Very long chain fatty acids increase the fuel density and decrease the cetane number.
- Microalgae oil methyl ester reduce unburned hydrocarbon emission significantly.

ARTICLE INFO

Article history:
Received 5 September 2014
Received in revised form 11 November 2014
Accepted 17 November 2014
Available online 4 December 2014

Keywords:
Microalgae
Fatty acid methyl ester (FAME)
Fuel property
Engine performance
Gaseous emission

ABSTRACT

In this study, the biodiesel properties and effects of blends of oil methyl ester petroleum diesel on a CI direct injection diesel engine is investigated. Blends were obtained from the marine dinoflagellate *Crypthecodinium cohnii* and waste cooking oil. The experiment was conducted using a four-cylinder, turbocharged common rail direct injection diesel engine at four loads (25%, 50%, 75% and 100%). Three blends (10%, 20% and 50%) of microalgae oil methyl ester and a 20% blend of waste cooking oil methyl ester were compared to petroleum diesel. To establish suitability of the fuels for a CI engine, the effects of the three microalgae fuel blends at different engine loads were assessed by measuring engine performance, i.e. mean effective pressure (IMEP), brake mean effective pressure (BMEP), in cylinder pressure, maximum pressure rise rate, brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), heat release rate and gaseous emissions (NO, NO_x, and unburned hydrocarbons (UHC)). Results were then compared to engine performance characteristics for operation with a 20% waste cooking oil/petroleum diesel blend and petroleum diesel. In addition, physical and chemical properties of the fuels were measured. Use of microalgae methyl ester reduced the instantaneous cylinder pressure and engine output torque, when compared to that of petroleum diesel, by a maximum of 4.5% at 50% blend at full throttle. The lower calorific value of the microalgae oil methyl ester blends increased the BSFC, which ultimately reduced the BTE by up to 4% at higher loads. Minor reductions of IMEP and BMEP were recorded for both the microalgae and the waste cooking oil methyl ester blends at low loads, with a maximum of 7% reduction at 75% load compared to petroleum diesel. Furthermore, compared to petroleum diesel, gaseous emissions of NO and NO_x, increased for operations with biodiesel blends. At full load, NO and NO_x emissions increased by 22% when 50% microalgae blends were used. Petroleum diesel and a 20% blend of waste cooking oil methyl ester had emissions of UHC that were similar, but those of microalgae oil methyl ester/petroleum diesel blends were reduced by at least 50% for all blends and engine conditions. The tested microalgae methyl esters contain some long-chain, polyunsaturated fatty acid methyl esters (FAMEs) (C22:5 and C22:6) not commonly

* Corresponding author. Tel.: +61 423819870.
E-mail address: aminuliut@gmail.com (M.A. Islam).

http://dx.doi.org/10.1016/j.fuel.2014.11.063

found in terrestrial-crop-derived biodiesels yet all fuel properties were satisfied or were very close to the ASTM 6751-12 and EN14214 standards. Therefore, *C. cohnii*- derived microalgae biodiesel/petroleum blends of up to 50% are projected to meet all fuel property standards and, engine performance and emission results from this study clearly show its suitability for regular use in diesel engines.

1. Introduction

Ever-diminishing global fossil fuel resources are increasing pressure to find sustainable alternative fuels and reduce dependency on fossil fuels. Mono alkyl esters of fatty acids traditionally obtained from vegetable oil are referred to as biodiesel. Biodegradability, renewability and low net carbon emission characteristics of biodiesel have generated significant interest in biodiesel, as a replacement option for petroleum diesel [15]. As a result, a number of studies compared combustion and emission performance of various biodiesel with petroleum diesel [13,9,29,17,24,32,33,50,8] and engine performance and emissions tests for vegetable oils have been reviewed recently [18].

Various chemical and physical properties of biodiesel contribute to engine performance and emission characteristics. Biodiesel often contains around 10% oxygen by mass, which influences its combustion performance and emissions significantly. In addition, biodiesel use results in reduction of emissions of unburned hydrocarbons (UHC), particulate matter (PM) and carbon monoxide (CO) [1,13,9,42,34,44]. However, generally, biodiesel use results in an increase in NO_x emissions [1,27,42,44,35,48]. Previous research has shown that microalgae oil methyl ester properties can satisfy biodiesel standards ASTM 6751-12 and EN14214, and use of this fuel should be comparable with petroleum diesel. However, the qualities of microalgae oil methyl esters vary with environmental conditions, and fatty acid composition of the oil is additionally strain-dependent. The performance of microalgae methyl ester in an actual engine has only been reported in the literature in the last year or so. *Ankistrodesmus braunii* and *Nannochloropsis* sp. were tested in a single cylinder Ricardo-E6 engine and found with slight reduction of engine torque with higher-pressure rise rate and heat release rate than that of petroleum diesel [20]. The emission characteristics, of microalgae methyl ester from *Chlorella vulgaris* was reported with reduced UHC and increase of NO_x while tested in a single cylinder Kirloskar engine [36]. Both the fuels have lower density but almost similar kinematic viscosity than that of microalgae methyl ester from this study. However, *Crypthecodinium cohnii* in this study contains high amounts of very long chain polyunsaturated fatty acids (C22:5 and C22:6) compared to *A. braunii* and *Nannochloropsis* sp. from [20] could alter the results.

A significant amount of publications report on the possibility of using microalgae as a potential source for biodiesel [46,49,14,23,45,20], as microalgal biodiesel does not compete with global food supplies [16]. It is also suggested that microalgae can produce 18,927 L of biodiesel per 242,812 m^2 compared to 227 L of soy-derived biodiesel per year [16]. The benefits of microalgae include rapid growth, high capacity of CO_2 fixation, and the possibility of intensive culture on non-arable land with smaller area requirements than terrestrial crops. These factors have all contributed to the current focus on algae research. However, a very limited number of works have been published with investigation of the physical and chemical properties, engine performance, and emission analysis of actual microalgae fuel in the modern diesel engine [47,36,43].

Therefore, the main objectives of this study are to detail the physical and chemical properties of the microalgal biodiesel and to investigate engine performance, which is then compared to petroleum diesel and a 20% waste cooking oil biodiesel/petroleum diesel blend. Biodiesel blend B20 is recognised an optimum-level blend because it represents a good balance of engine performance, fuel consumption, emission reduction and long-term storage ability than any other blend [11,6]. Chemical and physical properties of microalgal and waste cooking oil methyl esters were investigated, according to biodiesel standards ASTM 6751-12 and EN 14214 (Tables 1 and 2). A four-cylinder, turbo-charged diesel engine equipped with engine performance and emission instrumentation was used to investigate the effect of microalgal/petroleum diesel blends (10%, 20%, and 50%); waste cooking oil methyl ester/petroleum diesel blend (20%) and petroleum diesel were used as reference fuels.

The performance of the engine output is presented in terms of engine cylinder pressure, maximum pressure rise rate, indicated mean effective pressure (IMEP), brake mean effective pressure (BMEP), brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), and heat release rate. Gaseous emissions of nitric oxide (NO), nitrogen oxide (NO_x) and unburned hydrocarbons (UHC) are also presented for microalgae methyl ester/petroleum diesel blends, which are compared to petroleum diesel and the waste cooking oil methyl ester/petroleum diesel blend.

2. Materials and methods

2.1. Preparation of microalgae oil methyl ester

Dry microalgae biomass (heterotrophic dinoflagellate*: C. cohnii*) was obtained from Martek Biosciences Corporation, USA. A pilot-scale oil extraction from these microalgae was carried out with analytical grade n-hexane, in the Plant Science Laboratory of Southern Cross University, NSW, Australia. Before transesterification, the oil acid value was tested and found to be very low (below 0.2 mg. KOH g^{-1}), making it suitable for transesterification without soap formation. Total extracted lipids were divided into 2 L aliquots in a 5 L glass beaker on a magnetic stirrer hot plate. An amount of 15.8 g of 85% KOH was dissolved in 250 mL of 99.8% methanol, and slowly added to the oil at 55 °C, stirring constantly. The detailed process can be found in [26].

2.2. Experimental test fuels

Fuel properties, engine performance and emissions of microalgae biodiesel/petroleum diesel blends were compared with a 20% blend of waste cooking oil methyl ester/petroleum diesel and petroleum diesel. Microalgae biodiesel was prepared in three different blends by weight 10%, 20% and 50% and designated as D90A10, D80A20 and D50A50, respectively. A single blend with 20% waste cooking oil methyl ester was prepared and designated as D80WCO20. Microalgae fatty acid methyl ester composition was determined by GC/MS in the Plant Science Laboratory of Southern Cross University, NSW, Australia. Dry microalgae biomass was extracted in pilot-scale with the non-polar solvent n-hexane. The extracted lipid was transesterified and converted to fatty acid methyl ester. The EcoTech Biodiesel Company in Brisbane supplied waste cooking oil methyl esters. The composition of the pure fatty acid methyl esters of these two biodiesels were measured according