Effect of algae fuel addition on fuel consumption and thermal efficiency of single cylinder diesel engine

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Abstract. The objective of this paper is to evaluate the brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) of algae fuel blended in diesel fuel. Fuel blends of 1% of algae fuel (B1), 2% of algae fuel (B2), 3% of algae fuel (B3) and 4% of algae fuel (B4) to each 100 ml of fuel blend volume were prepared. Each algae-diesel fuel blend was tested on single-cylinder diesel engine by varying the engine loads (0, 2, 4 and 6 Nm) at a constant engine speed of 1500 rpm. Different BTE and BSFC engine performance levels were the measured parameters. Based on the result of the engine performance tests, it can be concluded that B4 blends in diesel fuel produced better BTE with 17% at 4 Nm engine load than diesel fuel. Meanwhile, the BSFC was lower for B4 with 16% compared to diesel fuel at lower engine load.

1. INTRODUCTION

Current trend of energy supply and consumption is flagrantly unsustainable from environmental, economic and sociological aspects. As the vital movers of economic growth, the continuing availability of energy is very important. A high energy consumption level contributes to a high standard of living in developed countries. Other than renewable energy and nuclear energy, petroleum products are one of the significant energy sources globally. Petroleum oil, coal, and natural gas are examples of fossil fuels. As the population growth has increased, the demands of fossil fuel have also been rising and will cause the depletion of fossil fuel. This urges researchers to find a solution to overcome the problem. New alternative fuel research has initiated in the late 1970s and early 1980s [1]. Alternative fuels, other than crude oil, can be applied with little or no alteration with contemporary petrol or diesel internal combustion engine. The alternative fuels become the interest of researchers because it is frequently generated from domestic resources that mitigate energy dependency. Alternative fuels also typically reduce vehicle exhaust emission that will reduce air pollution. Many studies have been conducted on alternative fuels, especially in transport vehicles, and they have revealed various possible alternative
fuels, such as biofuels, that can be used, namely biodiesel, methanol, ethanol, straight vegetable oils (SVO) and hydrogen [1,2].

Based on the classification of biofuels, it is shown that algae are the substrate from the third generation of secondary biofuels that is linked to utilization of carbon dioxide as its feedstock [3,4]. Biodiesel produced by algae is called algae biodiesel. Many advantages of biodiesel have been discovered, such as higher combustion efficiency, higher biodegradability, domestic origin and reduce the dependency on imported petroleum [5,6]. As the liquid transportation fuel alternative, algae fuel has been recommended as a sustainable solution and economically viable alternative [7]. In comparison to other crops, algae are the most favorable oil source owing to their rapid growth rate, ability to grow in broad range conditions, potential for higher yield rates and biodiesel properties of algae fuel which is comparable to the standard biodiesel [7-9]. Hence, algae have become a great interest as a source of biodiesel because it is more effective. Different types of fuels can also be suited to different species of algae [8].

However, studies related to the properties and performance of algae fuel applied on diesel engine are scarce [10,11]. Most of the existing studies have focused on the inclusion of algae with alcohols and diesel fuel but not raw algae. Application of biodiesel on diesel engine has drawback owing to high emission of carbon dioxide (CO₂) [12]. The emission of oxides of nitrogen (NOₓ) from the use of biodiesel is slightly higher than the use of diesel fuel [13,14]. By using biodiesel, the reduction in heating value increases the BSFC in percentage [15]. The increasing percentage of poon oil in the blend increases the exhaust gas temperature [16].

Therefore, the focus of this research is to investigate the properties of different volume percentage of blended algae fuel with diesel fuel as an alternative fuel. The properties of optimum blends of algae fuel and diesel fuel need to be clarified to facilitate further studies on biodiesel. In this research, the properties measured were calorific value, density and viscosity. Then, the effect of algae-diesel blends on engine performance was investigated, specifically for BSFC and BTE.

2. Materials and Methods

2.1. Algae Fuel Preparation

2.1.1. Algae oil separation from water

The algae used in this study were collected from the ponds of Sekolah Menengah Sains Tun Syed Sheh Shahabudin, Bukit Mertajam. Filtration and drying methods were used for separating the algae from water. Figure 1 shows the vacuum filtration machine used to obtain the sediment of algae due to pressure exerted from the vacuum. The sediment obtained was dried to remove moisture for oil extraction process. In the drying process, the industrial oven was used to dry the sediment of algae at 40°C for 18 hours.

2.1.2. Algae fuel extraction

The expeller/press method, solvent extraction process by hexane, and supercritical fluid extraction (SFE) method are popular methods available to extract oil from algae. The SFE method was selected as it is more efficient in extracting nearly 100% of oils than the conventional solvent separation methods [8]. The SFE method, shown in Figure 2, involved heating and liquefying the carbon dioxide below pressure so as to have the properties of gas and liquid. Algae fuel was obtained through extraction for about 1 hour for each process at temperature of 50°C and at 300 bar pressure by using CO₂ liquefied fluid as solvent (90%) and ethanol as co-solvent (10%). Finally, the BUCHI rotary evaporator shown in Figure 3 was utilized for solvent removal from the oil obtained, leaving only pure algae fuel. The evaporation process occurred about 5 minutes with a speed of 135 rpm and the bath temperature was set at 60°C.
Figure 1. Vacuum filtration machine

Figure 2. Supercritical fluid extraction
2.2. **Fuel Blending Preparation**

The blends of algae biodiesel fuel were prepared based on volume for engine testing, and essential properties were remained within the acceptable limit in accordance to the American Society for Testing Material (ASTM) standard. The volume percentages of algae fuel were selected from 1% to 4% out of 100 ml blended with diesel fuel. Table 1 summarizes the volume percentage of algae and respective nomenclature to differentiate each blend. All the diesel-algae mixtures were continuously stirred using the magnetic stirrer and hot plate for 15 minutes at room temperature and 500 rpm speed.

| Fuel Blend                  | Percentage of Algae | Nomenclature |
|-----------------------------|---------------------|--------------|
| 100 ml Diesel               | 0%                  | D100         |
| 99 ml Diesel + 1 ml Algae fuel | 1%                  | B1           |
| 98 ml Diesel + 2 ml Algae fuel | 2%                  | B2           |
| 97 ml Diesel + 3 ml Algae fuel | 3%                  | B3           |
| 96 ml Diesel + 4 ml Algae fuel | 4%                  | B4           |

2.3. **Fuel Blending Preparation**

Each developed sample was subjected to density, viscosity and calorific value test following the international standard procedures. In engine testing, a measurement of fuel properties is required to recognise the characteristics of fuel blends that may affect the performance and emissions of the engine. Additionally, the properties of the blended fuel were also analysed as they are critical factors for engine requirement, consumer satisfaction and industry standards. The properties of fuel blends obtained are shown in Table 2. For comparison, the properties of diesel fuel (D100) were also provided.
### Table 2. Properties of diesel and fuel blends

| Fuel property | Unit | Diesel fuel (D100) | 1% of algae fuel (B1) | 2% of algae fuel (B2) | 3% of algae fuel (B3) | 4% of algae fuel (B4) | ASTM Test Method |
|---------------|------|-------------------|----------------------|----------------------|----------------------|----------------------|----------------|
| Density       | kg/m³| 850               | 845.8                | 845.2                | 844.8                | 844.6                | ASTM-D 4052     |
| (at 15°C)     |      |                   |                      |                      |                      |                      |                 |
| Viscosity     | mm²/s| 2.6               | 3.069                | 3.003                | 2.943                | 2.920                | ASTM-D 445      |
| (at 40°C)     |      |                   |                      |                      |                      |                      |                 |
| Calorific Value | kJ/kg | 45500             | 44546                | 44529                | 44382                | 44190                | ASTM-D 4809     |

2.4. **Engine Setup**

Engine performance experiment was conducted using a vertical single-cylinder, four-stroke, and air-cooled diesel engine by the Yanmar TF-M by Yanmar Co. Ltd. This engine was combined with eddy current dynamometer with maximum power input of 20 kW at 2450 to 10000 rpm. Next, the control panel was used to vary the load, and the speed of the engine was adjusted. The full details of engine specifications are given in Table 3, and the schematic diagram of the engine setup is shown in Figure 4. The experiment was carried out using algae fuel mixed with different volume percentage of diesel fuel (D100): 1% of algae fuel (B1), 2% of algae fuel (B2), 3% of algae fuel (B3) and 4% of algae fuel (B4) to 100 ml of fuel blend volume.

### Table 3. Engine specification for experiment.

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

First, the single-cylinder diesel engine was warmed-up by running it for 15 minutes using D100 to ensure that the engine operation was perfectly stable. For the engine test condition, the engine speed was set at a constant 1500 rpm, while engine load was varied (2, 4, 6 Nm). Then, the D100 was changed to the fuel blends for running the engine to ensure the removal of residual diesel from the fuel lines. Each load was left to run until the volume of the fuel dropped for every 10 ml, and the time taken for each 10 ml drop was recorded. Finally, the fuel blends were changed with the next fuel samples, and the engine was left running until it reached a stable condition before the required data were recorded. The engine performance test was performed and repeated for three times to get an average data of the experiment. Based on the data for fuel consumption and calorific values obtained from the experiment, the engine performance of the blends was obtained.

BSFC signifies the level of efficiency of engine fuel consumption in its work performance and fuel consumption is determined based on mass flow rate per unit of time ($\dot{m}_f$). It is one of the crucial parameters because the engine was operated with various fuel types, indicating different levels of fuel performance either economic or otherwise. The BSFC parameter is defined as the ratio of mass flow rate per unit time divided by power output as expressed by equation (1):

$$BSFC = \frac{\dot{m}_f}{\text{Engine power}}$$

Where, $\dot{m}_f$ is fuel mass flow rate (g/hr), engine power $\frac{2\pi NT}{60000}$ and N is rotational engine speed (rpm) and T is torque.

BTE is described as the energy ratio in brake power ($bp$) divided by fuel energy input, which is the product of mass of fuels ($\dot{m}_f$). It is then multiplied by lower heating value of fuel blend, or known as fuel calorific value. This efficiency demonstrates the generation of output by the engine with the heat from the supplied fuel. Equation (2) denotes the BTE calculation.

BTE (%):

$$\eta_{bth} = \frac{3600}{\text{calorific value} \times BSFC} \times 100$$

Where, $\eta_{bth}$ is brake thermal efficiency (%), and calorific value is the blended fuel heating value (MJ/kg)
3. RESULTS AND DISCUSSION

The results obtained from the engine performance tests are discussed and the graphs are presented in this section. The engine performances, namely BSFC and BTE, are discussed based on the research objectives.

3.1. Brake Specific Fuel Consumption

Figure 5 shows the BSFC with engine load at constant 1500 rpm speed. Generally, higher consumption of fuel is observed for power generation owing to higher loss of heat in the combustion chamber walls at low engine speed (1500 rpm), which results in poor combustion efficiency. At 2 Nm engine load, D100 with 1390.537 g/kwh has the highest BSFC compared to other fuel blends. It could be due to the combined effects of viscosity, fuel density and low calorific value of the blends. For 2 Nm engine load, it was shown that the algae-diesel blends of B1, B2, B3 and B4 were lower with an average reduction of 23, 14, 19 and 16%, respectively, relative to D100. A research stated that the BSFC decreases when the engine speed is lower than 1300 rpm, and shows ascendant trend when the engine speed increases [10]. Besides, the decrease in BSFC in relation to the load is due to the increase in heat energy conversion into mechanical work with increasing combustion temperature [11].

Figure 5. BSFC against engine load at constant 1500 rpm speed.

Besides that, 11% decrease of B1 was recorded with 554.354 g/kwh at the engine load of 4 Nm as compared with D100. This can be related to two major factors, namely the decrease in calorific value in fuel and effect of fuel density. This result also showed the decrease of BSFC value due to the increment of mass fuel consumption at lower torque and lower thermal efficiency, which has also been described previously in past research [12]. Moreover, BSFC of the algae biodiesel decreased when the engine load increased. However, it can be observed that the BSFC for D100 in Figure 5 was the lowest among the algae-diesel fuel blends at higher engine torque (6 Nm). This is because BSFC is proportional to the calorific value and the amount of fuel injected; hence the BSFC for biodiesel is higher than the BSFC for pure diesel fuel for a constant engine output due to lower calorific value of biodiesel [13,14]. Comparable results were also reported by other studies as higher BSFC produced by the use of biodiesel compared to diesel [15,16]. This is also due to the higher density in the volumetric injection system, which causes higher BSFC [16,17].
3.2. Brake Thermal Efficiency

Variation in the BTE of D100, B1, B2, B3 and B4 at various engine loads with constant 1500 rpm speed is presented in Figure 6. It can be observed in Figure 6 that the BTE increased for all fuel blends when the engine load increased. Higher concentration of algae biodiesel improved the BTE of the engine. BTE for B2, B3 and B4 blends increased gradually along with the engine load but B1 showed 14% decrement, unlike D100 at load 6 Nm. This could be due to insufficient air during the experiment, resulting in lower oxygen concentration that causes incomplete combustion of the blends [15,18]. Besides that, the BTEs of B1, B2, B3 and B4 blend were higher, with an average increase of 33, 17, 17 and 17%, respectively, relative to D100.

![Brake Thermal Efficiency vs Engine Load](image)

**Figure 6.** BTE against engine load at constant 1500 rpm speed.

Generally, the BTE increases in two circumstances: when the concentration of the biodiesel in the blend increases, and when the speed of the engine increases at full load. This is also supported by the findings of previous researchers when BTE for the blends somewhat increases not similar to diesel fuel at high loads of both speeds and all injection timings [11]. High BTE shows that few amounts of unburned hydrocarbons are present in the engine, which leads to better and complete fuel combustion [15]. However, for certain engine speed, a decrease in BTE for all fuel blends indicates insufficient air that causes incomplete combustion of the fuel. Previous research has shown that at lower engine loads, BTE decreases for blends, leading to delay of combustion process and heat release in the expansion stroke which affects cylinder temperature [11]. Moreover, the amount of oxygen content in the blend affects the BTE [19].

4. CONCLUSION

Based on the result of this experiment, it can be concluded that the B4 blends in diesel fuel produced better BTE with 17% at 4 Nm engine load than diesel fuel. This could be affected by higher viscosity and oxygen content in the blends. Meanwhile, the BSFC was lower for B4 with 16% compared to diesel fuel at lower engine load. This was due to higher density and lower calorific value of algae biodiesel compared to diesel fuel. In conclusion, algae are suitable to reduce the usage of diesel fuel and replace diesel fuel in diesel engines.

It is suggested that the use of algae fuel to improve the strategies in reducing the NOx emission for biodiesel combustion is explored in future studies. The utilization of various algae fuel ratios can also be investigated. Type of engine used in future studies can also be changed to other engine types such as those which are not used for transport vehicles. Besides, the variables and constant of engine testing
parameter can also be changed to determine the effects on the emission characteristics, exhaust gas temperature and BSFC.

ACKNOWLEDGMENTS

The authors would like to express sincere gratitude to the Faculty of Mechanical Engineering (Universiti Teknologi MARA, Penang), Faculty of Mechanical Engineering (Universiti Teknologi MARA, Shah Alam), Department of Mechanical Engineering (Universiti Malaya) and Sekolah Menengah Tun Syed Sheh Shahabudin for their benevolent assistance in executing this research. The authors also would like to express sincere gratitude to Universiti Teknologi MARA (UiTM) for the opportunity to trigger this research and Fundamental Research Grant Scheme (FRGS) from the Ministry of Higher Education Malaysia (Grant No FRGS/1/2019/TK10/UiTM/02/16) for the financial support.

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