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Effect of Biodiesel blending on emissions and efficiency in a stationary diesel engine

S. Oberweis, T.T Al-Shemmeri

Faculty of Computing, Engineering and Technology
Staffordshire University
Beaconside, ST18 0AD Stafford (United Kingdom)
Phone number: +44 (0)1785 353255, email: s.oberweis@staffs.ac.uk, t.t.al-shemmeri@staffs.ac.uk

Abstract. This paper presents an investigation into the effect of biodiesel blending on emissions and efficiency in a non road diesel engine. Rapeseed based biodiesel blended in increments of 25% with fossil diesel. The emissions of CO_2 show a decrease in emission (g/kWh) with increased engine load. Within the range of tests carried out, the NOx emissions from biodiesel and its blends proved to be higher than those of petro-diesel fuel. Furthermore, in this study a correlation was found relating the NOx emissions and the flame temperature. The efficiency of the system is improved with increased biodiesel content in the fuel. As predicted the results for CHP show a considerable improvement to the overall efficiency.

Keywords

Biodiesel combustion, biodiesel blending, greenhouse gas emissions, alternative fuels, renewable energy combined heat and power

1. Introduction

The worryingly rapid depletion of fossil fuel is demanding an urgent need to carry out research work regarding alternative fuels. It is uncertain how much oil and gas resources are available or remain to be discovered. The Renewable Transport Fuel Obligation Program will, from April 2008, require 5% of all UK fuel sold on UK forecourts to come from a renewable source by 2010 [1]. Fossil fuels accounted for 85% of world's primary energy supply and over 94% of energy for transportation. The production of use of fossil fuels contribute to 80% of anthropogenic GHG emissions worldwide and fossil fuel power generation currently accounts for over one third of global annual carbon dioxide emissions [2].

In 1999, European countries signed a protocol to abate acidification, eutrophication and ground-level ozone in Gothenburg [3]. The protocol sets emission ceilings for 2010 for four pollutants: sulphur, NO_x, VOC's and ammonia. These ceilings were negotiated on the basis of scientific assessments of pollution effects and abatement options. Parties whose emissions have a more severe environmental or health impact and whose emissions are relatively cheap to reduce will have to make the biggest cuts. Once the protocol is fully implemented, Europe's sulphur emissions should be cut by a least 63%, its NOx emissions by 41%, its VOC emissions by 40% and its ammonia emissions by 17% compared to 1990. The protocol also sets tight limit values for specific emission sources (e.g. combustion plant, electricity production, dry cleaning, cars and lorries) and requires best available techniques to be used to keep emissions down. Only recently, has the European council decided to commit itself to increasing the percentage of renewable energies of the total primary energy consumption to 20% by 2020 inside the EU [4]. In recent years, the reduction in sulphur content is the most notable restriction. Due to diminishing fossil fuel reserves and more and more stringent emissions limits, biodiesel has yet again become popular [5].

While a litre of petrodiesel contains about 46 MJ, a litre of B100 contains approximately 33 MJ. The difference for small blends is not noticeable. Most users fuelling at with a relatively higher B20 blend do not even notice the small effect on engine power, torque or fuel economy, which is as little as 1% [6]. Although different blends of biodiesels are currently available on the market there is need for comparison regarding performance and emissions between diesel, biodiesel and their blends. This paper looks at the effects of biodiesel blending on the performance and emissions in a diesel generating set.

Combined heat and power generation or cogeneration has been considered worldwide as a major alternative to traditional systems in terms of significant energy saving and environmental conservation. The most promising target in the application of CHP lies in energy production for buildings, where small scale denotes systems with usually less than 100 kW electrical output. Micro-scale systems are the usually in the range of less than 15kW electrical output [7].

2. Characteristics of biodiesel

The term biodiesel commonly refers to fatty acid methyl esters made from vegetable oils or animal fats, whose properties are good enough to be used in diesel engines. Since vegetables have cetane numbers close to that of diesel fuel, they can be used in existing compression ignition engines with little or no modifications [8-10]. The production of biodiesel is currently regulated by standard EN-14214 in Europe [11, 12]. Oils that have been mechanically extracted from crops such as rape or nuts, can be used further to produce biodiesel. Usually one of the following methods is used:

- Base catalysed transesterification and esterification of oil with an alcohol [13]
- Acid catalysed transesterification of oil with methanol [14]
- Enzyme catalysed transesterification [15]

Normally the base catalysed method is preferred due to its lower operation temperature and pressure, high conversion efficiency and no intermediate steps involved. In a first stage potassium hydroxide (KOH) is mixed with an alcohol to form a base catalysed reactant. Note that, although any alcohol can be used, the carbon balance of the alcohol production reflects on the one of the biodiesel. In a second stage this base is mixed with the oil. This transesterification process produces an ester along with original potassium hydroxide, glycerol and fatty acids. The potassium hydroxide can be used numerous times as it only contributes as a catalyst in the process. The glycerol is used in pharmaceutical formulations, hydrogen gas production, as a fuel additive, anti-icing fluids, etc. Similar as for the bioethanol, although environmentally good, the production price (for growing the crop) reduces the competitiveness of biofuels. Several solutions can be applied to this problem, government incentives, increasing the oil yield per hectare, fuel tax exemptions, etc [16]. Biodiesels are characterised by their viscosity, density, cetane number, cloud and pour point, distillation range, flash point, ash content, sulphur content, carbon residue, acid value, copper corrosion, and higher heating value. Compared to D2 fuel (2.7 mm^2/s at 311 K), all of the vegetable oil methyl esters (3.6 – 4.6 mm^2/s) are slightly viscous and have a higher flash point [17]. The higher oxygen content of biodiesel improves the combustion process and decreases its oxidation potential. The structural oxygen content of a fuel improves its combustion efficiency due to an increase in the homogeneity of oxygen with the fuel during combustion. The use of biodiesel can extend the life of diesel engines because it is more lubricating then petroleum diesel fuel [18].

Several studies show a decrease in carbon dioxide emission due to blending diesel with biodiesel [19, 20]. The formation of mono nitrogen oxides can lead either to an increase or decrease due to blending [21, 22]. These papers show that in general pre 1997 diesel engines have an increase in NO_x emissions with increased biodiesel percentage due to problems with the injection timings, which is after all designed in accordance with the fuels viscosity [23].

Biodiesels are mono-alkyl esters containing approximately 10% oxygen by weight. The oxygen improves combustion efficiency, but it takes up space in the blend and therefore slightly increases the apparent fuel consumption rate observed while operating an engine with biodiesel. Kaplan et al. [24] compared sunflower oil biodiesel and diesel fuels at full and partial loads and at different engine speeds in a 2.5 kW engine. The loss of torque and power ranged between 5% and 10%. According to these values, the commercial diesel fuel has the greatest brake power.

3. Theoretical Model

A diesel engine is an internal combustion engine which operates using the Diesel cycle. Diesel engines use compression ignition, a process by which fuel is injected after the air is compressed in the combustion chamber causing the fuel to self-ignite. By contrast, a gasoline engine utilises the Otto cycle, in which fuel and air are mixed before ignition is initiated by a spark plug. Most diesel engines have larger pistons, therefore drawing more air and fuel which results in a bigger and more powerful combustion. Quite often the efficiency of a reciprocating engine is measured by its Brake Specific Fuel Consumption (BSFC). Equation (1) is used to determine the rate of fuel consumption divided by the power (P) produced.

$$BSFC = \frac{m_f}{3.6 \times P} \quad (1)$$

The efficiency of the system is the percentage ratio of usable energy output per energy input. The energy input is related to the fuel consumption (m_f) of the engine. The usable energy output, shown in Eq. (2), is for power generation (W_{el}) only. Extracting heat (W_h) from the exhaust gases for further use will decreases the amount of waste heat. This increase of the overall system efficiency is shown in Eq. (3).

Where *NCV* is the net calorific value of the fuel in *MJ/kg*.

$$\eta_{el} = \frac{W_{el}}{m_f \times NCV} \quad (2)$$

$$\eta = \frac{W_{el} + W_h}{m_f \times NCV} \quad (3)$$

4. Experimental engine and test facility

A. The test rig

The test rig consists of the prime mover which is a stationary diesel engine coupled to an electrical generator, shown in Fig.1, (engine specifications can be found in table I) and a heat exchanger.

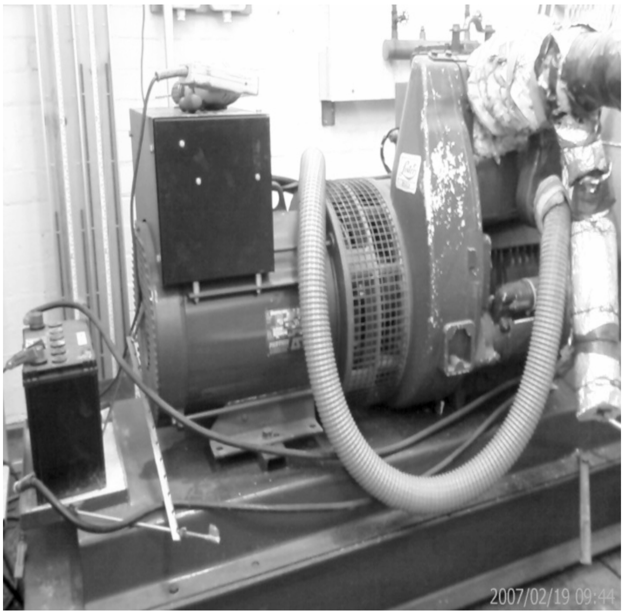

Fig.1. Experimental rig

In addition, instruments include: a data logger; a personal computer for logging and processing the data; an air box and a U-tube manometer to measure the air intake of the engine; a fuel flow rate measurement system to measure the fuel consumption; electrical voltage and current meters to measure power output of the engine; K-type thermocouples to measure air temperature, exhaust gas temperature and the temperatures at different points on the heat exchanger; and finally emission analysers to measure the composition of the exhaust gas, the specifications for the emission analysers are found in table II. Heat exchanger was supplied by GDM Heat Transfer Ltd for extracting heat from the exhaust gases for space heating purposes. The heat exchanger is made from aluminium and is of the cross-flow type with the hot air in the tubes and the cooling air through the fins.

Table I - Test engine specifications

Parameters	Value
Generator voltage [V]	415
Full load current [A]	10
Gen-Set power [kVA]	10.6
No of cylinders	2
Swept volume [cc]	1270
Compression ratio	15.9:1
Bore [mm]	95.3
Stroke [mm]	88.9
Speed fixed [rpm]	1500

Manufacturer - Lister-Petter; Model-TS2

B. Fuel samples and properties

The conventional petro-diesel fuel was supplied by ESSO UK part of the EXXON Mobil Corporation and represents the typical, British automotive, low sulphur (0.005%) diesel fuel. The biodiesel used in this study conforms to the European standards EN14214, regulating the manufacture of biodiesel. The ultimate analysis for the two fuels used in the experiment is obtained from the manufacturers. The fuels were blended in the laboratory and to prevent mixing of different blends in the tank, the engine was left running dry at the end of each test group. Bleeding the engine was necessary prior to every test run with a new fuel blend. The blends used in this experiment are B25, B50 and B75; the letter B assigned for Biodiesel followed by the percentage by volume blended. Additional runs were carried out with pure petro-diesel and pure biodiesel. Therefore there are five fuel samples tested in this study: B0, B25, B50, B75 and B100.

C. Parameters tested and experimental procedure

A series of tests were conducted using each of the above five fuel blends, with the engine working at a speed of 1,500 rpm and five engine loads ranging from no-load to full-load. In each test, volumetric fuel consumption rate, exhaust gas temperature, exhaust regulated gas emissions such as nitrogen oxides, carbon monoxide, carbon dioxide and total unburned hydrocarbons are measured. The experimental work started with preliminary investigation of the engine running on neat diesel fuel, in order to determine the engine's operating characteristics and exhaust emission levels, constituting a 'baseline' that is compared with the corresponding cases when using the subsequent fuel blends. The same procedure was repeated for each fuel blend by keeping the same operating conditions. For every fuel change, the engine was run ‘dry’ and after the ‘bleeding’ process, was left to run for thirty minutes to stabilise at its new conditions. Each test was repeated further three times to reduce experimental error.

Table II – Specifications of exhaust gas analysers used in present study

Type	Value
Manufacturer	Analytical development Co (ADC) O_2: Servomex
Model	WA154 O_2: 580
Object of measurement	CO, CO_2, NO_x, O_2
Range of measurement	CO = 0 ~ 3 % CO_2 = 0 ~ 20 % NO_x = 0 ~ 10,000 ppm O_2 = 0 ~ 100%
Resolution	CO = 0.002 % CO_2 = 0.1 % NO_x = 50 ppm O_2 = 0.1 %
Accuracy	1 ~ 2 % 0.05 % for O_2
Warm up time	15 min (self-controlled)
Speed of response	within 20s
Sampling	Directly sampled

5. Results and discussion

This work contributes to the ongoing research in renewable energies, mainly the use of biodiesel as an alternative or blending additive for commercial petro diesel.

Figure 2 shows the variation of BSFC with load for different fuels. The differences of BFSC values are very small at different engine load, when using different fuels. The variation of exhaust gas temperature with load for different fuels is shown in Fig. 3. There is a steady increase of temperature with engine load, as expected. The difference in temperature for various blends at the same engine load is minimal. This difference varies between 1% for B50 and 6% for petro and B100. As the exhaust temperature is higher with increased biodiesel content, there is a possibility of higher amounts of heat to be reclaimed when running on biodiesel.

Figure 4 shows the variation of CO_2 emissions with load for different fuels. It is observed that all the CO_2 emission of diesel fuels is higher than that of the blended fuels. There is an apparent decrease in CO_2 emission in g/kWh. However the absolute CO_2 in the exhaust gases increases with engine load.

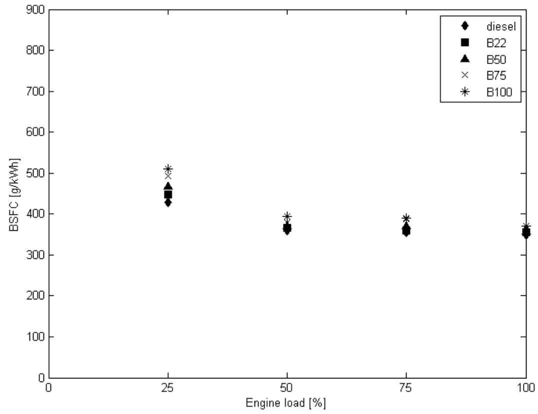

Fig.2. Variation of brake-specific fuel consumption of different fuels.

Figure 5 shows the variation of NO_x emission with load for different fuels. It is observed that as the NO_x increases directly with the degree of blending and as the latter is directly proportional to the temperature, the NO_x emission increases with increased temperature. NO_x emissions increase moderately with load as expected, similar to the effect of load on exhaust gas temperature but not at the same rate of increase. Petro diesel produces the least NO_x of these tests. Increasing the amount of biodiesel has a proportional effect on the rate of NO_x production, going up from 4 g/kWh (at no load) for petro diesel, up to 14 g/kWh for 100% biodiesel.

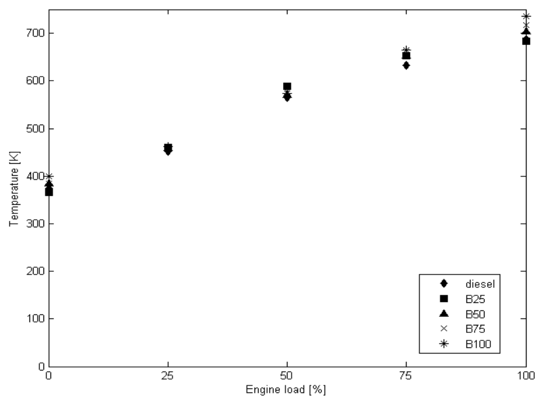

Fig.3. Variation of temperature with load for different fuels.

Figure 6 shows the variation of electrical output efficiency with load for different fuels. The efficiency of electrical output increases with increased engine load, as the engine is obviously working at its operating conditions. This is compared to an idle state where the engine is consuming energy without any usable energy output. An increase in efficiency can be seen with increased biodiesel content. This is due to the fact that the results are based on the energy content of the fuels versus the net electrical output of the generator and obviously the fuel consumption (Fig.2) does not change considerably with increased blend and load.

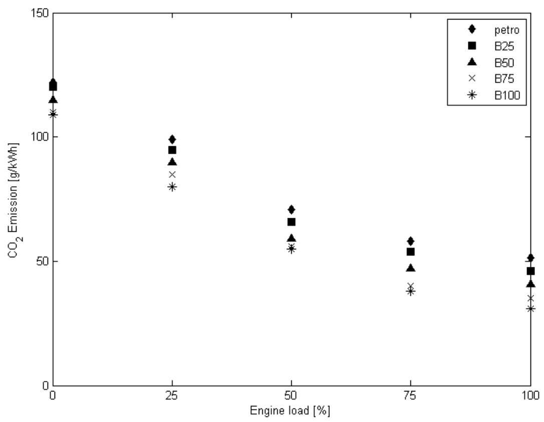

Fig.4. Variation of CO_2 emission with load for different fuels

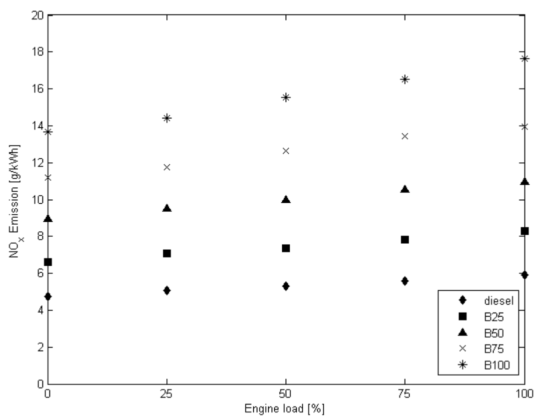

Fig.5. Variation of NOx emission with load for different fuels

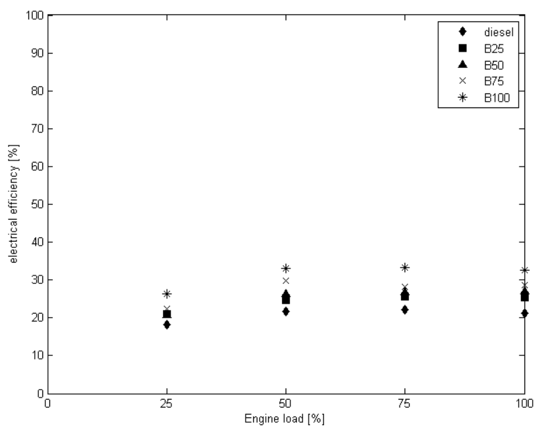

Fig.6. Variation of electrical efficiency with load for different fuels

Figure 7 shows the variation of the overall CHP performance utilisation of the system with engine load. As for the electrical efficiency, the overall CHP efficiency increases with increased engine load and blending. Adding the heat exchanger to the system to extract additional heat from the exhaust gases increases the energy utilisation of the system between 15% and 25%. This shows a substantial increase of performance utilisation by simply adding space heating capabilities to the system. It is evident from Fig. 7 that the combined mode of the system has double effects.

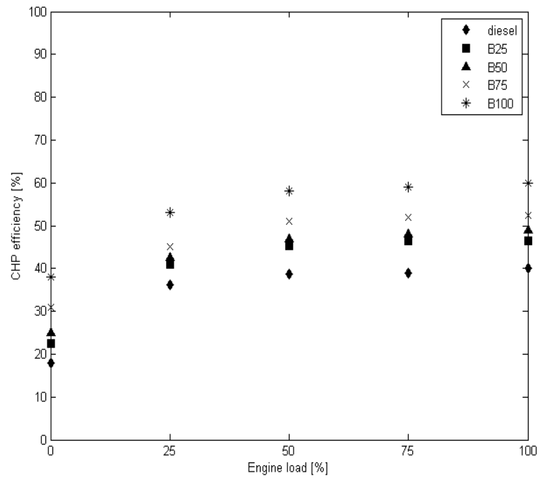

Fig.7. Variation of CHP performance utilisation with load for different fuels

The biodiesel contribution increases the power output as was shown in Fig.6 and the amount of heat release is higher for increased proportion of biodiesel as shown in Fig. 3. Therefore it is no surprise that the net utilisation factor (an appropriate term replacing efficiency used in CHP performance evaluation) is significantly higher than the efficiency of the system under single generation mode. At full load, the maximum efficiency of electrical generation only was about 20% for petro diesel rising to 32% for pure biodiesel (Fig. 6) whereas the utilisation factor for the CHP at full load is 40% for petro diesel increasing to 60% for pure biodiesel.

6. Conclusions

This work contributes to the ongoing research in renewable energies, mainly the use of biodiesel as an alternative or blending additive for commercial petro diesel. In this study the effect of blending biodiesel on emissions and efficiency in a non road diesel engine were tested. The findings were compared to published results from similar experiments. The main conclusions from the current study can be summarised as follows.

- There is a small difference in break specific fuel consumption for different blends at various engine loads.
- There is a steady increase of temperature with engine load, as expected
- It is observed that all the CO_2 emission of diesel fuels is higher than that of the blended fuels.
- It is observed that the NO_x emission increases directly with increased temperature.
- Increasing the amount of biodiesel has a proportional effect on the rate of NO_x production, going up from 4 g/kWh (at no load) for petro diesel, up to 14 g/kWh for 100% biodiesel.
- The biodiesel contribution increases the power output and the amount of heat release is higher for increased proportion of biodiesel.
- The efficiency of electrical output increases with increased engine load.
- The net utilisation factor is significantly higher than the efficiency of the system under single generation mode.
- Adding the heat exchanger to the system to extract additional heat from the exhaust gases increases the overall efficiency of the system between 15% and 25%.

It has to be said that these results are based on stationary diesel engine and hence a correlation between engine performance and emissions with road vehicles cannot be made. Furthermore, no modifications (e.g. injection time alteration, fuel pre-heating system) were made to engine to adjust for the lower viscosity of biodiesel compare to standard diesel. The quality of the rapeseed biodiesel was based on EN14214 standard concerning the production and no other biodiesel grades were tested in this study.

However these results show a good usefulness for diesel powered generating systems being adjustable for biodiesel and its blend. This can be of particular interest for farmers and other parties with easy and cheap access to biodiesel for the purpose of energy generation by reducing emissions to the environment and increase their carbon footprint. From an economical point of view, the use of biodiesel has been proven in numerous other papers and hence adds to benefits of its use.

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