Improvement of emissions characteristics and exhaust temperature in single cylinder diesel engine fuelled with algae oil additive

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Abstract. An experimental study has been carried out to evaluate the emission characteristics and exhaust gas temperatures of algae oil additive in diesel blends. Diesel fuel (D100) and fuel blends of algae oil at 1% (A1), 2% (A2), 3% (A3) and 4% (A4) concentration were prepared and put to test on an unmodified single cylinder diesel engine. The test was conducted at a constant engine speed of 1500 rpm with varying engine load (0, 2, 4 and 6Nm). The engine performance of exhaust gas temperature and exhaust emissions of carbon monoxide (CO), carbon dioxide (CO₂), and oxide of nitrogen (NOₓ) were measured and analyzed. The results showed that the properties of algae oil additive were comparable to diesel fuel and it was successfully used to run the diesel engine. In terms of exhaust emissions, A4 blends exhibited lowest CO and NOₓ emission by about 90.9% and 21% lower compared to pure diesel D100 at engine load of 6Nm, respectively. However, A4 blends also exhibited the highest CO₂ percentage emission which is about 31% more than D100 and exhaust gas temperature of 1.22% higher compared to D100 at 4 Nm engine load.

1. Introduction

Fossil fuels such as petroleum oil, coal, and natural gas are one of the major energy sources in this world, besides renewable energy and nuclear energy. They are important for the economic growth and development of the country. Today, their main consumption is in the transportation sector. The increasing usage of transportation worldwide has increased its energy consumption level, leading to an energy crisis where energy source availability and its consumption is an unsustainable state. Besides the energy crisis, fossil fuel is also the main contributor to an environmental crisis such as air pollution. The major exhaust emission emitted from internal combustion engines using fossil fuel are hazardous, i.e. hydrocarbons (HC), oxides of carbon (CO and CO₂), oxides of nitrogen (NO and NOₓ), and oxides of Sulphur (SO₂ and SO₄) [1]. Almost 98% of carbon emission from this energy combustion contributed to air pollution and other hazardous effects that have caused global warming and serious health concern [2].

1.1. Alternative Fuel

The depletion of fossil fuel in the near future triggered the researchers to come out with the alternative fuel. It is crucial to develop renewable yet clean fuels to meet the world demands and needs [4]. The research of the new alternative fuels began in the late 1970s and early 1980s [3]. Alternative fuels are
commonly produced from domestic resources, therefore, can reduce energy reliance. Some of the alternatives fuels are alcohols, vegetable oils, biodiesel, gaseous fuels, ethers, and fuel cell, [5]. These alternative fuels are also known to improve the productivity of the diesel engine while its combustion emission can reduce environmental pollution. Retrieved from other than crude oil, alternative fuels can be used with slight or no modification with the current petrol or diesel internal combustion engine. However, for diesel engine, one of the disadvantages of using alternative fuels such as biodiesel is its higher carbon dioxide (CO₂) emissions [6]. The emission of oxide of nitrogen (NOₓ) is also slightly higher when biodiesel is used compared to diesel fuel [7, 8]. According to Devan et al. [9] in the research of biodiesel, a higher percentage of biodiesel (poon oil) in the diesel blends able to reduce NOₓ emission but increases the Hydrocarbon (HC) and carbon monoxide (CO) emissions.

1.1.1. Algae as an Alternative Fuel
Biofuels can be classified into primary and secondary biofuels [10]. Based on the classification, biofuel produced from algae is classified in the third generation of secondary biofuel. As an alternative liquid transportation fuel, algae oil has been proposed as both a sustainable and economically feasible solution [11]. Compared to other crops, algae are the most promising source of oil due to its fast growth, its ability to grow in wide range conditions, have potentially higher yield rates and comparable properties to standard biodiesel [11-12, 14]. Furthermore, the oil content of algae (70% oil by weight of dry biomass) is 25 times higher than the oil content that yields from traditional biodiesel (oil palm) [13]. Algae can grow in bioreactors, farms, in fresh, brackish or salt water or non-arable lands which are unsuitable for growing conventional agriculture [15, 16]. The emissions from algae biodiesel showed a lower CO and HC emissions compared to petroleum diesel [17]. Nevertheless, the number of studies on the properties and performance of algae oil running on the diesel engine is still insufficient. The major studies are basically on the addition of algae with alcohols and diesel fuel but not the study of raw algae addition of algae with diesel fuel [18, 19]. Therefore, the present paper aimed to identify the exhaust emission of carbon monoxide (CO), carbon dioxide (CO₂), and oxide of nitrogen (NOₓ) and engine performance of exhaust gas temperature (EGT) at different concentration (1,2,3,4%) of blended raw algae fuel with diesel fuel in single cylinder diesel engine.

2. Materials and Methods

2.1. Preparation of Algae Oil

2.1.1. Algae separation from water
The method used for separation of algae from water is the filtration method followed by drying method. Vacuum Filtration machine was used to collect the sediment of algae using the pressure from the vacuum. The obtained algae sediment was then dried in an oven at 40 °C for 18 hours to remove the moisture completely.

2.1.2. Algae oil extraction
The supercritical fluid extraction (SFE) method was selected to extract oil from algae sediment. It is a more efficient method than conventional solvent separation method as it can extract nearly 100% of the oil [12]. The SFE method uses heated and liquefied carbon dioxide (CO₂) that is kept under pressure to the point that it has gas and liquid properties. Besides using CO₂ as the main solvent, SFE methods also used ethanol as co-solvent. During the process, the carbon dioxide is mixed and combined with algae which turns algae fully into the oil. After the extraction process, the rotary evaporator was then used to remove the solvent (ethanol) from the oil extracted to obtain only the pure algae oil.
2.2. Experimental Apparatus and Procedure

2.2.1. Fuel blending preparation and properties

Algae biodiesel fuel blends were prepared on the volume basis for engine testing while keeping the important properties within the acceptable limit following the American Society for Testing Material (ASTM) standard. Algae oil of different percentage (1, 2, 3 and 4%) was measured and added to 100 ml diesel oil. The blending process was conducted using a mechanical mixing method where the diesel-algae mixture is stirred continuously using a magnetic stirrer for 15 minutes at room temperature with a speed of 500 rpm. The basic properties of the fuels such as density, viscosity, and calorific value were measured experimentally. The density and viscosity of the algae biodiesel were measured by using Anton Paar viscometer and the calorific value was measured using bomb calorimeter. The properties of diesel fuel (D100) and algae biodiesel blends are listed in Table 1.

Table 1. Diesel fuel and algae biodiesel blends properties.

| Fuel property | Unit       | Diesel fuel (D100) | 1% of algae oil (A1) | 2% of algae oil (A2) | 3% of algae oil (A3) | 4% of algae oil (A4) | Standard Test Method |
|---------------|------------|-------------------|----------------------|----------------------|----------------------|----------------------|---------------------|
| Density (at 15°C) | kg/m³      | 850               | 845.8                | 845.2                | 844.8                | 844.6                | ASTM-D 1298         |
| Viscosity (at 40°C) | mm²/s      | 2.6               | 3.069                | 3.003                | 2.943                | 2.920                | ASTM-D 445-01       |
| Calorific Value | kJ/kg      | 45500             | 44546                | 44529                | 44382                | 44190                | ASTM-D 4809         |

2.2.2. Engine testing

The experiment of engine performance and emission characteristics were conducted on a vertical single cylinder, four strokes, air-cooled, diesel engine by the Yanmar TF-M by Yanmar Co. Ltd. The engine was coupled with eddy current dynamometer with a maximum power input of 20 kW at 2450 rpm to 10000 rpm. The full details of the engine are tabulated in Table 2. Exhaust gas composition was measured using the MRU gas analyzer Vario plus. The gas analyzer measures the emissions of CO, CO₂, and NOₓ for this experiment. The measurement range and accuracy of the gas analyzer are stated in Table 3.

Table 2. The experimental engine specification.

| Parameters             | Values                                      |
|------------------------|---------------------------------------------|
| Type                   | Vertical cylinder, 4-cycle air cooled diesel engine |
| No of cylinders        | 1                                           |
| Bore x Stroke          | 70 mm x 57 mm                               |
| Combustion             | Direct injection                            |
| Maximum Output         | 3.5 kW                                      |
| Engine Rated Speed     | 3600 rpm                                    |

Table 3. Exhaust gas analyzer measurement range and accuracy.

| Exhaust gas           | Measurement range | Accuracy                  |
|-----------------------|-------------------|---------------------------|
| Carbon monoxide (CO)  | 0-10,000 ppm up to 10% | ± 0.03% or ±3% of reading |
| Carbon dioxide (CO₂)  | 0-30%             | ± 0.5% or ±3% of reading  |
| Nitrogen oxides (NOₓ) | 0-200 ppm         | ± 5 ppm or 5% reading     |
2.2.3. Engine test procedure.
The experiment was carried out by using the diesel fuel (D100) and algae blended with diesel fuel with different percentage: 1% of algae oil (A1), 2% of algae oil (A2), 3% of algae oil (A3) and 4% of algae oil (A4) to each 100ml of fuel blend volume and the procedures of the engine testing were as follows:

1. The engine and the gas analyzer were warmed-up by running using D100 for 15 minutes until it reaches a steady condition including constant engine temperature.
2. The A1 blends are fuelled in fuel tank up to 100ml.
3. The gas analyzer was set up to ensure the receiver is pointed directly towards the incoming gas expelled from the machine.
4. The running speed of the engine was set at 1500 rpm, while its engine load was first set at 0 Nm.
5. The time taken for 10 ml drop of fuel blend in each run was recorded. The corresponding results on the gas analyzer and exhaust temperature were observed and recorded.
6. Step 4 and 5 were repeated at an engine load of 2 Nm, 4 Nm, and 6 Nm.
7. Step 1 until 6 was then repeated with A2, A3, A4, and D100 blend.

3. Results and Discussion

3.1. Carbon Monoxide (CO) Emission
Result of CO emission (in ppm) for algae biodiesel at different engine load at 1500 rpm is presented in Figure 1. From the figure, the trends of CO emission were inconsistent as engine load is increased. At 0Nm engine load, D100 showed the least CO emission which is 0.667 ppm while A4 blends showed the highest CO emission which is 15.333 ppm. At high engine load of 6 Nm, A2 blends showed the highest CO emission of 28.667 ppm which is 56% higher compared to D100, while A4 blends showed the lowest CO emission of 1.667 ppm which is about 90.9% lower compared to D100. There was more CO emission produced at higher engine load due to the high amount of burned fuel mixture [20]. The drastic reduction of CO emission for algae biodiesel A3 and A4 at high load may be due to better mixing of blends that improved the combustion [21]. The presence of algae in blends affect the CO emission as algae biodiesel has high oxygen content and low viscosity. As the viscosity of fuel is low, the formation of CO emission will also be lower [22].

![Figure 1. CO Emission vs Engine Load at a constant speed of 1500 rpm.](image-url)
3.2. Carbon Dioxide (CO₂) Emission
The variation of CO₂ emission with engine load at a constant speed of 1500 rpm is shown in Figure 2. Based on the result, algae biodiesel mostly exhibited a higher percentage of CO₂ emission compared to D100 at all engine load, except for A1 blends. At 6 Nm engine load, A4 blends have the highest CO₂ percentage emission which is 31% more than D100. On the other hand, at 0 Nm, 2 Nm, 4 Nm, and 6 Nm engine load, A1 blends exhibited 30%, 21%, 5% and 11% less CO₂ emission than D100, respectively. The higher CO₂ emission of algae biodiesel was generally due to its higher content of oxygen. The high oxygen bounded in the biodiesel provides better mixing rate that will lead to better oxidation of fuel which resulted in more CO converted to CO₂ [23].

![Figure 2. CO₂ Emission vs Engine Load at a constant speed of 1500 rpm](image)

3.3. Nitrogen Oxides (NOₓ) Emission
The NOₓ emission of D100, A1, A2, A3, and A4 at different engine load at a constant speed of 1500 rpm is shown in Figure 3. Based on the result, the NOₓ emission increased along with the increment of engine load. At 4 Nm engine load, A4 blends showed the highest NOₓ emission which is 71% higher compared to D100. However, at an engine load of 6 Nm, A4 blends showed reduction by 21% compared to D100, due to the decrease of premixed combustion that was led by poor mixing of fuel [6]. In addition, the higher in-cylinder temperature is favored for NOₓ formation due to high in-cylinder pressure, particularly at high load. Besides that, higher combustion temperature and higher oxygen concentration during the combustion process are some of the factors affecting NOₓ formations [24]. Similar results were also obtained by other researchers since the higher adiabatic flame temperature and higher oxygen contents of the biodiesel blends produced higher NOₓ emissions [25-28].
Figure 3. NO\textsubscript{x} Emission vs Engine Load at a constant speed of 1500 rpm

3.4. Exhaust Gas Temperature (EGT)

Figure 4 shows the engine performance of exhaust gas temperature (EGT) with engine load at a constant speed of 1500 rpm. Based on the result, the EGT mostly increased as the engine load increased due to the injection of more fuel into the cylinder. At 4 Nm engine load, A4 blends exhibited the highest EGT with 1.22% higher compared to D100. Al-Shemmeri et al [29] reported that the NO\textsubscript{x} emitted and the exhaust gas temperature is interrelated to each other as the higher temperature of the combustion will result in the higher forms of NO\textsubscript{x} emissions. Besides, the formation of the NO\textsubscript{x} emission also can be related to the engine operation depending on air-fuel equivalence ratio as NO\textsubscript{x} were affected with the temperature of the combustion. In addition, the algae biodiesel happened to have higher exhaust gas temperature than diesel ascribable to the presence of oxygen content in the fuel that causes better combustion as EGT depends on the oxygen content of the fuel and the injection rate [30]. However, the decrement of EGT at 6 Nm engine load may due to the surrounding humidity during engine testing which also affects the engine performance especially air intake temperature.

Figure 4. EGT vs Engine Load at a constant speed of 1500 rpm

4. Conclusion

The exhaust emission and exhaust gas temperature of diesel fuel and algae biodiesel blend were successfully collected from running in a vertical single cylinder unmodified diesel engine at different engine load. The following conclusion can be drawn:
The density, viscosity and calorific value of algae blended with diesel fuel are within an acceptable range when compared with standard diesel fuel according to the ASTM standard.

- At high engine load of 6 Nm, A4 blends have the lowest CO and NOx emission by almost 90.9% and 21% lower than D100, respectively, as it has high oxygen content and low viscosity.
- At 4 Nm engine load, A4 blends exhibited the highest CO2 percentage emission which is about 31% more than D100, while its exhaust gas temperature was 1.22% higher than D100.
- CO2 emission for algae biodiesel increased due to its high oxygen content resulted from better mixing that leads to better combustion. Better oxidation of fuel resulted in more CO being converted to CO2.
- NOx emission is higher for algae biodiesel compared to diesel fuel due to its higher oxygen content and premixed combustion.
- EGT increased as algae oil content in the blend increased. The EGT depends on the humidity, oxygen content of the fuel and the injection rate.

However, there are still many improvements and research needed to be done especially in the use of a different ratio of algae fuel and different set of engine test conditions to have lower exhaust emissions and better engine performance.

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