Energy Conversion and Management 95 (2015) 342–351

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Engine performance, combustion, and emissions study of biomass to liquid fuel in a compression-ignition engine

Dolanimi Ogunkoya, Tiegang Fang *

Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695, USA

ARTICLE INFO

Article history:
Received 30 October 2014
Accepted 11 February 2015
Available online 28 February 2015

Keywords:
Biofuel
Fischer Tropsch
Biomass to liquid
BTL
Diesel engines
Combustion
Emissions

ABSTRACT

In this work, the effects of diesel, biodiesel and biomass to liquid (BTL) fuels are investigated in a single-cylinder diesel engine at a fixed speed (2000 rpm) and three engine loads corresponding to 0 bar, 1.26 bar and 3.77 bar brake mean effective pressure (BMEP). The engine performance, in-cylinder combustion, and exhaust emissions were measured. Results show an increase in indicated work for BTL and biodiesel at 1.26 bar and 3.77 bar BMEP when compared to diesel but a decrease at 0 bar. Lower mechanical efficiency was observed for BTL and biodiesel at 1.26 bar BMEP but all three fuels had roughly the same mechanical efficiency at 3.77 bar BMEP. BTL was found to have the lowest brake specific fuel consumption (BSFC) and the highest brake thermal efficiency (BTE) among the three fuels tested. Combustion profiles for the three fuels were observed to vary depending on the engine load. Biodiesel was seen to have the shortest ignition delay among the three fuels regardless of engine loads. Diesel had the longest ignition delay at 0 bar and 3.77 bar BMEP but had the same ignition delay as BTL at 1.26 bar BMEP. At 1.26 bar and 3.77 bar BMEP, BTL had the lowest HC emissions but highest HC emissions at no load conditions when compared to biodiesel and diesel. When compared to diesel and biodiesel BTL had lower CO and CO_2 emissions. At 0 bar and 1.26 bar BMEP, BTL had higher NOx emissions than diesel fuel but lower NOx than biodiesel at no load conditions. At the highest engine load tested, NOx emissions were observed to be highest for diesel fuel but lowest for BTL. At 1.26 bar BMEP, diesel had a higher smoke opacity than BTL and biodiesel. At 3.77 bar BMEP, BTL had the highest smoke opacity with diesel fuel having the lowest opacity. This work also demonstrated the effectiveness of BTL as a renewable alternative fuel with characteristics comparable to regular diesel fuel.

1. Introduction

Rising cost as a result of depleting fossil fuel reserves as well as problems relating to greenhouse gas emissions have been the most important drivers for seeking out new sources of energy [1]. For internal combustion (IC) engines, liquid biofuels have emerged as viable alternatives to fossil fuels. Biofuels are 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 [2]. Biodiesel is a type of biofuel made from the trans-esterification process and involves reaction of oil or fatty acids from oil with an alcohol in the presence of a catalyst [3]. 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, greater lubricity, generally with lower emissions and most of all has similar properties to petro diesel [4].

Biomass to liquid (BTL) fuel is a second generation biofuel and a synthetic fuel. Unlike first generation biofuels which use specific parts of the biomass for biodiesel production, second generation biofuels can be made from any portion of the biomass. BTL is produced based on processes from the production of gas to liquid (GTL) and coal to liquid (CTL) using the Fischer Tropsch (FT) process [5,6]. The steps involved in the BTL fuel production are gasification, gas cleaning and synthesis. Gasification is the first step in BTL production, which involves the breakdown of the feedstock in a reactor at high temperature and high pressure into synthetic gases, mainly carbon monoxide (CO) and hydrogen (H_2). Gasification can be divided into three parts: pyrolysis, char gasification, and partial char combustion [7]. Increased temperature during pyrolysis results in an enhanced syngas production as a result of the hydro-cracking of heavy hydrocarbons and additional production through reforming [8]. Gas cleaning is the removal of contaminants as a result of tar production in the reactor, which is

* Corresponding author.
E-mail address: tfang2@ncsu.edu (T. Fang).

http://dx.doi.org/10.1016/j.enconman.2015.02.041
0196-8904/

necessary due to the sensitivity of catalyst in the synthesis stage [6]. The final stage is the reaction of CO and H_2 in the presence of an iron or cobalt catalyst to form hydrocarbons. It is possible to adjust the final products to meet specific fuel requirements (gasoline, jet fuel or diesel). The process of converting BTL fuels by the FT process has several benefits. Syngas produced in the gasification stage from the breakdown of biomass can lead to the production of a variety of products such as synthetic fuels, lubricating oils, synthetic waxes and chemical feedstocks [5]. BTL fuels have little to no sulfur or aromatic content, high fuel ignition quality and low fuel density [9]. As the fuel is produced from a renewable energy source, it can be CO_2 neutral with the additional benefit of reduced emissions from tailoring of the fuel to meet certain combustion requirements. Research carried out by Ng et al. [9] showed that oxides of Nitrogen (NO_x), CO and particulate matter emissions for Sundiesel (a BTL fuel) they used were lower when compared to regular diesel fuel. From combustion analysis, in-cylinder pressure of Sundiesel was observed to reach its peak before conventional diesel fuel which had a higher peak pressure. Ignition delay between the two fuels as well as their heat release rate plots were observed to be similar with conventional diesel fuel having a slightly higher heat release rate. Ng et al. also observed a slight decrease in BSFC for BTL compared to conventional diesel [9].

Disadvantages from using BTL come from the cost of biomass which would normally be wood and the environmental impact of harvesting and re-growing the trees as feedstock. Sunde et al. [10] estimated the cost of BTL production to be at about $3.55 – $5.67 per U.S gallon which puts the price range at about the same cost for fossil based diesel. Similarly, Vliet et al. [11] estimated that BTL production cost breaks even when oil prices rise above $75/barrel of oil. Sundae and colleagues also estimated that BTL from sustainably managed forest biomass and woody waste may have lower overall environmental impact than fossil diesel.

BTL is a fuel made up of paraffins with very little to no sulfur and aromatic content and as an FT fuel, its end product is expected to be similar to GTL fuels which are generally FT fuels made from natural gas. Several works have been done on the use of GTL fuels in diesel engines with very positive results. Moon et al. [12], Li and Huang [13] investigated GTL fuels in turbo-charged diesel engines. In both of these cases, total hydrocarbon (THC) emissions and CO emissions were lower than regular diesel fuel. Moon et al. observed an increase in NO_x emissions [12]; however, Li and Huang found a reduction in both NO_x and smoke emissions [13]. Abu-Jrai et al. conducted several experiments in a single-cylinder diesel engine under different engine operating conditions and observed improved engine efficiency as well as reduced NO_x and smoke for GTL fuel [14,15]. They did, however, observe an increase in CO emissions. Similar to Ng's observations, Abu-Jrai observed that GTL had a similar combustion profile with conventional diesel. For the different conditions tested, GTL fuel was observed to have generally lower peak in- cylinder pressure and lower heat release rates when compared to conventional diesel fuel. Clark et al. [16] and Lapuerta et al. [17] carried out experiments using GTL in diesel engines. Their experiments both showed a reduction in particulate matter (PM). Clark et al. also observed reductions in NO_x from experiments carried out in several buses and tractors. In addition to obtaining lower PM emissions, Lapuerta and colleagues also observed a decrease in smoke opacity and a reduction in THC. In an experiments carried out using a Euro III common rail heavy duty diesel engine fueled with GTL, Wang et al. observed reduced NO_x, CO and THC emissions as well as a decrease in max torque and power of the diesel engine when compared to regular diesel fuel [18]. Unlike GTL which is produced from a FT based process that uses natural gas, dimethyl ether (DME) is an alternative fuel that can be synthesized from natural gas. From the review by Park and Lee [19], the combustion of DME in a CI engine produces lower NO_x, HC, CO and PM emissions. DME however has some drawback particularly with regards to its poor lubricity, low LHV and low viscosity.

There is an increasing demand for sustainable alternative fuel production and BTL fuel as a renewable fuel from biomass offers a sustainable solution. There are few studies in the literature on the effects of BTL on engine performance, in-cylinder combustion, and emissions. The main objective of this work is to better understand how BTL fuel performs in a diesel engine when compared with conventional diesel and biodiesel fuels, specifically in terms of engine performance, combustion, and gaseous exhaust emissions.

2. Experimental setup

The experiment was conducted in a 7.35 kW (10 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 has a jerk-type mechanical fuel injection system with an initial injection pressure of 19.6 MPa. 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 engines crank angles (CADs). The shaft encoder provided a resolution of 0.1 CAD per pulse. A M5100 series pressure transducer was used to measure load cell pressure to determine the 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 at certain time intervals during engine operation with an OHAUS GT2100 Scale. Atmospheric pressure was measured using a SSI tech pressure transducer and intake and exhaust temperatures were measured with K-type thermocouples. Data from each sensor was sampled by a NI PCI-MIO-16E-4 data acquisition board controlled by a custom Labview program. For each engine load condition, one hundred firing cycles of in-cylinder pressure data were collected with twenty-five cycles averaged for analysis. In-cylinder pressure data was obtained continuously with a resolution of 0.1 crank angle degree. A moving average filter covering a span of 20 data points was then applied to the collected data before further analysis was carried out using Matlab and Microsoft Excel. Gaseous emissions were measured with an FGA 4000XDS gas analyzer (Infrared Industries, Inc.). The measurement principle and accuracy of gaseous emissions were summarized in our previous publication [20] and are not included here due to length of the paper. Smoke opacity measurement was taken at the end of the exhaust tail pipe with a Wager 6500 full flow smoke meter. The

Table 1
Engine specifications.

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	7.35 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