Int.J.Curr.Microbiol.App.Sci (2020) *9*(10): 17-23

EXCELLENT PUBLISHERS

International Journal of Current Microbiology and Applied Sciences
***ISSN: 2319-7706* Volume 9 Number 10 (2020)**
Journal homepage: http://www.ijcmas.com

Original Research Article https://doi.org/10.20546/ijcmas.2020.910.003

Performance Evaluation of Diesel Engine using Fuel Oil Produced from Plastic Waste

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Keywords

Fast pyrolysis, Waste plastic, Fuel oil, Engine performance

Article Info

Accepted:
04 September 2020
Available Online:
10 October 2020

A B S T R A C T

Recently, the pyrolysis is proposed for plastic waste management. It efficiently converts plastic waste into fuel oil. In this paper, the fuel properties of fuel oil, diesel-fuel oil blends, and their performance in the diesel engine are presented and discussed. The most of the fuel properties of fuel oil produced from plastic wastes were on par with diesel fuel. Diesel engine testing unit (3.7 kW, single-cylinder) was used to study the engine performance and emissions during the use of plastic waste derived fuel oil and their blends. The results found that the brake-specific fuel consumption of engine operated with fuel oil and diesel at full load conditions was 294 and 276 g/ kWh, respectively. The brake thermal efficiency for the engine testing at full load with fuel oil and diesel was found to be 27.50 and 28.08 %. The maximum exhaust gas temperature recorded for full load condition was 452ºC for fuel oil, whereas it was 418ºC for diesel fuel. At full load conditions, the recorded higher carbon dioxide emission was 7.84 % for fuel oil and 6.92% for diesel fuel. The observed higher carbon monoxide emission was 0.142 % for fuel oil alone, whereas that of diesel fuel was 0.081% at full load condition. Maximum NOx emission at full load condition was measured as 905 ppm for fuel oil alone, whereas that of diesel fuel was 861 ppm.

Introduction

Presently, petroleum fuels are contributing a significant share in the automobile sector. Over-dependence on these fuels led to insecurity and colossal money spent on crude oil imports. In order to make self-sustainability for developing countries like India, searching alternate fuels from cheap feedstocks is the need of the hour. For alternate fuel production, plastic waste is a potential candidate and would be competitive to biomass feedstocks. Generally, plastic waste creates pollution and affects the ecosystem. Therefore, there is a need for technology to convert these wastes into useful products. Pyrolysis can be used to produce fuel oil by degrading the plastic wastes under heat, pressure, and an oxygen-free environment (Perkins *et al.,* 2018). The quantity of liquid, gas, and solid residues can vary with the pyrolysis conditions. A condensed liquid obtained from the pyrolysis of plastic waste is called as fuel oil.

The fuel oil can be used as fuel in furnaces, boilers, and diesel engines. The non-condensable gases and solid residues do not have much energy value compared to fuel oil. This paper aims to investigate the performance and emission characteristics of a diesel engine with fuel oil and their blends with diesel (FO_{20}, FO_{40}, $FO_{60,}$ and FO_{80}) and were compared with diesel fuel.

Materials and Methods

A laboratory-scale fast pyrolytic reactor was used for converting waste plastic into fuel oil. Five kg of plastic wastes was used in each experiment. Based on preliminary studies, the optimal reaction temperature and nitrogen gas purging rate were found as 450^{o}C and 10 ml/min, respectively. The plastic waste was fed in to the reactor at the rate of 1 kg/h using a screw auger. The gases were released from the plastic wastes under optimal pyrolysis conditions. The condensable gases were allowed to cool in the condenser to get the fuel oil.

The standard methods were used to analyze the properties of fuel oil namely; specific gravity (IS: 1448-1972), kinematic viscosity (ASTM 445-72), calorific value (ASTM D 2015-77), flashpoint (ASTM D93), carbon residue (ASTM D524-IP14/65) and ash content (ASTM D 482).

The fuel oil and its blended fuels were used as fuel in the engine to assess its performance. The blending ratios used for fuel oil with diesel are FO_{20} (20% Fuel oil + 80% diesel), FO_{40} (40% Fuel oil + 60% diesel), FO_{60} (60% Fuel oil + 40% diesel), FO_{80} (80% Fuel oil + 80% diesel) and FO_{100} (100% Fuel oil + 0% diesel). For this study, a 3.7 kW diesel engine (Kirloskar make, India) with a brake drum and a mechanical spring coil load (maximum and minimum load: 100 kg and 5 kg) setup was used.

The technical details of the diesel engine are given below.

General details: 4-stroke, compression ignition, constant speed, vertical, water-cooled, direct injection

Number of cylinders: One
Bore: 80 mm
Stroke: 110 mm
Swept volume: 553 cc
Clearance volume: 36.87 cc
Compression ratio: 18: 1
Rated output: 3.7 kW at 1500 rpm
Rated speed: 1500 rpm
Injection pressure: 240 bar
Fuel injection timing: 24^{o} BTDC
Fuel: High-speed diesel

The engine performance was evaluated for four different loads *viz.,* 25, 50, 75, and 100%. Initially, the engine was run with diesel and changed to testing fuel after 15 min. During engine testing, the observations such as fuel consumption, speed of engine crankshaft, and emission profile were recorded at one h interval.

The speed of the engine's shaft was measured using a non-contact type photo-tachometer (Lutron DT-2234B, Taiwan). From fuel consumption and power developed by the engine, the brake specific fuel consumption (BSFC) was calculated as per BIS (1980). A portable exhaust gas analyzer (KM9106-Quintox, UK) was used to measure exhaust gas compositions and temperature.

Results and Discussion

Characterization of fuel oil

The fuel properties such as specific gravity, kinematic viscosity, calorific value, flash point, ash content, and carbon residue of fuel oil, diesel, and blends are presented in Table 1.

The fuel oil's specific gravity was recorded as 0.802, which was lower than diesel (0.840). The specific gravity of blended fuels (0.811 to 0.833) was found closer to diesel fuel (0.840). The kinematic viscosity of fuel oil and its blended fuels followed an increasing trend with an increase in the amount of diesel level. The viscosity of fuel oil and diesel fuels were closer values (1.9 – 4.1 mm^2/s, Ahmad *et al.*, 2014). The calorific value of the fuel oil was found to be 96 % of diesel fuel (46.45 MJ/ kg). The flashpoint of fuel oil and diesel fuel was 43 and 50^oC, respectively. However, the flashpoint of fuel oil blended fuels was decreased with an increase in the amount of fuel oil in the fuel. The ash content of fuel oil was lower than the diesel (0.01%). The ash content of fuel oil blended fuels was decreased with an increase in the amount of fuel oil in the fuel. The carbon residue of fuel oil was higher than diesel (0.21%). The carbon residue of fuel oil blended fuels was increased with an increase in the amount of fuel oil in the fuels (Mani *et al.*, 2009. The fuel properties of fuel oil and its blended fuels meet the diesel fuel standards.

Engine testing with fuel oil

Engine tests were conducted with full throttle condition, and the speed variations were obtained by increasing the load. Initially, engine tests were performed with diesel at fully throttled and no-load conditions. A separate fuel feed line was used to feed diesel blended fuel oil in to the engine in subsequent trials. For testing the effect of fuels on engine performance, trials were conducted to evaluate the characteristics such as BSFC, brake thermal efficiency (BTE), exhaust gas temperature, and compositions.

Before running the engine with new blended fuel, the fuel of the previous experiment was drained out from the tank and pipelines.

Brake specific fuel consumption (BSFC)

The BSFC was calculated by fuel consumption divided by the engine's rated power output, and it was depicted in Fig. 1.

The BSFC of the engine was decreased with an increase in load. The BSFC of the engine at full load (100%) for fuel oil (FO_{100}) and diesel were 294 and 276 g/kWh, respectively. The BSFC of fuel oil blends (FO_{20} to FO_{80}) ranged from 280 to 290 g/kWh. The variation in BSFC with load for different fuels and their blends was declined with increased load. The BSFC in case of blends was higher compared to diesel in all the loads, due to its lower calorific value, high density and hence higher bulk modulus. The higher bulk modulus results in more discharge of fuel for same displacement of the plunger in injection pump, thereby resulting increase in BSFC (Devaraj *et al.*, 2015; Gungor *et al.*, 2015).

Brake thermal efficiency (BTE)

BTE is defined as actual brake work per cycle divided by the amount of fuel chemical energy indicated by the lower heating value of a fuel. The BTE for tested fuel oil and its blends are shown in Fig. 2.

At full load (100%), the BTE of the engine running with fuel oil (FO_{100}) and diesel was 27.50 and 28.08%, respectively. The BTE of fuel oil blends (FO_{20} to FO_{80}) decreased from 27.91 to 27.64 %.

Table.1 Fuel properties of fuel oil, diesel and their blends

Properties	Diesel (FO_0)	20 % Fuel oil -diesel blend (FO_{20})	40 % Fuel oil -diesel blend (FO_{40})	60 % Fuel oil -diesel blend (FO_{60})	80 % Fuel oil -diesel blend (FO_{80})	Fuel oil (FO_{100})
Specific gravity	0.840	0.833	0.826	0.817	0.811	0.802
Kinematic viscosity @40°C, mm^2 s^{-1}	3.52	3.65	3.78	3.91	4.02	4.12
Calorific value, MJ kg^{-1}	46.45	46.07	45.68	45.28	44.91	44.52
Flashpoint, °C	50	49	47	46	45	43
Ash Content, %	0.01	0.009	0.008	0.006	0.005	0.004
Carbon Residue, %	0.21	0.30	0.37	0.43	0.51	0.60

Fig.1 BSFC at different load for fuel oil blends

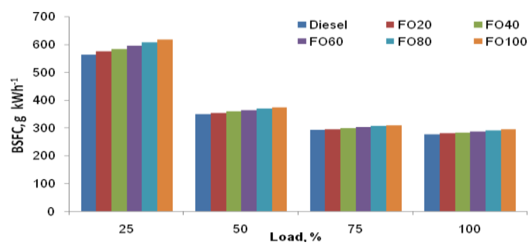


Fig.2 BTE at different load for fuel oil blends

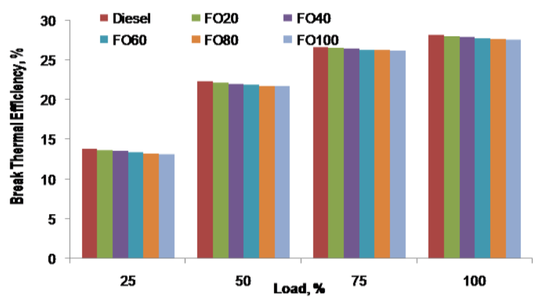


Fig.3 Exhaust gas temperature at different load for fuel oil blends

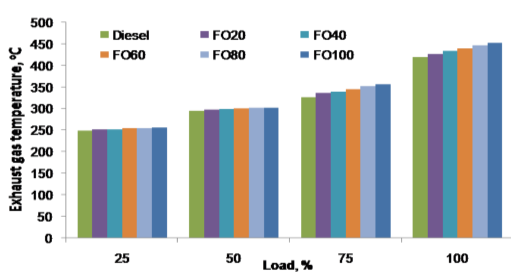


Fig.4 CO_2 emissions at different load for fuel oil blends

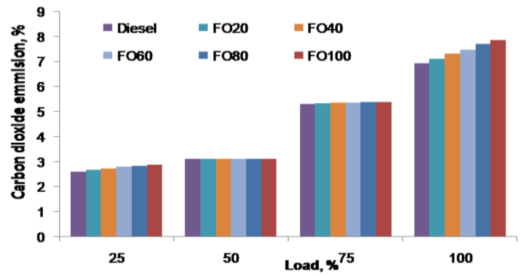


Fig.5 CO emissions at different load for fuel oil blends

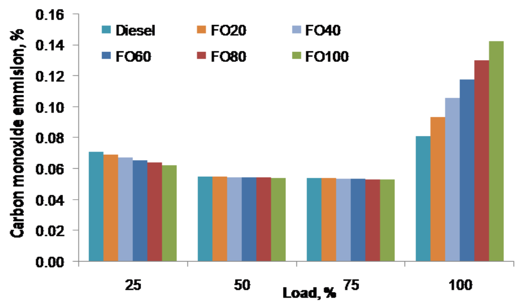
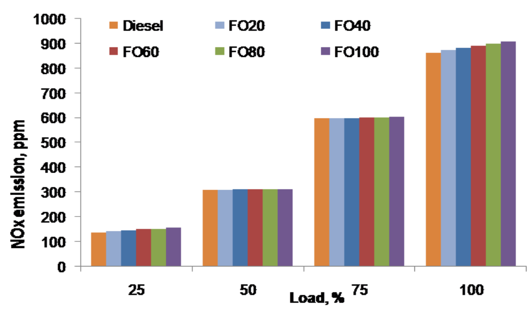


Fig.6 NOx emissions at different load for fuel oil blends



The variation in brake thermal efficiency with load for different fuels and their blends were increased with an increase in load. Lower fuel consumption may be one of the reasons for increased BTE. This is in accordance with the results reported by Devaraj *et al.*, (2015) and Mani *et al.*, (2009).

Emission profile

The exhaust emission from the diesel engine was monitored with an exhaust gas analyzer, and results are discussed briefly, as given below.

Exhaust gas temperature

Generally, the exhaust gas temperature is an indicator of the amount of waste heat carried along with exhaust gases. The exhaust gas temperature for tested fuel oil and its blends are shown in Fig. 3. The exhaust gas temperature of blended fuel oil at full load (100%) was higher than 75% load. The maximum exhaust gas temperature at full load condition was noted as 452ºC for fuel oil (FO_{100}) and 418ºC for diesel fuel. This is in accordance with the results reported by Mani *et al.,* (2009). The exhaust gas temperature increased with an increase in load and amount of fuel oil blends. The rise in exhaust gas temperature may be due to ignition delay and increased quantity of fuel injection. The exhaust gas temperature could be reduced by adjusting the injection timing/injection pressure or injection timing of fuel in the diesel engine.

Carbon dioxide (CO_2) emission

The emission of CO_2 at different loads for diesel, fuel oil, and their blends are shown in Fig. 4.

The CO_2 emission of blended fuels at full load (100%) was higher than at 75% load. Maximum carbon dioxide emission at full load conditions were noted for FO_{100} and diesel was 7.84 % and 6.92%, respectively. The CO_2 emission varied between 7.11 to 7.68% for fuel oil blended (FO_{20} to FO_{80}) fuels. The rise in CO_2 emission increased with an increase in the blended amount of fuel oil and also increased with increased load is due to the presence of reduced amount of carbon to hydrogen ratio and excess oxygen (Devaraj *et al.,* 2015; Venkatesan *et al., b*2019; Killol *et al.,* 2019).

Carbon monoxide (CO) emission

The formation of CO emissions at different loads for diesel, fuel oil, and their blends are shown in Fig. 5.

The CO emission of blended fuel oil at full load (100%) was higher compared to other load conditions. Maximum CO emission at full load conditions was observed as 0.142% for FO_{100}, whereas that of diesel fuel was 0.081%. The CO emission varied between 0.093 and 0.130% for fuel oil blended (FO_{20} to FO_{80}) fuels. The raise in CO emission increased with an increase in the blended amount of fuel oil. This is in accordance with the results reported by Devaraj *et al.*, (2015).

Oxides of nitrogen (NOx) emission

The nitrogen oxides obtained from the reaction between nitrogen and oxygen at relatively high temperatures. NO is a significant component of the NOx emission. The formation of NOx at different loads for diesel, fuel oil, and blends is shown in Fig. 6.

The NOx emission of blended fuel oil at full load (100%) was higher than other loads. Maximum NOx emission at full load condition was observed as 905 ppm for FO_{100}, whereas that of diesel fuel was 861 ppm. The NOx emission varied between 871 and 896 ppm for fuel oil blended fuels (FO_{20} to FO_{80}). The rise in NOx emission increased with an increase in the blended amount of fuel oil and also increased with all the loads, this may be due to increase in combustion temperature. This is in accordance with results reported by Devaraj *et al.,* (2015), Venkatesan *et al.,* (2019), and Killol *et al.,* (2019).

In conclusion, the pyrolysis is a suitable technology to produce fuel oil from plastic wastes. Engine performance studies conducted with fuel oil and varying blends with diesel. The fuel properties of fuel oil were found on par with diesel fuel. Under full load testing (100%), the break specific fuel consumption of engine for the fuel oil and diesel was 294 and 276 g/kWh, respectively. The break thermal efficiency of fuel oil blends (FO_{20} to FO_{80}) decreased from 27.91 to 27.64 %. The maximum exhaust gas temperature was found as 452ºC at full load testing with fuel oil, which was lower than diesel fuel. The carbon dioxide, carbon monoxide, and NOx emissions were found as maximum under engine operated in full load for fuel oil.

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How to cite this article:

Selvaraj, M., S. Sriramajayam, D. Ramesh and Karthikeyan, S. 2020. Performance Evaluation of Diesel Engine using Fuel Oil Produced from Plastic Waste. *Int.J.Curr.Microbiol.App.Sci.* 9(10): 17-23. doi: https://doi.org/10.20546/ijcmas.2020.910.003