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Effects of Engine Cooling Water Temperature on Performance and Emission Characteristics of a Compression Ignition Engine Operated with Biofuel Blend

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ABSTRACT

The temperature of the coolant is known to have significant influence on engine performance and emissions. Whereas existing literature describes the effects of coolant temperature in engines using fossil derived fuels, very few studies have investigated these effects when biofuel is used. In this study, Jatropha oil was blended separately with ethanol and butanol. It was found that the 80% jatropha oil + 20% butanol blend was the most suitable alternative, as its properties were closest to that of fossil diesel. The coolant temperature was varied between 50 °C and 95 °C. The combustion process enhanced for both diesel and biofuel blend, when the coolant temperature was increased. The carbon dioxide emissions for both diesel and biofuel blend were observed to increase with temperature. The carbon monoxide, oxygen and lambda values were observed to decrease with temperature. When the engine was operated using diesel, nitrogen oxides emissions correlated in an opposite manner to smoke opacity; however, nitrogen oxides emissions and smoke opacity correlated in an identical manner for biofuel blend. Brake specific fuel consumption was observed to decrease as the temperature was increased and was higher on average when the biofuel was used. The study concludes that both biofuel blend and fossil diesel produced identical correlations between coolant temperature and engine performance. The trends of nitrogen oxides and smoke emissions with cooling temperatures were not identical to fossil diesel when biofuel blend was used in the engine.

KEYWORDS

Biofuel, Compression ignition engine, Coolant temperature, Emission, Performance.

INTRODUCTION

Fossil diesel is widely used in a variety of applications, including transportation, combined heat and power generation, industry and irrigation. Hence, it is a large

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contributor to global greenhouse gas emissions and therefore the need to find a renewable alternative fuel is paramount. Use of biofuels as an alternative fuel have been around since before the 1850's, and early cars such as the 'Ford Model T' was originally designed to run on ethanol. However, investments in the biofuels industry began to rise after two world wars and the oil crisis during the late 1900's [1]. The use of first generation biofuels has been debated, as there would be increased prices in the food industry, especially in developing countries [2]. Sustainable 2nd generation biofuels produced from non-food materials can be used as an alternatives to diesel in the Compression Ignition (CI) engines; engine performance and exhaust emission results varied depending on the type of biofuels and engines used. Biofuels could offset about 80% of the life cycle greenhouse gas emissions by replacing fossil diesel use in the internal combustion engines [3]. Engine modifications such as optimisation of compression ratio, injector geometry, cylinder and piston materials, and dual fuelling techniques are recommended for adapting waste derived pyrolysis oils use in the engines [4]. Bergthorson *et al*. [5] reported that oxygenated biofuels produced lower soot emissions than fossil based hydrocarbon fuels. Biodiesel produced less Carbon dioxide (CO_2) and unburnt Hydrocarbon (HC) emissions when compared with fossil diesel [6]. On the other hand, biodiesel emits high Nitrogen oxides (NO_x) and Particulate emissions (PM), which can be reduced by emulsification techniques [7]. Rakopoulos *et al*. [8] reported that the ignition delay did not change but the maximum in-cylinder pressure was decreased when biofuels were used instead of fossil diesel. Alcohols are being used as a blend component with biofuels and/or diesel to improve the combustion characteristics and to reduce pollution. Compared to pure diesel operation, low NO_x and CO_2 emissions have been observed with ethanol-diesel fuel blends [9, 10]. Lujaji *et al*. [11] reported that biofuel blend containing cotton oil, butanol and diesel gave lower thermal efficiency than pure diesel. Smoke and NO_x emissions were found to decrease by a small amount when the butanol blends were used. On the other hand, CO_2 and HC emissions were observed to increase when butanol-diesel blends are used [12]. Jatropha Oil (JO) is non-edible plant oil with the potential to be utilised as a diesel substitute in CI engines [13]. Kumar *et al*. [14] reported that Jatropha-butanol blends gave higher thermal efficiency and lower brake specific fuel consumption than diesel. Similar results were reported when Jatropha biodiesel-butanol blends were used instead of neat Jatropha biodiesel [15]. In this study, jatropha-alcohol blends will be tested in the CI engine to investigate the effect of cooling water temperature on engine performance and exhaust emission.

CI engines are regarded as the most efficient type of internal combustion engines as they offer good fuel economy and low CO_2 emissions. However, at higher loads, considerable amount of particulate matter and nitrogen oxide NO_x are produced from CI engines [16, 17]. The cooling system in CI engines maintain the thermal integrity of the engine structure, as the coolant passes through the case (jacket) surrounding the engine. Therefore, the temperature of combustion within the engine is directly affected by the cooling system. In addition, the cooling system also has an influence on the lubricating oil temperature and the exhaust recirculation gas temperature [18]. Effects on engine performance due to the changes in the temperature of the engine coolant and intake air have been previously investigated, when operated with fossil diesel [19-25]. It was reported that the HC emissions were 25% lower and NO_x emissions were 7% higher when the coolant temperature was increased [20]. NO_x and soot emissions increased as the air intake temperature was increased [21, 22]. Torregrosa *et al*. [23] reported that the ignition delay decreases as the coolant temperature increases. They also reported that increased air temperature influenced NO_x and HC emissions – NO_x gas emission increased at high temperatures for all loads and HC emissions decreased at high temperatures [23]. It was reported that lower coolant temperature may reduce NO_x emissions by up to 30%; with minor improvements to specific fuel consumption, Carbon monoxide (CO) and HC emissions [24]. The chemical composition and physicochemical properties of the biofuels are different than fossil diesel (and gasoline). Hence, it is expected that the effects of coolant temperature on biofuels combustion and exhaust emissions would not be similar to that of standard fossil diesel/gasoline operation. Although researchers investigated the effects of coolant temperature on engine performance and emissions fuelled with fossil diesel; rarely any literature exists investigating the same when biofuel is used in the engine.

The aim of this study is to investigate the effects of cooling water temperature on the performance and exhaust emission characteristics of a CI engine operated with biofuel blend. Jatropha-alcohol blends will be created and physical and chemical properties of these blends will be measured. The properties of the fuels will be analysed and compared against each other, with diesel as the benchmark. A 2-cylinder CI engine will be tested using diesel and a chosen biofuel blend. The temperature of the cooling water will be varied. Engine performance and emission results will then be analysed and discussed to see how the engine performance and emissions vary with the coolant temperature.

MATERIALS AND METHODS

The materials and methods used in this study were:

- Sourcing biofuel and preparation of the biofuel blends;
- Measurement of the properties of the fuels (including equipment used, standards and accuracy);
- Preparation of the engine test rigs (including instrumentations) and associated measurements. They are explained below in two categories.

Biofuels and properties

Standard diesel was sourced from a local service station. Fisher Scientific brand ethanol and butanol were used to prepare biofuel blends. JO is a renewable biofuel, oil was obtained through a supplier, and was manually filtered using a 1 micron sock filter to remove dissolved solids. Fuel properties of JO, diesel, Ethanol (ET), Butanol (BL) and blends (80% JO + 20% BL, 70% JO + 30% BL, 80% JO + 20% ET, and 70% JO + 30% ET) were measured internally using various analytical equipment (Parr Bomb Calorimeter, SETA Flash Point Tester, Hydrometer, Canon Fenski U-tube Viscosity Meter). Viscosities of fuels were measured at various temperatures using a constant temperature bath. All measurements were repeated three times, and an average value was calculated and used in the analysis. Cetane Numbers (CN) of pure JO, BL and fossil diesel were collected from literature [26-28]; however, CN of the JO blends were not measured in this study.

Engine testing and measurements

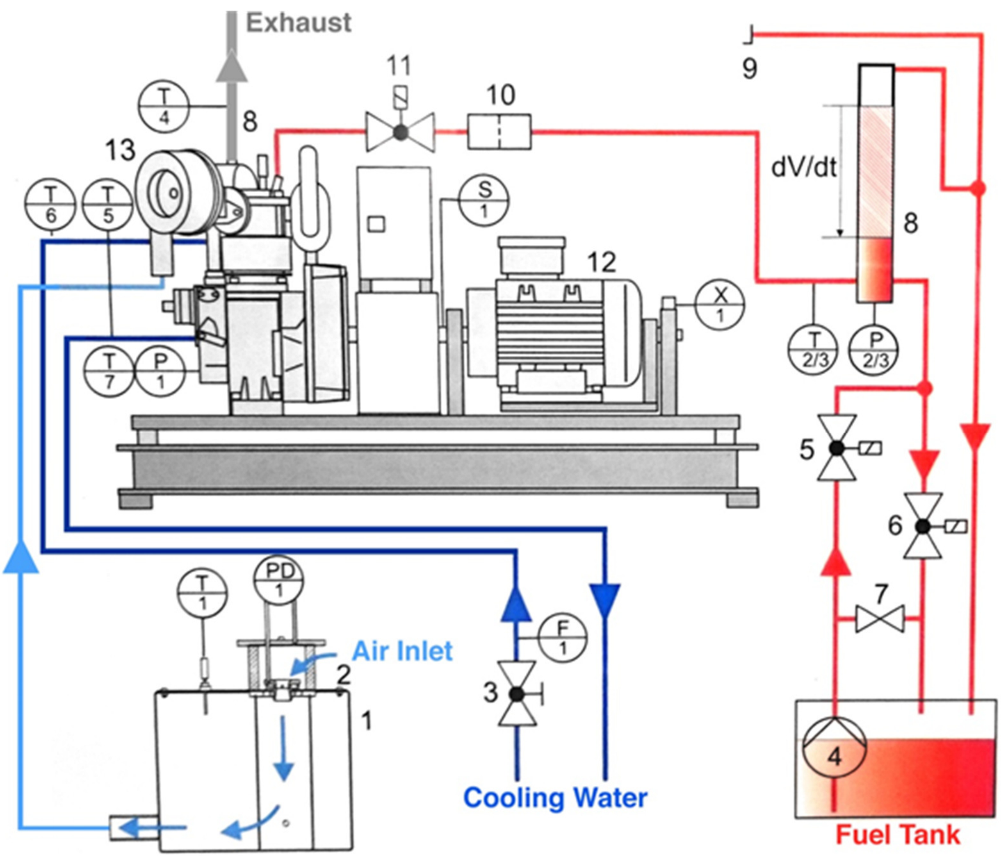
A 2-cylinder Yanmar 2TNV70 engine was used in this experiment – specification of the engine is shown in Table 1. The engine was connected to a GUNT CT-300 test stand (Figure 1). The engine was tested at constant speed of 2,500 rpm and at various load settings (60%, 80% and 100% load). The engine loads were set in Newton-meter (Nm) as percentage torques of the rated power output, e.g. 100% load means the torque required for rated power output at 2,500 rpm.

The performance parameters were recorded from the control panel of the test rig are: speed (rpm), torque (Nm), air intake (litres/min), air temperature (°C), fuel inlet temperature (°C), exhaust gas temperature (°C), coolant water inlet and outlet temperatures (°C), oil temperature (°C), oil pressure (bar) and the time taken to consume a set volume of fuel. The emissions of CO, CO_2, HC, NO_x, and O_2 gases in the exhaust were measured using a Bosch BEA 850 analyser. Smoke opacity values were measured using a BOSCH Smoke meter. An asynchronous motor was used to apply load on the engine.

Table 1. Specification of the CI engine used in the experiment

Manufacturer	Yanmar
Model	2TNV70
No. of cylinders	2
Type of injection	Indirect
Cooling system	Liquid cooled
Bore × Stroke [mm]	70 × 74
Displacement [L]	0.570
Rated output	7.5 kW at 2,500 rpm

The engine has an unconventional liquid cooling system, which uses water supplied directly from the mains (Figure 1). There is no radiator within this set-up, and the outlet water, from the engine jacket, is sent to an external reservoir. This allows greater control of the cooling water flow rate. The outlet cooling water temperature was varied by using the flow rate control valve. As the flow rate is increased, the outlet water temperature decreases. Engine performance and emission parameters were recorded for each load settings.



1. Settling tank
2. Air filter
3. Cooling water control valve
4. Fuel pump
5. Filling valve
6. Drain valve
7. Bypass
8. Fuel measurement
9. Diesel return line
10. Fuel filter
11. Shut off valve
12. Asynchronous motor
13. Combustion engine

Figure 1. GUNT CT-300 experimental test rig

RESULTS AND DISCUSSION

The properties of the fuel blends and engine test results are discussed separately in the following sub-sections. The blend results were compared with the corresponding fossil diesel results.

Fuel properties

Fuel properties of pure diesel, jatropha, ET, BL and JO blends are shown in Table 2. The density of JO is considerably higher than the density of diesel and both of the alcohols. The ignition delay could be longer for fuels with high density. When JO is blended with the alcohols, the density of the blend decreases as the proportion of alcohol is increased. The JO blends containing ET are less dense when compared to the fuel blends containing BL, due to the density of pure ET being lower than pure BL. The viscosity of the fuel is important, higher the viscosity larger will be the fuel droplets sizes and hence poorer combustion inside the engine cylinder. It was found that the JO-alcohol based fuel blends have a lower viscosity than 100% pure JO at room temperature, due to the low viscosities of ET and BL. However, the kinematic viscosities of all the blends are still considerably higher than the viscosity of 100% pure diesel. The 70% JO + 30% ET blend has the lowest measured viscosity out of all four blends. Figure 2 shows how the kinematic viscosity of the fuels varied as the temperature was increased. At 80 °C, the kinematic viscosities of all fuel blends are comparable to the viscosity of fossil diesel. The flash point temperature for 100% pure JO is much higher than that of diesel (Table 2). The 80% JO + 20% BL blend has reasonable flash point temperature.

Table 2. Fuel properties of jatropha, diesel and blends

Fuel sample	Viscosity at room temp. (22.8 °C) [cSt]	HHV [MJ/kg]	Density [kg/m^3]	Flash point [°C]	CN
100% Diesel	3.28	44.95	835.00	62.50	50.20
100% JO	57.07	39.45	914.33	206.00	44.60
100% BL	35.69	35.69	810.00	34.33	17.00
100% ET	28.11	28.11	790.00	17.00	8.00
80% JO + 20% BL	24.16	38.50	894.00	38.67	-
70% JO + 30% BL	18.08	37.14	883.33	36.33	-
80% JO + 20% ET	19.70	36.61	890.67	17.00	-
70% JO + 30% ET	13.65	35.94	878.00	17.00	-

Heating value of the fuel is another important parameter, higher heating value will produce higher power output i.e., for the same engine load less fuel is required for fuel with higher calorific value. Diesel has the highest heating value, whilst ET has the lowest. It was observed that as the proportion of alcohol was increased in the blends, the Higher Heating Value (HHV) decreased. Blends containing ET have a lower HHV, on average, when compared to blends containing BL. The 80% JO + 20% BL blend has the highest HHV and is close to the value of 100% pure JO, making it the most desirable blend to use in the engine. CN for diesel is the highest and lowest for ET. CN of JO-alcohol blends were not measured. BL has a higher CN than ET, it can be assumed that the fuel blends made of BL have a higher CN, on average, when compared to the ET based blends.

By comparing the properties of JO and JO-alcohol blends with the corresponding properties of the standard fossil diesel, JO-BL blends were found to be feasible fuel for the diesel engine. Furthermore, among the JO-BL blends, it was determined that 80% JO

+ 20% BL was the most suitable biofuel blend to use in the engine, as its measured properties were closest to that of pure diesel.

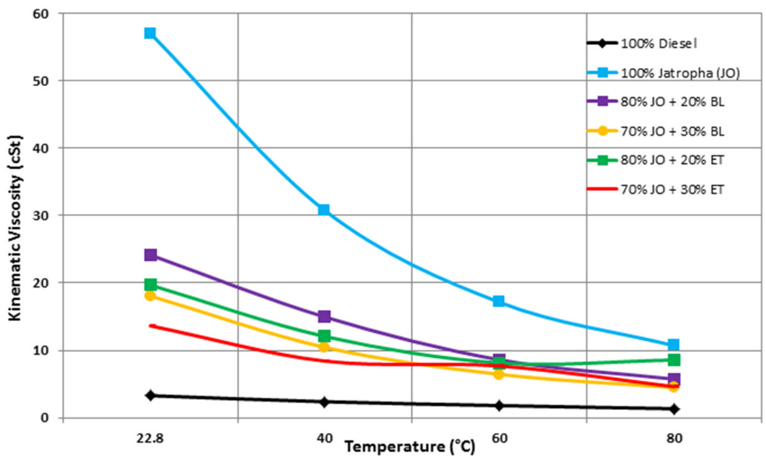
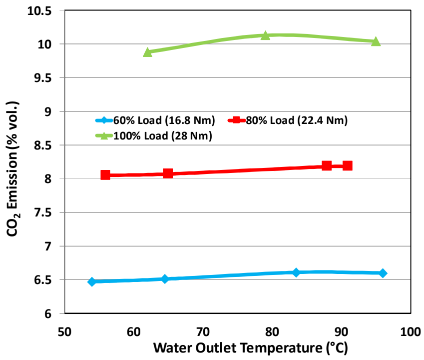


Figure 2. Viscosity results at various temperatures

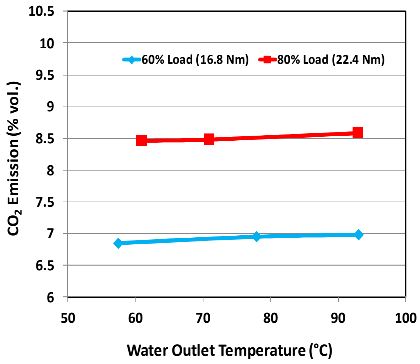
Engine test results

The 80% JO + 20% BL biofuel blend was used in the engine at various loads and coolant temperature. The performance and emission results were compared with pure diesel operation (Figures 3-5). At full load (100% load), the high content of BL in the blend caused a high concentration of butanol vapour in the combustion chamber which caused minor engine knocking, and hence 100% biofuel results are not shown in the figures. It was observed that for both biofuel and diesel, as the cooling water temperature was increased, there was an increase in the CO_2 emissions, for all loads (Figure 3a). The increase in CO_2 emissions caused due to better burning of the fuel in the combustion chamber. CO_2 emissions trends were identical for both fuels; however, at low load, the CO_2 emissions were slightly higher in the case of JO-BL blend (Figure 3a). It was seen that at 80% load, diesel CO emissions didn't change much with the increase in combustion temperature; whereas biofuel CO emissions decreased by about 31% when the temperature was increased from 60 to 90 °C. This can be explained as, at high combustion temperature, combustion of biofuels improved due to the higher oxygen content in the biofuel blend. As a result of improved combustion, biofuel CO emissions decreased. However, at partial load, trend of biofuel CO emissions with the water temperature was different, CO emissions were minimum at about 80 °C (Figure 3b). The reason for this could be that the change in the CO emissions were very low compared to the measurement accuracy of the instrument used in this study. In addition, it was observed that, in general, biofuel CO emissions were higher than diesel. Compared to fossil diesel operation, higher amount of biofuel blend was combusted in order to produce the same power output. Hence, it was believed that, for the same engine load, higher amount of biofuel burning caused higher CO emissions than that of fossil diesel. Figure 3c shows that the O_2 emissions decreased by a small amount with the increase in cooling temperatures for both biofuel and diesel fuels. As the quality of combustion increases at higher temperatures, more oxygen is used within this process; therefore O_2 emissions are expected to decrease. However, for all loads, JO-BL blend emitted lower O_2 gases than diesel (Figure 3c), most of the oxygen present in the biofuel was converted to either CO or CO_2 gases (Figure 3a and 3b).

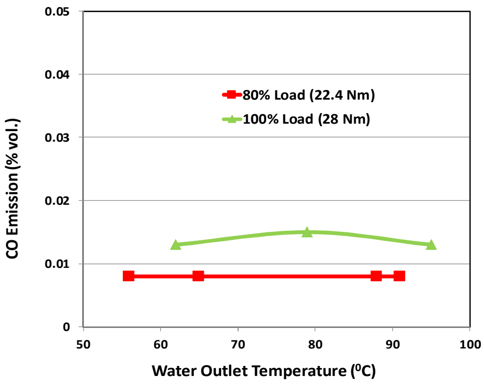
In the case of JO-BL blend operation and at 60% load, it was observed that the NO_x emissions decreased as the cooling water temperature was increased. However after reaching a minimum value, the NO_x emissions began to increase (Figure 4a). On the other hand, at 80% load, the opposite was observed; the NO_x emissions increased with cooling water temperature until reaching a maximum value; then NO_x emissions decreased as the cooling water temperature increased. When compared to diesel, the NO_x values behaved differently for both loads – NO_x emissions tend to increase at higher temperatures overall, except at 60% load. It was found that at 80% load, JO-BL blend gave lower NO_x levels than diesel even at 93 °C (Figure 4a). Biofuel smoke opacity emissions are directly related to NO_x emissions (Figure 4b). However, in the case of diesel, smoke opacity and NO_x emissions values were in opposite manner. Exhaust gas temperature is important for heating application in combined heat and power plant. For both fuels, the exhaust temperature increased, for all engine loads, as the temperature of the cooling water was increased (Figure 4c). The increased temperature of combustion produces exhaust gases at higher temperatures. Exhaust temperatures results for both diesel and biofuel blend were very similar to each other (Figure 4c).



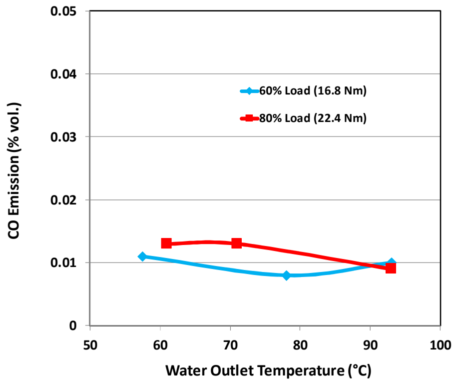
(a) fossil diesel: CO_2 emissions



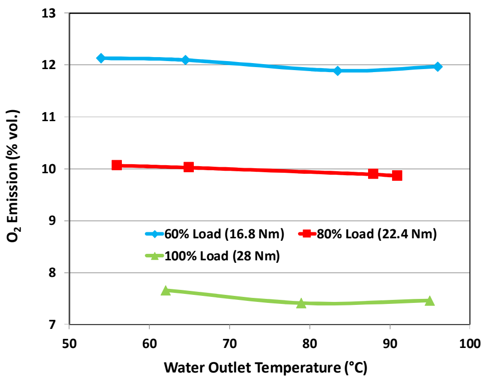
(a) biofuel: CO_2 emissions



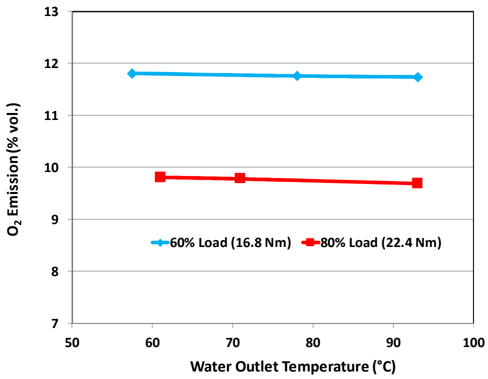
(b) fossil diesel: CO emissions



(b) biofuel: CO emissions

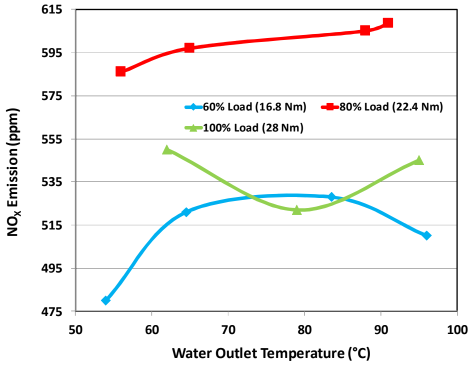


(c) fossil diesel: O_2 emissions

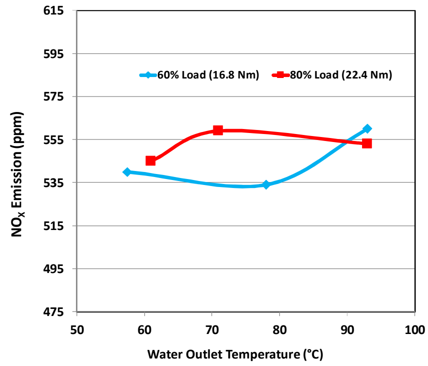


(c) biofuel: O_2 emissions

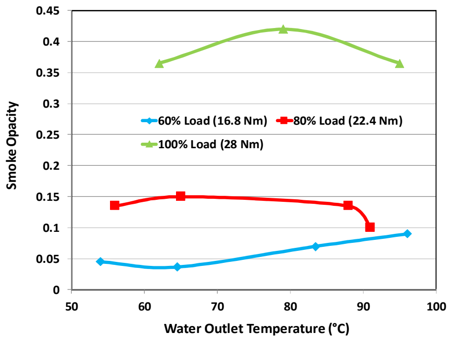
Figure 3. Exhaust emissions results as a function of engine coolant temperature



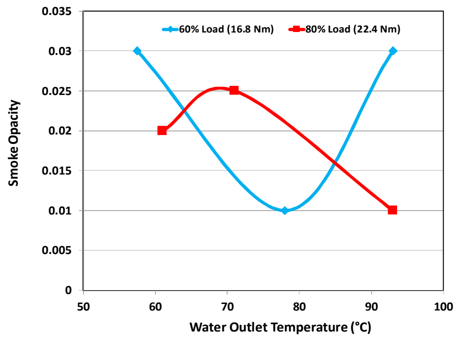
(a) fossil diesel: NO_x emissions



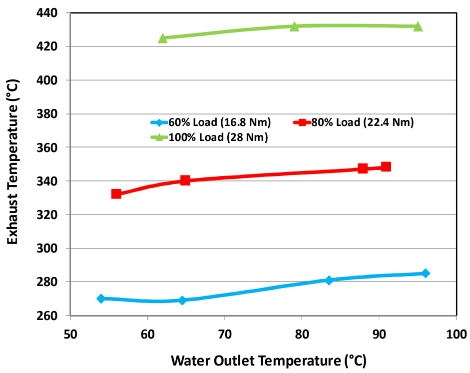
(a) biofuel: NO_x emissions



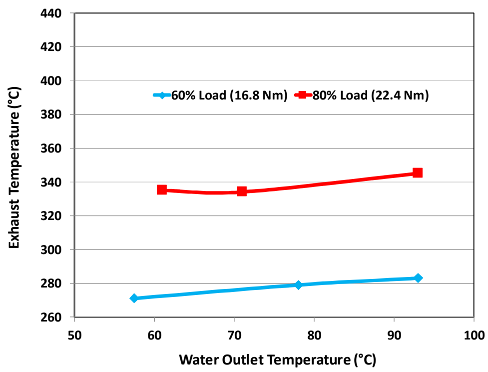
(b) fossil diesel: Smoke opacity



(b) biofuel: Smoke opacity



(c) fossil diesel: Exhaust temperature



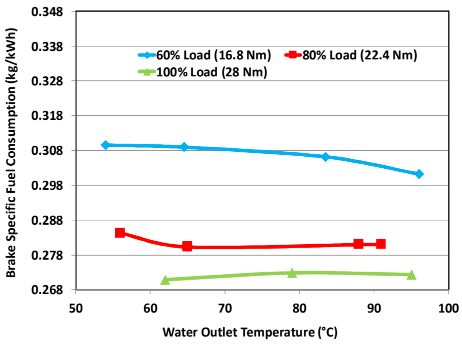
(c) biofuel: Exhaust temperature

Figure 4. NO_x, smoke emission and exhaust gas temperature results as a function of engine coolant temperature

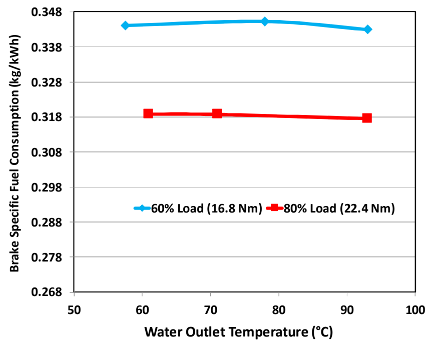
Across all loads, Brake Specific Fuel Consumption (BSFC) of both fuels decreased, as the coolant temperature was increased (Figure 5a) – meaning less fuel is required to produce the same amount of power when the temperature of combustion is increased. Interestingly, at 60% load, biofuel BSFC value increased slightly with the cooling water temperature, before it gradually decreased (Figure 5a). When compared to diesel, biofuel BSFC values are higher at each load (Figure 5a). This is due to the difference in the properties of the two fuels. The biofuel was measured to have a lower heating value, therefore it was observed that the average BSFC was higher for the biofuel blend to provide the same power output, at all loads, when compared to diesel.

In addition, the higher viscosity of the biofuel blend also contributes to increasing the BSFC, as the viscosity affects the spray characteristics of the fuel during the injection period and high viscosity leads to less efficient mixing of the fuel with air. In general, for both fuels, the overall thermal efficiency increased as the temperature of the cooling water was increased (Figure 5b). The thermal efficiency is directly linked to the BSFC –

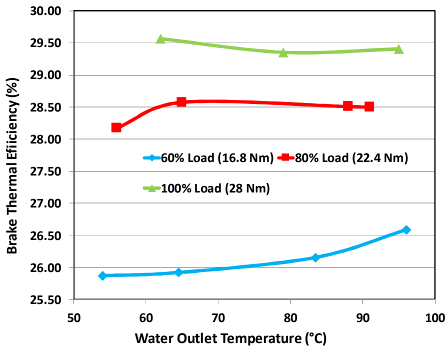
the higher is the load higher is the efficiency due to the lower BSFC values at higher loads. The thermal efficiency of the biofuel blend is slightly higher when compared to diesel, for example, at 80% load; this is 3.5% higher than the corresponding diesel value. The oxygen content in biofuel is higher than fossil diesel. It was thought that micro-emulsion phenomenon (due to the BL component in the blend) and higher oxygen content in the biofuel blend helped to achieve higher brake thermal efficiency than fossil diesel. The volumetric efficiency is linked to the air flow rate. The air flow rate was observed to decrease with the increase in coolant temperature, but only very slightly; hence the volumetric efficiency decreased as the temperature of the cooling water was increased (Figure 5c), for all loads. This is similar to what was observed when diesel was used to operate the engine – for example, at 80% load; the biofuel volumetric efficiency is 1% higher as compared to diesel.



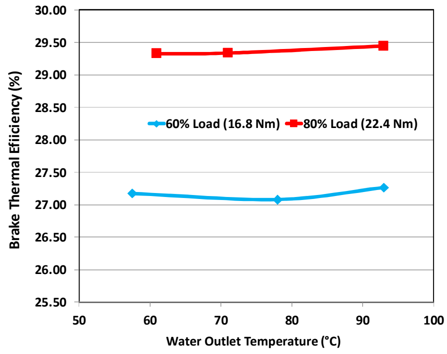
(a) fossil diesel: BSFC



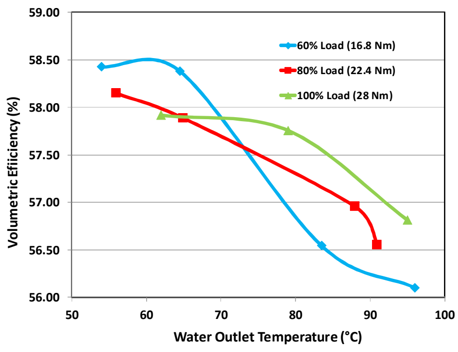
(a) biofuel: BSFC



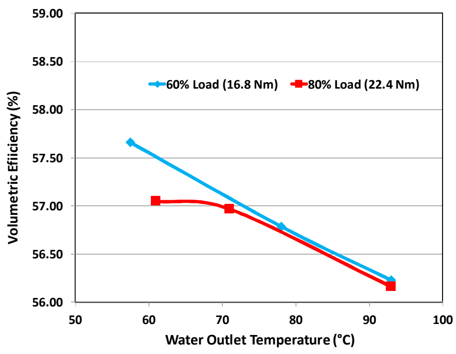
(b) fossil diesel: Thermal efficiency



(b) biofuel: Thermal efficiency



(c) fossil diesel: Volumetric efficiency



(c) biofuel: Volumetric efficiency

Figure 5. Results showing engine performance characteristics as a function of engine coolant temperature

CONCLUSIONS

Renewable alternatives such as biofuels and optimisation of the engine operating parameters can enhance engine performance and reduce emissions. In this study the fuel properties of fossil diesel, JO and JO-alcohol blends were measured; and biofuel blends properties were compared with the corresponding properties of fossil diesel. JO-BL blend was tested in a 2 cylinder, 4-stroke, indirect injection CI engine to investigate the effect of cooling water temperature on engine performance and exhaust emission characteristics. The engine was operated at 60%, 80% and 100% loads and the cooling water temperature was varied between 50 °C and 95 °C. It was found that blending JO with alcohols significantly improved the fuels properties of JO. Blend containing 80% JO and 20% BL was selected for engine testing due to better properties amongst all four biofuel blends.

Our initial study showed that effect of coolant temperature on engine performance and exhaust emission characteristics differ when the engine was operated on biofuel blend instead of diesel. The major findings of the study are summarised below:

- Overall, for both diesel and biofuel operation, the increase in the coolant temperature enhanced the combustion process. As a result of better combustion, CO_2 emissions were increased. In general, it was found that both CO and CO_2 emissions were higher, and O_2 emissions values were lower, when the engine was operated with the biofuel blend, in comparison to diesel;
- At 80% load, diesel CO and O_2 emissions didn't change much with the increase in combustion temperature; whereas biofuel CO and O_2 emissions decreased by about 31% and 6% respectively; when the temperature was increased from 60 to 90 °C;
- Exhaust gas temperatures results for both diesel and biofuel blend were very similar to each other. No clear trends were observed on NO_x and smoke emissions. At 80% load and at 90 °C temperature, JO-BL blend gave 10% lower NO_x levels than diesel. The smoke and NO_x gas emission trends were correlated in an identical manner for biofuel blend;
- For both fuels, the BSFC was observed to decrease with temperature. The thermal efficiency of the biofuel was found to be slightly higher than diesel. On the other hand, for both biofuel and diesel, the volumetric efficiency decreased slightly with the increase of coolant temperature.

Overall, it can be concluded coolant temperature does have significant influence on engine performance parameters and exhaust emission gases, and depends on the type of fuels and engines used. The coolant temperature for each biofuel blend needs to be established by carrying out engine tests for optimum engine performance and low exhaust gas emissions.

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