THE EFFECT OF MICROALGAE BIODIESEL ON COMBUSTION, PERFORMANCE, AND EMISSION CHARACTERISTICS OF A DIESEL POWER GENERATOR

by

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Microalgae oil is expected to be a relevant source of biofuel in the future as it is more favorable to confront the problems of food shortages and greenhouse emission challenges raised by conventional biofuels. Therefore, in this study, a most common kind of microalgae that have a great potential, Chlorella protothecoides, was evaluated as fuel in terms of its combustion and emission characteristics in a Diesel engine-powered generator set at constant engine speed of 1500 rpm under various loads after converting its oil to biodiesel by typical base-catalyzed transesterification process. A biodiesel/diesel blend at the rate of 20% by volume was tested too. According to results obtained, using biodiesel resulted in an increase in fuel consumption, in a slight reduction of efficiency, and in sharp reductions in both unburned hydrocarbon emissions and smoke opacity especially at light loads, despite increasing NO_x *emissions were observed when compared with conventional petroleum diesel. In addition, premixed combustion ratio was higher for biodiesel than for diesel while total combustion duration took shorter for biodiesel especially at higher loads. The overall results of the study reveals that the combustion parameters of the biodiesel studied here are within the typical ranges of conventional biodiesel fuels.*

Key words*: microalgae oil, biodiesel, combustion, diesel generator*

Introduction

Of all alternative energy sources, which are increasingly gaining importance worldwide, and which can be used instead of fossil fuels, biodiesel draws the most attention to the energy issue. Biofuels, becoming prevalent all over the world, provide countries with contributions to their energy supply, and also they provide alternative income sources and employment for producers growing raw materials for biofuel particularly in rural areas. In addition to all these, when biofuels come into question, it is seen that especially biodiesel stands out. Biodiesel is an alternative diesel fuel that should conform to international standards for blending and using in Diesel engines [1]. It lessens exhaust emissions such as unburned HC, CO, and particulate matter (PM) [2]. It is biodegradable and has excellent lubricant properties, no aromatic compounds and sulfur content [3]. These characteristics make biodiesel a promising alternative to conventional diesel fuels. Although some significant criticisms such as utilizing cultivated areas for energy, increase in cost of food and

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agricultural products, tendency to increase greenhouse gas emissions are made about biodiesel, it is expected that the popularity of biodiesel will continue to rise in the forthcoming years. For example, the European Commission's new target, in all fuel consumption, is to use 10% biofuel in transportation sector by 2020 [4], and it is expected that large amount of biofuel in 2020 will be covered by biodiesel as a consequence of increasing dieselization process occurring in Europe.

On the other hand, in the literature, it is pointed out that sustainable biofuels are required to be eco-friendly, socially acceptable, and economically viable [5]. The biofuel should be produced from sustainable biomass feedstocks that neither compete with food crops nor cause land-use changes (directly or indirectly) to prevent the rise of food prices and greenhouse-gas emissions [6], and to ensure its sustainability. However, almost entire biofuel production in 2020 is expected to come from crops grown on land that could be used to satisfy food and feed markets and that can adversely affect food supply and GHG emissions. Therefore, in order to avoid future competition between biofuel and food production and to reduce such emissions, it is necessary to develop *new advanced biofuels* that are not in competition with food crops, but in contribution to GHG emissions, as mentioned in the recent European directive [4]. Similarly, according to the revised EPA Renewable Fuel Standard program (RFS2), 11.1 billion gallons of biofuel production in 2009 will reach to 36 billion gallons in 2022 and its 21 billion gallons will come from *advanced biofuels* in the United States where the use of low levels of biodiesel in diesel fuel is mandated [7].

Hence, in the light of above concerns and perspectives, microalgae is seen as the most promising non-food source of biofuels, and its potential is dramatically growing in the biofuel market [8]. Because of the fact that some microalgae types contain much more oil than those of other arable crops, and their growing process is easier, and they are not negatively affected from seasonal and climatic changes, and they can be produced in great amounts in a short time, they are advantageous [9]. In addition, the fact that agricultural fields are not used when they are grown, and they can reproduce even in very small areas rapidly and in large quantity, and they do not need to have fertile lands for growing are some of the most important advantages they have [10]. Therefore, there is a considerable interest in the use of biodiesel derived from microalgae oil in Diesel engines. More recently, Islam *et al*. [11] compared the combustion characteristics of microalgae and waste cooking oil biodiesel fuels in a modern Diesel engine. In another study [12], the combustion characteristics of the mixture of algae-derived biodiesel and conventional diesel with the proportion of 20% v/v were studied in a single-cylinder DI engine at 1500 rpm and different load conditions. Furthermore, Hariram and Kumar [13] used the biodiesel obtained from *Spirulina sp*. microalgae in a single-cylinder DI Diesel engine while Haik *et al*. [14] tested raw algae oil and its methyl ester in a DI Diesel engine, and biodiesel from the microalgae *Chlorella protothecoides* was tested in an agriculture tractor engine by Al-lwayzy and Yusaf [15] and so on. *Chlorella protothecoides* oil is selected for current study as it is a very suitable source to produce biodiesel having some superior properties for fuel production over other kinds of microalgae reported in [16]. It is obtained by an combined technology, cell and metabolic engineering, to produce source material in bioreactors for producing biodiesel mainly in Texas, USA. In Turkey, there are studies on some seaweed species under laboratory conditions.

However, most of the studies reported in the literature regarding to biodiesel use are carried out on single or multi-cylinder engine dynamometer tests while very few have been performed with Diesel engine powered generator sets (DEPG) which operate at a fixed speed and variable load conditions on the contrary automotive Diesel engines operate in almost completely transient conditions. This causes differences in the combustion and emission characteristics, hence the combustion analyze in DEPG run by biodiesel is more meaningful. However, studies on biodiesel fueled DEPG are not only limited but also inconsistent with regard to exhaust emissions, that is, differing results have been reported for the change in exhaust emissions [16-18]. This is probably due to the emission characterization of non-road engine which can be more complicated considering the large number of DEPG types with different size and power outputs. Also research on the combustion and emissions of DEPG running on microalgae biodiesel is lacking.

In summary, despite the food-grade oils are mostly used to produce biofuels, researchers are looking for non-land and non-food feedstock for producing biofuels such as microalgae oil, which is expected to be a relevant source of biofuel in future. On the other hand, most of researchers focus on the overall performance of biodiesel in chassis or engine dynamometer tests of on-road engines. Still, limited information has been known about the combustion parameters of biodiesel as well as its blend with conventional diesel in DEPG. Furthermore, no study has been reported earlier in the research literature about the combustion and emissions of DEPG run by microalgal-biodiesel while current and future policies restrict conventional biofuels (such as biodiesel from oil crops) as mentioned above. Therefore, this work was aimed to examine the combustion and emission levels of a DEPG running on the biodiesel obtained from transesterification of microalgae oil and its blend with conventional diesel.

Experimental

Fuels

Three fuels were tested in the present work. The first one was an ultra-low sulfur diesel fuel following EN590 standards, as a reference fuel, typical of the commercial diesel fuels sold in fueling stations and the second was microalgae biodiesel while third one was a blend of the former with 20% (v/v) of biodiesel (B20). As beyond 2020 higher percentages than 10% are expected, so we tried to anticipate that trend by testing 20% biodiesel blend, which has advantages such as lower emissions and no need for modification.

A single-cell and heterotrophic microalgae oil, which is obtained from *Chlorella protothecoides species*, was supplied by a commercial distributor (Soley Biotechnology), located in Istanbul, Turkey, and used to produce biodiesel. It had an acid value of 0.28 mgKOH/g and water content of 734.7 ppm which was reduced to 0.22 mgKOH/g and 220 ppm after applying heat treatment. Transesterification conditions were agreed after investigating the effect of KOH concentration, reaction temperature and time at constant molar ratio of 6:1 and algal-biodiesel was obtained with an ester yield of 98.6% and ester content of 96.6% under optimal conditions, which were presented in [19] along with detailed information on the process for producing biodiesel. Also, free and total glycerol contents (0.002% and 0.014 %, respectively) were determined to be below the limits specified by the Standards, showing the fact that the production process attained very good conversion rates. Furthermore, all fuel properties of produced biodiesel were in agreement with EN 14214 standards as shown in tab. 1. From GC analyze, it was found that obtained biodiesel was highly unsaturated (92.67%) and contained mainly oleic, C18:1, (63.96%) and linoleic acids, C18:2, (20.506%), leading to a good balance of low-temperature properties (CFPP, –10 °C) and ignition quality (CN, 57.3), tab. 1. Calculated cetane index (CCI) was determined as a function of density at 15 °C and the T10, T50, and T90 distillation curve points in accordance with the ASTM D4737 in the case of diesel fuel while for biodiesel; it was estimated from the correlation proposed in [20].

Table 1. The specifications of biodiesel and petroleum diesel

Property	Unit	EN 14214	Biodiesel	Diesel
Density at 15 °C	kg/m^3	860-900	881	840
Kin. viscosity at 40 °C	mm^2/s	3.5-5.0	4.491	3.185
Lower heating value (LHV)	kJ/kg	–	37560	42850
Cetane number (CN)	–	51min.	57.3	55
Water content	mg/kg	500 max.	190	156.4
Acid value	mg	0.50 max.	0.21	–
Sulfur content	mg/kg	10 max.	6.79	9.8
Flash point	°C	101 min.	141	60.5
Cold filter plugging point (CFPP)	°C	–	–10	–14
PAH content	%mass	–	5.8	4.4
Lubricity at 60 °C	µm	–	226	456
Distillation	°C	–		
IBP			326.6	169
10%			336.3	201
50%			337.8	263
90%			348.3	324

Table 2. Specifications of the engine

Engine model	4DW81-23D
Fuel injection	Direct injection
Power output	18 kW at1500 rpm
Intake system	NA
Bore × stroke	85 × 100 mm
Displacement	2400 cm^3
Number of cylinder	4
Compression ratio	17:1
Number of injector nozzle	4

Experimental equipment and methodology

A diesel engine powered generator set (DEPG), which is at less expense than full-scale dynamometer testing, was used for current experimental work. It is equipped with a four-cylinder Kraft 4DW81-23D diesel engine with rated power of 18 kW at 1500 rpm (tab. 2) coupled to a 20 kVA three phase 230/400 V brushless synchronous alternator for loading. It is also equipped with auxiliaries to control and monitor both engine and generator. A scheme of the installation used is shown in fig. 1. The load is controlled by changing the electric load applied to the generator using electric resistance heaters which consume electricity produced by the generator. It was calculated by measuring the power through voltage and current using a display unit. The loads applied to the generator for all fuels tested were 3.6 kW, 7 kW, and 10.2 kW at 1500 rpm, which are representative of low-medium load (about 20%, 40%, and 60% of the maximum power output at rated speed) in stationary engines, being typical operating conditions for gen-sets on the contrary automotive engines operate in almost complete-

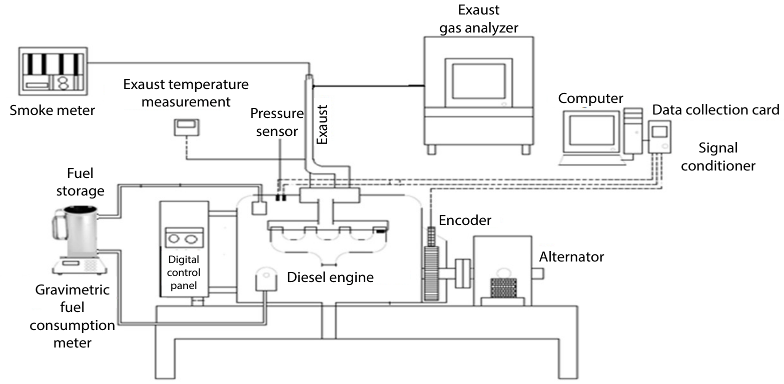

Figure 1. Experimental installation

ly transient conditions. The 20% of the maximum power output at 1500 rpm is representative to light load whereas 40% and 60% represents medium-high load condition. On the other hand, in order to make a fairly comparison among the fuels having different energy and oxygen content, the same engine load has to be taken into account rather than the same fuel mass.

A digital scale was used to measure the fuel flow by mass. Before every fuel change, the fuel lines were cleaned by using a hand pump, and the engine was left to run for a sufficient period of time (10-15 minutes) to stabilize at its new condition. Exhaust emissions were measured with a Capelec Cap 3200 device, which enables to measure both gaseous emissions and smoke opacity (with 1ppm of accuracy for both total HC and NO_x emissions and 0.1% for opacity). It was calibrated and its lines were cleaned before the experiments.

The cylinder pressure (as average of 100 measurements per cycle) was measured with a fiber optic pressure sensor (Optrand D33294-Q, which is referenced to the crank angle recorded by a shaft encoder). The cylinder pressure signals were monitored and stored with the data acquisition system FebriS v1.0 by NELpresto, and then used to determine the main parameters of the combustion process, such as the rate of heat release (RoHR) using eq. (1), the premixed combustion ratio and the combustion duration in order to achieve a better understanding of the combustion process of fuels tested:

$$\frac{\mathrm{d}Q}{\mathrm{d}\theta}=\frac{\gamma}{\gamma-1}p\frac{\mathrm{d}V}{\mathrm{d}\theta}+\frac{1}{\gamma-1}V\frac{\mathrm{d}p}{\mathrm{d}\theta} \tag{1}$$

where $\mathrm{d}Q/\mathrm{d}\theta$ is the heat release per crank angle, γ – the specific heat ratio, V – the instantaneous cylinder volume and $\mathcal{P}$ – the in-cylinder pressure.

Results and discussion

Combustion characteristics

The effect of biodiesel and its blend with diesel on combustion characteristics was discussed in terms of cylinder gas pressure (CGP), rate of heat release (RoHR) and other combustion parameters such as the start of combustion (SOC), the end of combustion (EOC), premixed combustion ratio (PCR), premixed combustion duration (PCD), and combustion duration (CD). Figures 2-4 shows the change in CGP and RoHR values obtained at constant speed and under different loadings for fuels tested according to crank angle (CA).

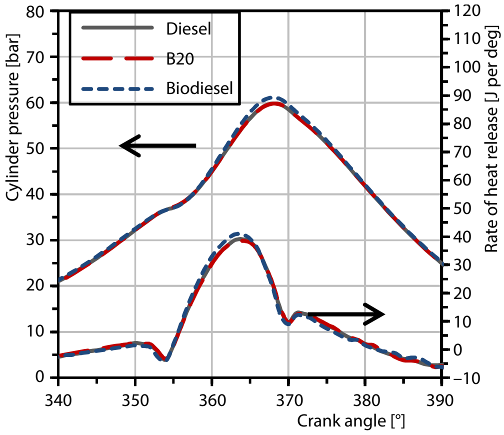

Figure 2. The CGP and RoHR comparison among tested fuels at 20% load

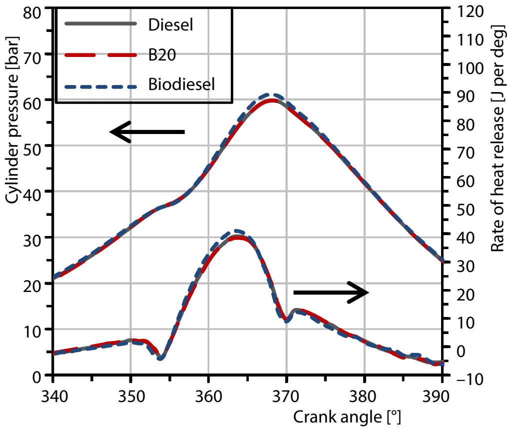

Figure 3. The CGP and RoHR comparison among tested fuels at 40% load

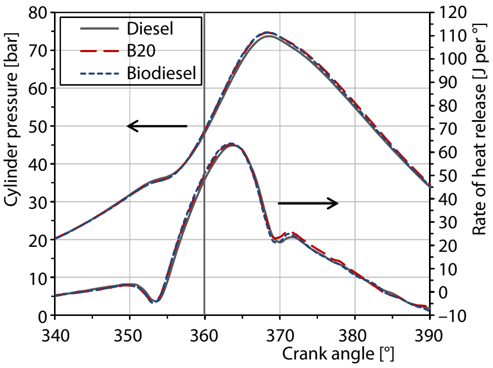

Figure 4. The CGP and RoHR comparison among tested fuels at 60% load

For all fuels tested, CGP and RoHR increased with the increase of load which can be explained with the increase in fuel consumption, as seen in figs. 2-4. Moreover, for all fuels tested, under each load condition, it is seen from the figures that the RoHR is around negative value before the beginning of heat release. This stems from the fact that the injected fuel absorbs heat from the cylinder wall in order that it can be vaporized. The peaks of CGP and RoHR were obtained under 10.2 kW power output conditions for all fuels tested as about 73.6 bar and 62.8 J/ºCA, 74.5 bar and 63 J/ºCA, and 74.7 bar and 63.4 J/ºCA for diesel, blended fuel and biodiesel, respectively. The peak CGP values were measured at 8 °CA aTDC for all fuels tested while the location of the peak RoHR was 4 °CA aTDC for diesel and blended fuel and 3.5 °CA aTDC for biodiesel. Similar results were also obtained at the operation under 3.6 kW and 7 kW loads. As is seen, with the use of biodiesel and its blend, a slight increase in peak CGP and RoHR was obtained in comparison to diesel use. This can be attached to the increase in the accumulated fuel (the increase fuel consumption due to the lower energy content) at ignition delay period and the oxygen content of these fuels which lead to fast burning of the accumulated fuel. Apparently, the CGP and RoHR curves are very similar for all of the fuels, and there is no clear difference when comparing diesel to biodiesel fuel. This comparable tendency in CGP and RoHR occurrence suggests that biodiesel and blended fuel have similar combustion characteristic with conventional diesel.

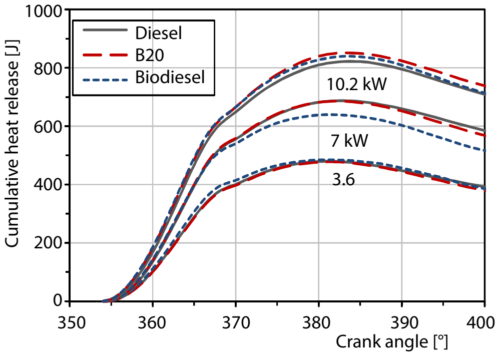

Figure 5. The CHR *vs.* CA for tested fuels at different loads

Figure 5 shows CHR diagram for test fuels at different load conditions according to CA. Biodiesel and blended fuel show identical pattern of CHR for all loads in comparison to diesel. CHR increases with increasing load for all the fuels as mass of fuel burning increases with increasing load.

As can be seen in tab. 3, which shows the combustion parameters, SOC for biodiesel and blended fuel is the same as for diesel while EOC is earlier for biodiesel and blended fuel than for diesel except for a low load (3.6 kW) in which the position of EOC is same for all fuels tested. Moreover, the combustion is taken shorter at medium-high loads for biodiesel and blended fuel than for diesel. At 7 kW and 10.2 kW load, the point of EOC for diesel is 383 and 384 °CA aTDC as compared to 381 and 383 °CA aTDC for biodiesel. However, in all cases, the maximum difference is not exceeding 2 °CA. The PCR, which is given in tab. 3, is seen to be deceased with load increase for all fuels tested. Increase in load leads to decrease PCR owing to improving the combustion conditions and increasing RoHR during controlled combustion phase due to increasing fuel consumption. The highest PCR were obtained for biodiesel due to improved combustibility of biodiesel having extra oxygen content that is not present in diesel. PCD for all fuels tested were at the same ranges at

3.6 kW and increased with load increase, except for biodiesel at 7 kW where it was same with the value at 3.6 kW. In tab. 3, CD is seen to be prolonged with the increase in load for all tested fuels due to the increase in fuel consumption. At 3.6 kW, CD took 27 °CA for all tested fuels while at medium-high loads it was shorter for biodiesel and blended fuel than for diesel. CD for diesel at 7 kW load condition is 29 °CA as compared to 28 and 27 °CA for blended and biodiesel fuel, respectively. Similarly, it was 30 °CA for diesel at 10.2 kW whereas 29 °CA for both blended and biodiesel fuel. In case of biodiesel, 2 °CA and 1 °CA drop in CD at 7 kW and 10.2 kW load conditions, respectively, is observed while for blended fuel, the maximum difference is not exceeding 1 °CA. In both cases, the drop in CD is due to advance in injection timing that leads to higher combustion rate and less PCD and hence lower CD. It is further observed that shorter combustion duration leads to higher thermal efficiency especially at higher loads, fig. 8.

Table 3. Combustion parameters for tested fuels at different loads and 1500 rpm

	3.6 kW			7 kW			10.2 kW		
	diesel	blend	biodiesel	diesel	blend	biodiesel	diesel	blend	biodiesel
SOC (°bTDC)	354	354	354	354	354	354	354	354	354
EOC (°aTDC)	381	381	381	383	382	381	384	383	383
P_{max} (bar)	59.8	59.78	61.1	68.9	69.5	68.6	73.6	74.5	74.7
θP_{max} (°aTDC)	8	8	8	9	8.5	8	8.5	8	8
HRR_{max} (J/°CA)	39	38.5	40.8	54.8	54.8	53.2	62.8	63	64.4
θHRR_{max} (°aTDC)	4	4	3.5	4	4	4	4	4	3.5
CD (°CA)	27	27	27	29	28	27	30	29	29
PCR (%)	0.814	0.811	0.836	0.786	0.792	0.825	0.763	0.753	0.766
PCD (°CA)	12	12	12	14	13	12	15	14	14

Exhaust emissions

For fuels tested, the changes of NO_x emissions with load are shown in fig. 6. The NO_x emissions increased with the increase in load for all fuels tested. The reason for this is the increase of in-cylinder temperature with the load increase. As known, in formation of NO_x,

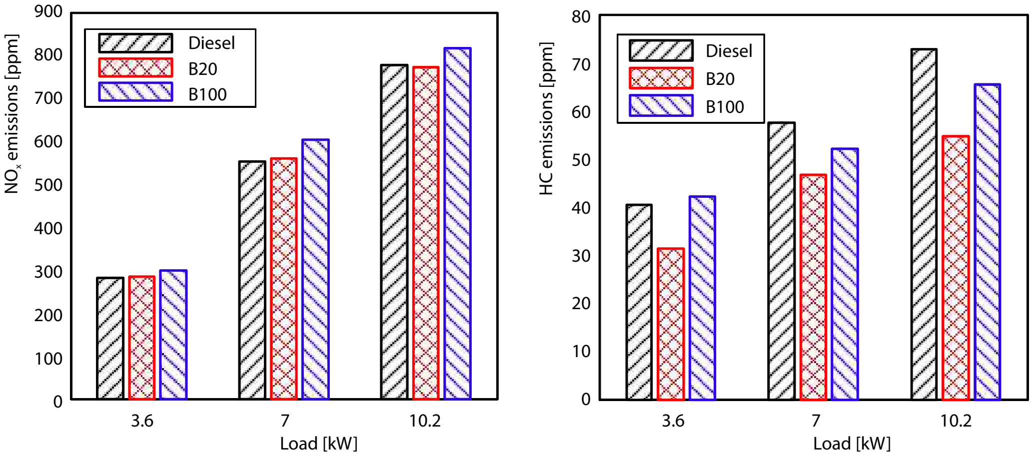

Figure 6. Changes in NO_x and unburned HC emissions

high temperature and duration being exposed to high temperature and amount of air have great importance. In this study, NO_x emissions increased for all fuels tested as a result that in-cylinder temperature increased with the increase of fuel consumption with the load increase although the air consumption did not change since the experiments were carried out under constant speed. Maximum NO_x for all tested fuels, at 10.2 kW, was measured as 854 ppm, 850 ppm, and 892 ppm for diesel, blended fuel and biodiesel, respectively. The NO_x emissions increased compared to diesel when blended fuel and biodiesel were used except for the fact that there was a slight decrease in blended fuel compared to diesel at 10.2 kW. In addition, this increase became more apparent with the increase in the load, as found in other studies [21]. For example, under 3.6 kW load conditions, NO_x turned out to be 1% and 5.5% more in use of blended fuel and biodiesel according to diesel, respectively, while the change in NO_x was found at the rate of 1.3-0.5% and 9.2-4.5% for blended fuel and biodiesel when the load was increased to 7 kW and 10.2 kW, respectively. On the other hand, on average, according to diesel, NO_x emissions increased at the rate of 0.4% and 6.5% in use of blended fuel and biodiesel, respectively. According to Environmental Protect Agency (EPA) [22], the increase in NO_x emissions for biodiesel is around 10% while for blended fuel, the change in NO_x emissions becomes in the direction of increase or decrease 2% compared to conventional diesel. Therefore, in this study, the results obtained for blended fuel and biodiesel are comprehensible. It is well known that additional oxygen in the environment enhances the combustion by increasing hydrocarbon oxidation in combustion chamber during combustion [23]. In this case, increasing of NO_x emissions is an expected result owing to increase in-cylinder temperature. Thus, in this study, when compared to diesel, increase in NO_x was more in usage of biodiesel than blended fuel. On the other hand, it is quite well known that fuel injection advance is effective on NO_x emissions [24]. In Diesel engines with mechanically controlled fuel injection systems where modification has not been carried out, injection time determined according to conventional diesel can be advanced in case of biodiesel fuels possessing high viscosity values are used [2]. In this instance, prior to the start of combustion, there will be higher in-cylinder heat and pressure as soon as the combustion has started since excess amount of fuel will accumulate in the cylinder. Consequently, high temperature leads more NO to occur.

For fuels tested, the change in unburnt HC emissions with the load is shown in fig. 6. Unburnt HC emissions increased for all fuels tested with the increase in load. Unburnt HC emissions increased with the increase in load due to increase in fuel consumption at almost constant amount of air (because of constant engine speed). This is also reported by other researchers [25]. At 10.2 kW, maximum HC was measured as 81 ppm, 61 ppm, and 73 ppm for diesel, blended fuel, and biodiesel, respectively. Under these conditions, HC emissions turned out to be less at the rate approximately 24.7% and 9.8% for blended fuel and biodiesel, respectively, according to diesel use. However, at light loads, decrease in HC was less. In general, at 3.6 kW, apart from a slight increase in biodiesel use (47 ppm) compared to diesel (45 ppm), when biodiesel and blended fuel were used, unburnt HC emissions decreased compared to diesel. On average, unburnt HC decreased at the rate of 22% and 6.3% with the use of blended fuel and biodiesel, respectively. As the reason of the decrease in unburnt HC emissions, that biodiesel contains oxygen can be shown. However, as can be understood from fig. 6 and the values given, decrease in HC emissions were not proportional with biodiesel content of the fuel, *i. e.* decreasing trend did not continue at the same rate with the biodiesel content of the fuel. In literature [26], although blended fuel (B20) was reported that it is a convenient diesel/biodiesel mixture in terms of both fuel properties and emission reduction and that it can be profited from its superior properties in comparison with conventional diesel, the results obtained demonstrate that some other factors are effective on unburnt HC emissions. It is considered that the properties such as high cetane number and oxygen content are being effective parameters on the decrease of incomplete combustion products in case of B20 use; however, that its properties such as the high viscosity and low volatility of biodiesel having effect on fuel atomization and evaporation in case of pure biodiesel use are more dominant. These are being more important especially for test engine with a mechanically controlled low-injection pressure system as in current study. Also, it is stated in the literature that low injection pressure causes increase in unburnt HC emissions [27].

Smoke opacity (SO) values measured for fuels tested are shown in fig. 7 where a significant increase with the increase in the load for all fuels tested is seen. The fuel injected to cylinder increases when the load is increased. This case causes diffusion combustion time to get longer; on the other hand, since the time after the end of diffusion combustion during expansion period shortens and there is less oxygen, leads to the carbon oxidation to decrease, which causes more smoke occurrence. Maximum SO was measured under 10.2 kW conditions for all fuels tested. Under these conditions, it was measured as 72.1%, 21.3%, and 16.9% for diesel, blended fuel, and biodiesel, respectively. Accordingly, SO, in comparison to diesel, appeared to be lower with the rate of approximately 70.4% and 76.6% for the use of blended fuel and biodiesel, respectively. However, at 3.6 kW, although it was measured as 9.6% with diesel, it turned out to be unmeasurably low level for other fuels. On the other hand, at 7 kW, SO were measured as 26.8%, 1.8%, and 1.7% for diesel, blended fuel and biodiesel, respectively. On average, when compared with diesel, SO with the use of blended fuel and biodiesel turned out to be lower at the rate of 78.6% and 82.8%, respectively. It was reported that due to extra oxygen it contains, there was significant amount of decrease in SO for biodiesel compared to conventional diesel. According to EPA, although it is stated that in biodiesel and blended fuel use, PM emissions decreased at the rate of 47% and 12%, respectively, there are also studies reporting that reduction reaches to 90% [2]. In this study, decreases in high degrees were also obtained. The reason for this is contemplated that there is the effect of smoke opacity values measured at the rate of 0% at low engine loads are also effective.

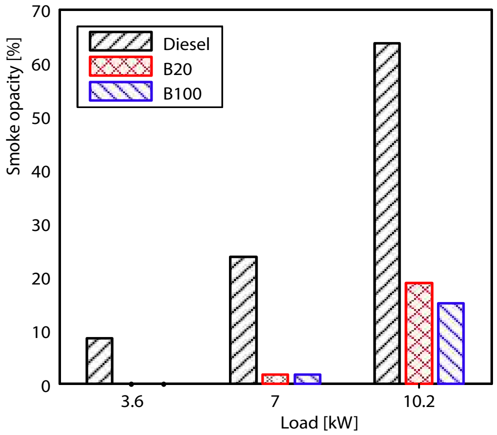

Figure 7. Smoke emission change for test fuels under different loads

Performance indices

Variation of specific fuel consumption (SFC) and thermal efficiency with the load is shown in fig. 8 for tested fuels. In the figure, it was observed that SFC decreased with the increase of load for all tested fuels at fixed engine speed. The fact that combustion gets better at high loads, and in-cylinder temperature increases due to the decrease heat losses, and engine output capacity increases lead to SFC to decrease. The highest SFC at 3.6 kW was calculated as 429.7 g/kWh, 452 g/kWh, and 541.3 g/kWh for diesel, blended fuel, and biodiesel, respectively. Under this load, SFC increased at the rate of 5.2% and 25.9% according to diesel for the blended fuel and biodiesel, respectively. When the load was increased to 7 kW and 10.2 kW, the approximate rise in blended fuel was 1.5-2.4% and in biodiesel was 8.4-9%, respectively.

As can be seen, the big difference at low loads decreased with the increase in the load. This case shows that when the load increases, the effect of some negative properties such as high viscosity of biodiesel weakens. However, when biodiesel and blended fuel were used, SFC was high under all loads compared to diesel. On average, SFC, according to diesel, increased at the rate of approximately 3.2% and 15.3% with the use of blended fuel and biodiesel, respectively. The basic reason for SFC increase is that heating value of biodiesel is lower than that of diesel fuel. Therefore, the heat loss in case of biodiesel has to be met with the increase in fuel consumption in order to maintain the same output power.

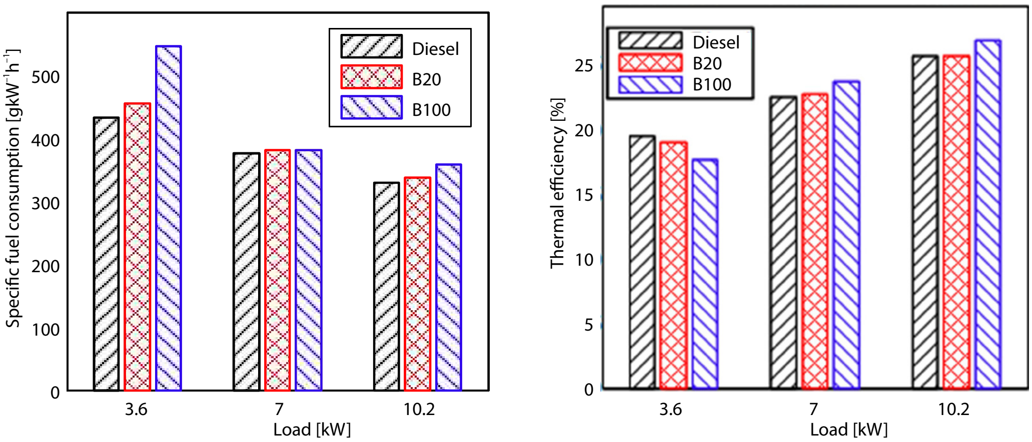

Figure 8. Changes in specific fuel consumption and efficiency

Thermal efficiency is a more convenient parameter than SFC in terms of comparisons of different fuels. In this study, the change of thermal efficiency values obtained for different fuels with the load is shown in fig. 8. It increased with the rise in load for all tested fuels. The reason for this is increase in output power with increase in load. Furthermore, when biodiesel and blended fuel were used under such low loads as 3.6 kW, the efficiency decreased compared to use of diesel by nearly 2.5% and 9.4%, respectively. However, with the increasing load to 7 kW and 10.2 kW, an increasing trend in efficiency was also observed according to diesel. For example, for biodiesel the approximate rise was 4.7% at 7 kW, and at 10.2 kW it was calculated as 5.2%. In case of blended fuel, on the other hand, the efficiency was very close to the values attained with the use of diesel. As the reason why efficiency decreased at low load condition, the high fuel consumption and poor atomization characteristics of biodiesel, which developed at higher loads, can be given. On the other hand, as the extra oxygen helps to accelerate the combustion process, more heat is released near TDC for biodiesel fuel which improves thermal efficiency. In addition, when the average values are taken into account, no significant variation in efficiency is observed by using blended fuel and biodiesel in comparison to diesel.

Conclusions

- Biodiesel was obtained from transesterification of single-cell and heterotrophic microalgae (*Chlorella protothecoides*) oil and then tested in a diesel gen-set under constant speed and variable load conditions in pure and blended (in percentage of 20% (v/v)) form as fuel comparing with conventional diesel operation. According to experimental results, using biodiesel and blended fuel instead of conventional diesel led to an increase the specific fuel consumption by 15.3% and 3.2%, on average, respectively. Furthermore, increased efficiency was obtained with biodiesel and blended fuel according to conventional diesel up to nearly 5% under high load, however, under such low loads as 3.6 kW, it decreased by nearly 9% compared to use of conventional diesel. On average, unburnt HC emissions decreased compared to diesel when biodiesel and blended fuel were used by approximately 6.3% and 22%, respectively. Smoke opacity was measured as 72.1% for diesel, 21.3% for blended fuel and 16.9% for biodiesel under highest load. Despite no significant difference was observed between diesel and blended fuel in NO_x emissions, the use of biodiesel led to increase of NO_x emissions approximately at the rate of 6.5% on average, compared to diesel. Cylinder gas pressure and heat release were slightly higher for biodiesel and blended fuel than for diesel. Nonetheless, all fuels tested displayed similar tendencies in pressure occurrence which shows that biodiesel and blended fuel have similar combustion characteristics with conventional diesel.

- Consequently, microalgae-biodiesel has a potential to be replaced with conventional diesel and biodiesel fuels for using in diesel gen-set without any modification, and blended fuels with small proportion of microalgae-biodiesel (such as 20% by volume) can be considered to be viable alternative fuel providing neutral or even advantageous NO_x when compared to diesel at the cost of a benefit in unburnt HC and smoke opacity, without significantly affect the fuel consumption. When the obtained results are generally evaluated, it is comprehended that biodiesel produced from microalgae oil have similar characteristics with conventional biodiesel fuels such as soy, canola and palm oils, and its use and production will contribute to eliminate possible concerns to appear in the future about *bio-fuel vs. food production*.

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References

[1] Altun, S., Rodriguez-Fernandez, J., Biofuels Derived from Turkish Industry Wastes – A Study of Performance and Emissions in a Diesel Engine, *Environmental Progress & Sustainable Energy, 35* (2016), 3, pp. 847-52

[2] Lapuerta, M., *et al.*, Effects of Biodiesel Fuels on Diesel Engine Emissions, *Prog. Energy Combust., 34* (2008), 2, pp. 198-223

[3] Bereczky, A., Effect of the Use of Waste Vegetable Oil Based Biodiesel on the Landscape in Diesel Engines, *Thermal Science*, *21(2017),* 1B, pp. 567-579

[4] ***, Directive (EU) 2015/1513 of the European Parliament and of the Council of 9 September 2015, Amending Directive 2009/28/EC on the Promotion of the Use of Energy from Renewable Sources, *Official Journal of the European Union,* Brussels, 2015

[5] Tokunaga, K., Eby Konan, D., Home Grown or Imported, Biofuels Life Cycle GHG Emissions in Electricity Generation and Transportation, *Applied Energy, 125*, (2014), July, pp. 123-131

[6] Tilman, D., *et al.* Beneficial Biofuels – The Food, Energy, and Environment Trilemma, *Science*, *325* (2009), July, pp. 270-271

[7] ***, USEPA, Finalizes Regulations for the National Renewable Fuel Standard Program for 2010 and beyond, EPA-420-F-10-007, 2010

[8] Uma, B.-H., Kim, Y.-S., Review: A Chance for Korea to Advance Algal-Biodiesel Technology, *Journal of Industrial and Engineering Chemistry*, *15* (2009), 1, pp. 1-7

[9] Milano, J., *et al.* Microalgae Biofuels as an Alternative to Fossil Fuel for Power Generation, *Renewable and Sustainable Energy Reviews*, *58* (2016), May, pp. 180-197

[10] Mata, T. M., *et al.*, Microalgae for Biodiesel Production and other Applications, A Review, *Renewable and Sustainable Energy Reviews*, *14* (2010), 1, pp. 217-232

[11] Islam, M. A., Combustion Analysis of Microalgae Methyl Ester in a Common Rail Direct Injection Diesel Engine, *Fuel*, *143* (2015), Mar., pp. 351-360

[12] Ramesha, D. K., *et al.,* An Experimental Study on Usage of Plastic Oil and B20 Algae Biodiesel Blend as Substitute Fuel to Diesel Engine, *Environmental Science and Pollution Research, 23* (2016), 10, pp. 9432-9439

[13] Hariram, V., Kumar, G. M., Combustion Analysis of Algal Oil Methyl Ester in a Direct Injection Compression Ignition Engine, *Journal of Engineering Science and Technology*, *8* (2013), 1, pp. 77-92

[14] Haik, Y., *et al*., Combustion of Algae Oil Methyl Ester in an Indirect Injection Diesel Engine, *Energy, 36* (2011), 3, pp. 1827-35

[15] Al-Lwayzy, S. H., Yusaf, T. Chlorella Protothecoides Microalgae as an Alternative Fuel for Tractor Diesel Engines, *Energies*, *6* (2013), 2, pp. 766-83

[16] Tang, S., *et a*l., Impacts of Biodiesel Blends on PM 2.5, Particle Number and Size Distribution, and Elemental/Organic Carbon from nNon-Road Diesel Generators, *Fuel*, *172* (2016), May, pp.11-19

[17] Altun, S., Effect of the Degree of Unsaturation of Biodiesel Fuels on the Exhaust Emissions of a Diesel Power Generator, *Fuel*, *117* (2014), Part A, pp. 450-457

[18] Valente, O. S., *et al*., Fuel Consumption and Emissions from a Diesel Power Generator Fueled with Castor Oil and Soybean Biodiesel, *Fuel*, *89* (2010), 12, pp. 3637-3642

[19] Yasar, F., Production of Biodiesel from Algae Oil and Use as an Alternative Fuel in a Diesel Engine (in Turkish), Ph. D. thesis, Institute of Science and Technology, Batman University, Batman, Turkey, 2016

[20] Lapuerta, M., *et al*., Correlation for the Estimation of the Density of Fatty Acid Esters and its Implications, A Proposed Biodiesel Cetane Index*, Chemistry and Physics of Lipids*, *163* (2010), 7, pp. 720-727

[21] Manickam, M. V., *et al*., Effect of Steam Injection on NO_x Emissions and Performance of a Single Cylinder Diesel Engine Fuelled with Soy Methyl Ester, *Thermal Science*, *21* (2017), 2, pp. S473-S479

[22] ***, https://www3.epa.gov/region9/waste/biodiesel/questions.html, (accessed on 23 May 2016)

[23] Ozsezen, A. N., Investigation of the Effects of Biodiesel Produced from Waste Palm Oil on the Engine Performance and Emission Characteristics (in Turkish), Ph. D. thesis, Science and Technology Institute, Kocaeli University, Kocaeli, Turkey, 2007

[24] Kegl, B., Experimental Investigation Review of Biodiesel Usage in Bus Diesel Engine, *Thermal Science*, *21* (2017), 1, pp. 639-654

[25] Jamrozik, A., *et al*., Effect of Diesel-Biodiesel-Ethanol Blend on Combustion, Performance, and Emissions Characteristics on a Direct Injection Diesel Engine, *Thermal Science*, *21* (2017), 1, pp. 591-604

[26] Agarwal, A. K., Das, L. M., Biodiesel Development and Characterization for Use as a Fuel in Compression Engines, *Journal of Engine and Gas Turbines Power*, *123* (2001), 2, pp. 440-447

[27] Jindal, S., *et al*., Experimental Investigation of the Effect of Compression Ratio and Injection Pressure in a Direct Injection Diesel Engine Running on Jatropha Methyl Ester, *Applied Thermal Engineering*, *30* (2010), 5, pp. 442-448

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