Evaluation of a compression ignition engine performance and emission characteristics using diesel-essential oil blends of high orange oil content

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Abstract

In this research, waste stream essential oil such as orange oil is used as a diesel fuel partical replacement to be tested in a diesel engine. Like diesel fuel, orange oil does not contain any oxygen since it is constituted of limonene (a colourless liquid aliphatic hydrocarbon) and has almost similar density and cetane number. A 6-cylinder diesel engine is operated using various blends of orange and diesel fuel. The engine was operated with three different fuel blends: neat diesel, 74% diesel + 26% orange oil (D74O26) and 59% diesel + 41% orange oil (D59O41). All the orange oil blends produced nearly the same brake power from the engine experiment compared to neat diesel fuel. Furthermore, all orange oil blends emit less particulate matter, and the 'count mean diameter' of the emitted particles is also lower than base diesel. Based on the obtained results, these blends can be suggested to be used in a diesel engine.

Keywords: Orange oil; Engine performance; Emissions; Diesel; Renewable energy.

1. Introduction

The development of a country depends significantly on its transportation, mining, and power generation sectors. The diesel engine, well known as the compression ignition (CI) engine, has become a source of power for these sectors due to its innate efficiency, durability, and power output. Hence, a significant proportion of passenger vehicles and the heavy machinery market is driven by these engines [1, 2]. With the increase in global energy consumption owing to increasing energy demand in power generation and transport sectors, petroleum fuel reserves are diminishing as they are a finite resource. This limited availability of fossil fuels has triggered a severe threat to worldwide energy security [3, 4]. Furthermore, petroleum diesel is a non-renewable energy source, and the diesel engine is a significant contributor of pollutants and adversely affects the environment and human health.

Therefore, researchers have been looking for a potentially sustainable and renewable alternative energy source that can help reduce emissions and improve a diesel engine's engine performance [5, 6]. One of the possibilities in attaining this would be using waste stream essential oils, as it has been reported that these oils result in improved combustion of diesel engines [7, 8]. Waste stream essential oils have minimal commercial value. Due to strict regulation regarding the disposal of these oils and the high cost associated with disposal, the producers have forced to stock these oils in large containers, which further adds storage cost to the already high production cost. If these low-value products could be utilised in other sectors, particularly on the farm, e.g. to operate diesel engines, it would enormously help them. They would be able to reduce diesel dependency, lower fuel cost, as well as lower fuel cost and store the waste stream essential oils. Hence, a study associated with using these waste stream essential oils in diesel engines can be of interest to the producers, which could unearth new possibilities.

For this study, orange oil was selected because it is renewable in nature and has very similar properties to neat diesel [9, 10]. A handful of research has been carried out using waste orange peel oil. Ashok et al. [11] studied the performance, emission, and combustion characteristics of 20% by volume of waste orange peel oil (OPO) blended with diesel in a diesel engine. They reported better combustion characteristics for OPO blends due to the inherent oxygen content and comparable cetane number (CN). They also reported a significant reduction in hydrocarbon (HC), carbon monoxide (CO), and smoke emissions for the OPO blend. Deep et al. [12] investigated the performance and emission characteristics of 10-20% OPO biodiesel blends on an unmodified diesel engine. They reported a 4-23% increase in brake thermal efficiency (BTE) and a 3.8-19.2% decrease in brake specific energy consumption (BSEC). Thus, it can be seen that, in the past studies, lower volume percentages of orange oil were used. Hence, in this study, two blends of orange oils: 26% orange oil with 74% diesel and 41% orange oil with 59% diesel, has been used, and engine performance and emission characteristics were evaluated.

2. Materials and Methods

The experiments were carried out in the Biofuel Engine Research Facility (BERF) laboratory of Queensland University of Technology (QUT). A fully instrumented 6-cylinder common rail turbocharged diesel engine (ISBe22031) was used for the tests, and the specifications are presented in Table 1. A Kistler encoder (Kistler 2614) was used to record engine speed and crank angle data.

The engine was run at 1500 rpm (maximum torque speed) with 3 loads (25%, 50% and 100% load) for the engine tests. For this particular engine speed, the engine was run with a wide-open throttle position which was considered as 100% load (full load), and the other two loads were calculated based on the full load [13]. Before start measurements, the engine was first warmed up for about 30 minutes using diesel fuel. The measurements were started once the lubricating oil temperature reached 90°C. Two separate fuel tanks, one for neat diesel fuel and the other one for biodiesel blends, were used to avoid mixing between fuels. A schematic of the experimental set up is shown in Figure 1, and engine details are given in Table 1. Figure 2 shows the pictorial view of the engine testbed and utilised equipment. A fast aerosol mobility spectrometer DMS 500 (Cambustion Ltd.) was used for particle number (PN) measurements. Using a re-inversion tool, the particle mass (PM) was computed from DMS data [14]. The raw exhaust was diluted in a dilution tunnel (partial flow). California Analytical Instruments Models CAI-600 CLD NO/NO_X digital analyser and CAI-603 NDIR Gas (Gas analyser) were used for NO_X and CO emission measurements.

The engine was operated with three different fuel blends: neat diesel (Appendix 1), 74% diesel + 26% orange oil (D74O26) and 59% diesel + 41% orange oil (D59O41). The critical properties of these blends are given in

Figure 2. Pictorial view of the engine setup and utilised equipment

Table **2**. Gas Chromatography-Mass Spectrometry result of neat orange oil is shown in Appendix 2. The property tests were carried out at QUT and Colorado State University (the Engines and Energy Conversion Laboratory). The property analysis details can be found in Rahman et al. [15]. The quality certificate of the diesel and GC-MS of pure orange oil are given in Appendices. The GC-MS was carried out at the University of the Sunshine Coast, Queensland, Australia.

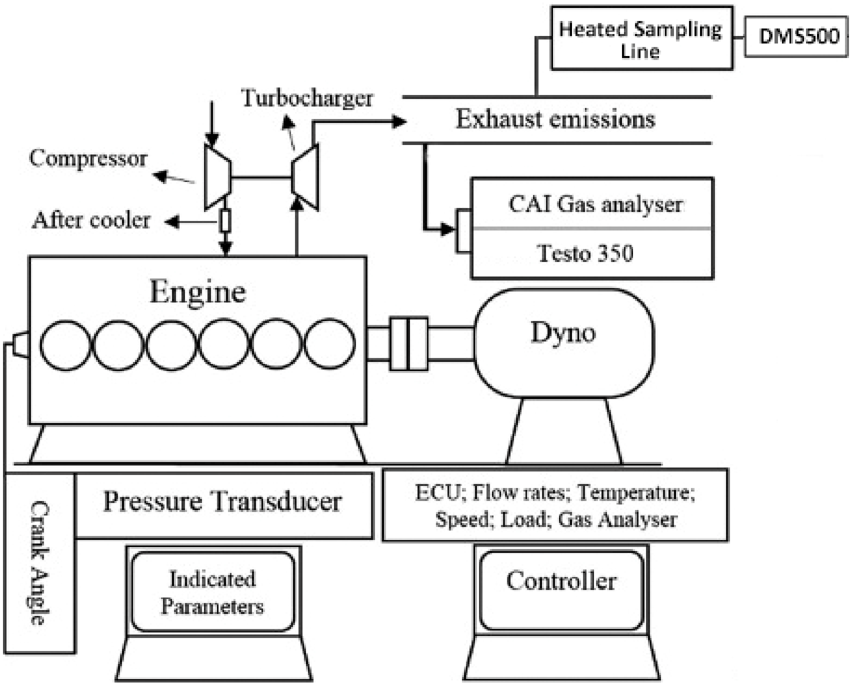

Figure 1. Engine campaign schematic diagram

Table 1. Test engine specification

Model	Cummins ISBe220 31
Capacity	5.9 Litres
Maximum power	162 kW at 2000 RPM
Maximum torque	820 Nm at 1500 RPM

Number of cylinders	6
Number of valves per cylinder	4
Compression ratio	17.3:1
Bore x Stroke	102 x 120 (mm)
Dynamometer	Electronically-controlled water brake dynamometer
Injection system	Common rail
Emission certification	Euro IIIA
Aspiration	Turbocharged

Figure 2. Pictorial view of the engine setup and utilised equipment

Table 2. Fuel Properties of used fuels in the study

Properties	Diesel	Orange oil	D74O26	D59O41
Diesel volume percentage (%)	100	0	74	59
Orange oil volume percentage (%)	0	100	26	41
Kinematic viscosity @40°C (mm^2/s)	2.75	1.45	2.41	2.22
Density (kg/m^3)	822.8	842.5	828.0	830.9
Lower Heating Value (LHV) (MJ/kg)	43.95	45.15	44.26	44.44
CN (#)	54.0	19.5	45.1	40.0

To ensure accurate measurement of exhaust emissions, CO emissions were measured using two gas analysers (CAI 600 and Testo 350). For each fuel, the test was repeated three times and the repeatability of the results was confirmed by calculating the standard deviation (Appendix 3). The data presented in this paper are the average values of the measured exhaust emissions.

3. Results and Discussions

3.1. Performance parameter study

BP is defined as the power available at the crankshaft, which can be calculated using the following equation:

$$BP = \frac{2\pi NT}{60000}\,(kW) \qquad (1)$$

where N denotes engine speed in rpm (1500 rpm) and T denotes Torque produced in Nm.

Error! Reference source not found. shows the variation of brake power between neat diesel and orange oil-diesel blends. From the figure at all loads, the brake power of orange oil blends was almost the same as the base diesel. This is most likely due to the relative calorific value of orange oil-diesel blends compared to that of reference diesel.

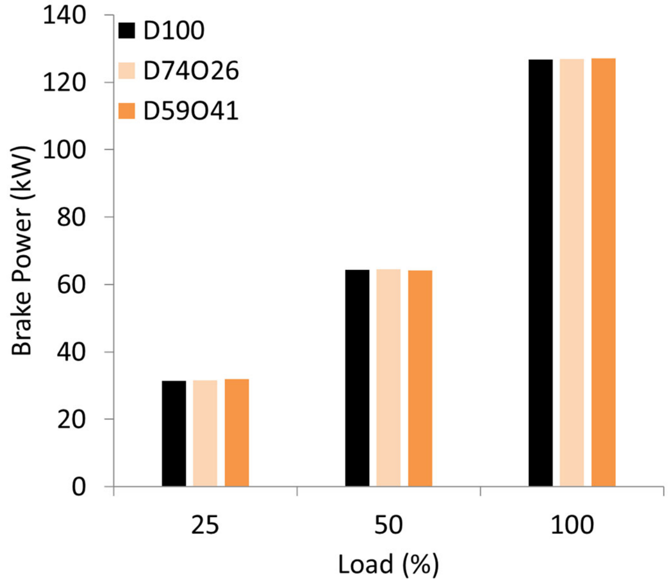

Figure 2. Brake power variation of fuel blends

Brake specific fuel consumption (BSFC) is a measure of an engine's fuel effectiveness that burns fuel and produces power. It is defined as the amount of fuel consumed for the generation of one unit of power output and can be calculated using the following equation:

$$BSFC\ (\frac{kg}{kWh}) = FC\ \left(\frac{kg}{hr}\right) \times BP\ (kW) \qquad (2)$$

Where FC is the fuel consumption in (kg/hr) and BP is in kW.

The formula used to find fuel consumption is as follows:

$$FC = \frac{\rho \times V \times s}{t} \quad (\frac{kg}{hr}) \qquad (3)$$

where, s is the specific gravity of fuel, V = volume of fuel consumed, ρ = density of fuel in kg/m^3 and t = time.

It is typically used for comparing the efficiency of engines with output power. As shown in **Error! Reference source not found.**, in all loads, orange oil-diesel blends have lower BSFC (except 50% where BSFC of D74O26 was higher) compared to pure diesel, which can be due to having slightly higher LHV and lower viscosity, which improves the combustion [16].

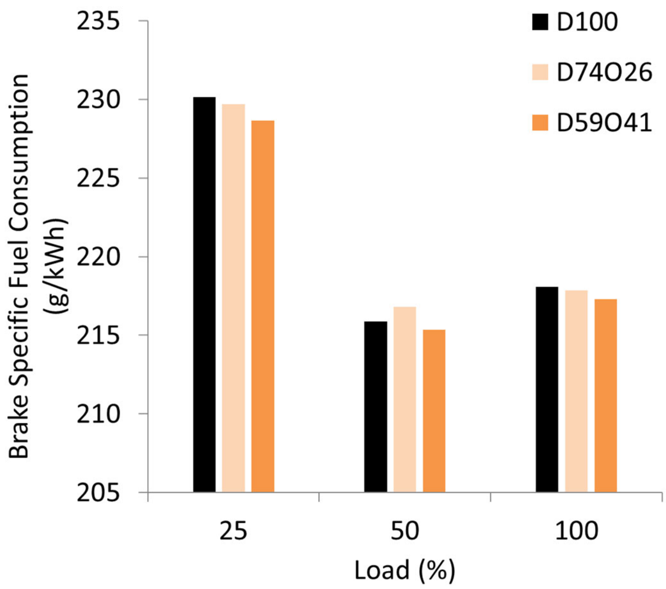

Figure 3. Brake specific fuel consumption variation of fuel blends

The variations in indicated specific CO emissions for baseline diesel fuel and the orange oil blends are illustrated in Fig. 4. CO emissions are generally formed due to overly rich or overly lean mixtures [17]. In overly lean mixtures, CO emissions are caused by partial oxidation. In overly fuel-rich regions, the fuel lacks adequate air causing CO emissions [17-19]. At all loads, orange oil blends emit less CO than base diesel, which might be associated with higher calorific value, resulting in improved combustion. For all the fuels tested, CO emission is highest at 25% load, which can be attributed to lower mechanical efficiency occurs due to higher friction loss and overly lean mixtures result in incomplete combustion which increases CO emissions.

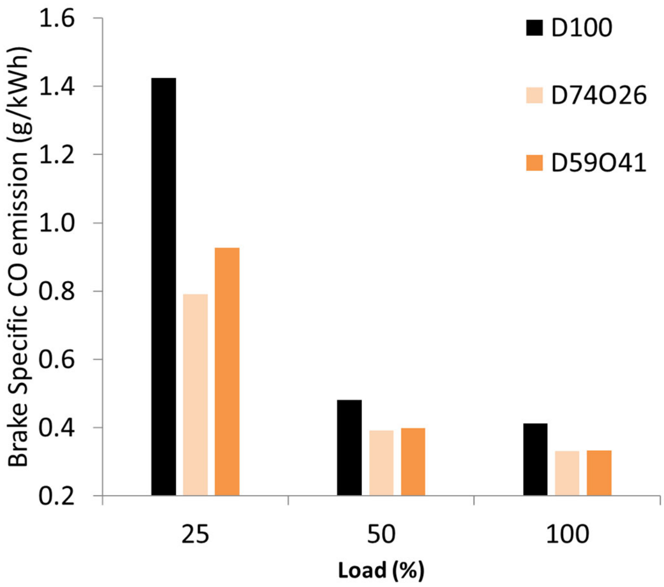

Figure 4. Brake specific CO emission variation of fuel blends

3.2. Emission parameter study

Error! Reference source not found. shows that brake specific NOx emission for orange oil-diesel blends is higher than neat diesel fuel. This can be due to having lower CN. The reduction of fuel CN would increase engine exhaust NO_X emission. The reason is that, as the engine ignition delay increases premixed combustion phase would also be increased, and more fuel would be burned during the premixed combustion phase. The maximum combustion temperature would be increased, which increases the NO_X formation [20].

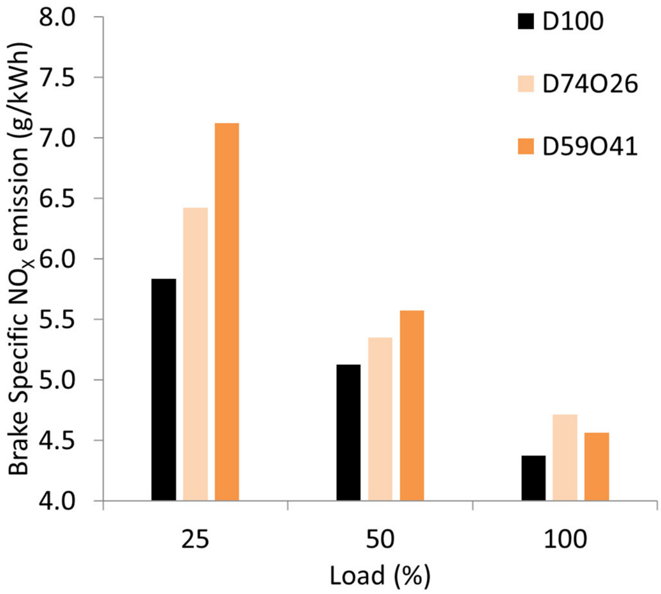

Figure 5. Brake specific NO_X emission variation of fuel blends

Figure 6 shows the variation of brake specific PM emission of neat diesel and orange oil blends. From the figure, it is quite evident that, at all loads, orange oil blends emits lower PM compared to diesel. D74O26 and D59O41 reduced PM by 13.8-37.4% and 21.2-62.3%, respectively, compared to that of diesel fuel. This might be due to complete combustion in which the soot particles are oxidised more than the neat diesel. Furthermore, due to having a lower CN, more fuel would be burned during the premixed combustion phase, which increases the maximum combustion temperature, which might also be responsible for the soot particles' oxidation [21].

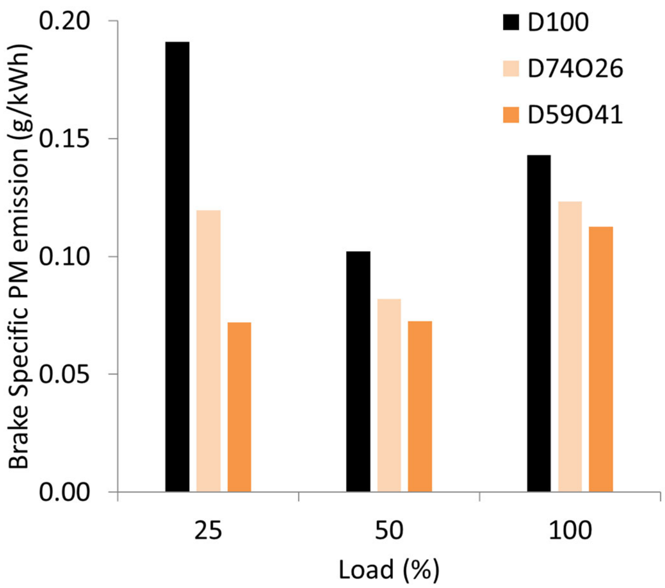

Figure 6. Brake specific PM emission variation of fuel blends

Figure 7 represents the median count diameter of the fuel blends at various load. The median count diameter reduces with the increase in the blend's orange oil percentage for each load. This shows that diesel fuel emits larger size particles compared to orange oil blends.

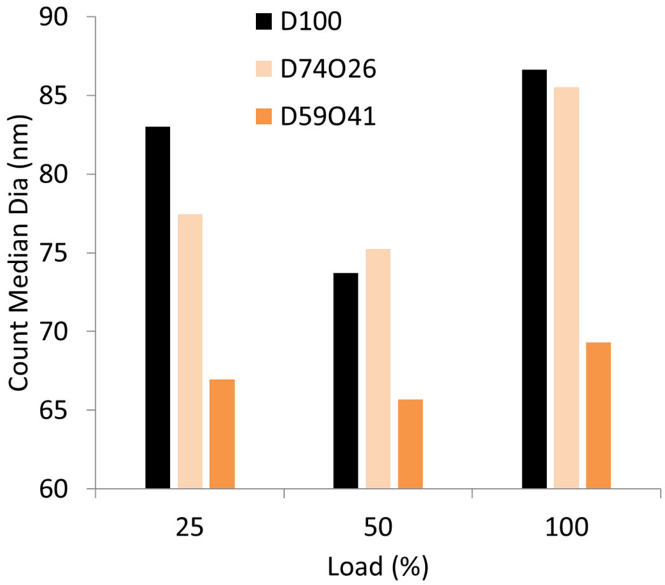

Figure 7. Variation of CMD for different fuel blends

4. Conclusion

An inclusive investigation was performed to evaluate engine performance and emission parameters of a 6-cylinder, 5.9L, turbocharged diesel engine fuelled with orange oil blends (26% and 41% blended with diesel). The results were compared to neat diesel (100D). Engine test runs were conducted by using the selected fuels at 3 loads with constant engine speed (1500 RPM). Based on experimental observation, the following conclusions can be made:

- Orange oil has 2.7% higher LHV, 2.4% higher density and 47% lower viscosity compared to diesel fuel. However, the CN was about 645 lower compared to diesel fuel.
- Orange oil blends produced comparable BP to that ofdiesel fuel.
- The BSFC was lower for the orange oil blends compared to that of diesel fuel. However, at 50% load, where D74O26 has higher BSFC.
- Orange oil blends reduced CO, PM emission compared to that of diesel fuel.
- Orange oil blends produced smaller size particles than that of diesel fuel, and the size reduces with an increase in the orange oil percentage.
- The NO_X emission for the orange oil blends were 4.3-10.1% higher compared to that of diesel fuel.

Finally, based on the obtained results, these blends can be suggested to be used in a diesel engine.

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Appendices

Appendix 1. Quality certificate of diesel used in the oxygenated study

CALTEX REFINERIES (Qld) Ltd
ACN 008 425 581
P.O. Box 40
Wynnum QLD 4178
Telephone: +61 7 3362 7291
Facsimile: +61 7 3362 7295

Quality Certificate

Automotive Diesel -Xtra Low Sulfur

Date : 29-04-2017 **Tank :** D2067
Batch No: DX1568 **Product Code:** DXLQS

CALTEX

METHOD	TEST	SPECIFICATION			RESULT	UNITS
ASTM D4176	Appearance @ 25°C	1	max		1	
ASTM D4737A	Cetane Index (Calculated)	46	min		54.0	
ASTM D5773	Cloud Point (D2500 equivalent)	0	max		0	deg C
ASTM D1500	Colour (ASTM)	2.0	max		L1.0	
ASTM D2624	Conductivity	80-600			455	pS/m
ASTM D2624	Temperature at time of measurement	Report			22.1	deg C
ASTM D130	Copper Corrosion (3 Hrs @ 50 deg C)	1	max		1a	
ASTM D4052	Density @ 15 deg C	0.820-0.850			0.8379	kg/L
ASTM D86	10% Recovered	Report			230.0	deg C
ASTM D86	50% Recovered	Report			273.0	deg C
ASTM D86	90% Recovered	Report			325.5	deg C
ASTM D86	95% Recovered	360	max		339.6	deg C
ASTM D86	FBP	Report			354.4	deg C
IP 387	Filter Blocking Tendency	1.41	max		1.01	
ASTM D93	Flash point	64.0	min		75.5	deg C
IP 450	Lubricity (wsd 1.4) @ 60°C	0.460	max		0.423	mm
Declaration	Lubricity Additive - Tolad 9121	Report			104	mg/kg
Declaration	Total Lubricity Additve content	300	max		104	mg/kg
ASTM D6591	Aromatics	15	min		28.7	mass%
ASTM D6591	Polyaromatic Hydrocarbons	11.0	max		5.7	mass%
Calculated	Stadis 450 (RDE/A/621) content	7	max		1.2	mg/L
ASTM D7039	Sulfur (Total)	10	max		7.3	mg/kg
ASTM D2709	Water and Sediment	0.05	max		<0.01	vol%
Declaration	Additives (other)	Report			Nil Addition	mg/L
ASTM D974	Acid Number (Total)	0.30	max	*	<0.30	mg KOH/g
ASTM D482	Ash	100	max	*	<100	mg/kg
ASTM D4530	Carbon Residue (10 % Bottoms)	0.20	max	*	<0.2	mass%
ASTM D445	Viscosity @ 40 deg C	2.0 - 4.5		*	2.0 to 4.5	sq.mm/sec
ASTM D974	Acid Number (Strong)	nil		*	Nil	mg KOH/g
ASTM D2274	Oxidation Stability	25	max	*	<25	mg/L

* Based on frequency testing # Denotes result off specification

Note 1:- Nil Bio-Diesel (FAME) has been added to this product

This fuel conforms to Australian National Fuel Standards for 2001.

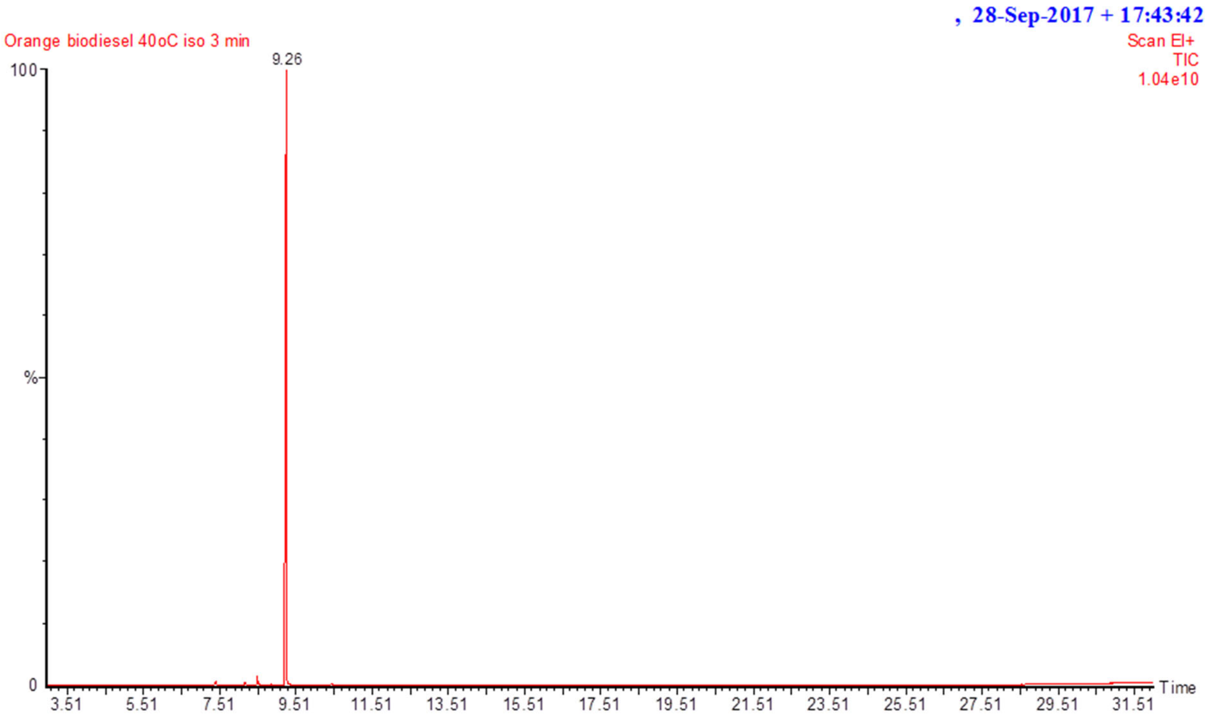
All tests have been performed with the latest revision of the tests indicated. The accuracy of the test results is within the limits of precision shown in the methods.

This certificate relates specifically to the sample tested, but relates also to the entire batch in so far as the sample is drawn according to ASTM D4057.

Date testing completed : 29-04-2017
Approved Signatory : [signature]
Name : K. Baines
Date : 29-04-2017

ID : 705471

Appendix 2. Gas Chromatography-Mass Spectrometry result of neat orange oil



Appendix 3. Standard deviation of different parameters

Parameter	Standard Deviation
CO	±0.071 g/kWh
CMD	±1.2 nm
NO_X	±0.06 g/kWh
PM	±0.03 g/kwh

Table of abbreviation

BSEC	Brake specific energy consumption
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
CI	Compression ignition
CMD	Count mean diameter
CN	Cetane number
LHV	Lower Heating Value
OPO	Orange peel oil
PM	Particulate matter
PN	Particle number