Journal of Thermal Engineering, Vol. 5, No. 6, Special Issue 10, pp. 214-220, December, 2019
Yildiz Technical University Press, Istanbul, Turkey

COMBUSTION ANALYSIS OF CI ENGINE FUELLED WITH ALGAE BIOFUEL BLENDS

M. P. Joshi[1,2*] and S. S. Thipse[3]

ABSTRACT

Algae-based biofuels are the most capable solutions to energy catastrophe and global warming for years to come due to its potentially high yield, higher growth rate, biodegradable, nontoxic, carbon neutral, low emission profile, use of non-arable land and non-potable water with less attention and resource consumption. A biofuel produced from chlorella algae oil through a transesterification process was used in this study. Experimental tests were performed on a single cylinder, four stroke, direct injection, naturally aspirated diesel engine at constant engine speed of 1500 rpm and compression ratio of 18 at various loading conditions to evaluate the performance, emission, and combustion characteristics using algae biofuel blends of 5%, 10%, 20%, and 30%, moreover the results are compared with those of standard diesel. The brake thermal efficiency showed decreasing trend (upto 5%) whereas specific fuel consumption (upto 7%) and exhaust gas temperature (upto 3%) showed increasing trend for algae biofuel blends compared to diesel. Reduction in hydrocarbon (upto 28%) and carbon monoxide (upto 22%) emission was noted for algae biofuel blends along with a marginal increase in NOx (upto 13%) emissions. Also, algae biofuel blends showed almost comparable combustion results compared to conventional diesel, however, the blends confirm shortened ignition delay due to their earlier start of combustion. From this study, we can conclude that small fraction by volume (20%) of algae biofuel addition with diesel has exhibited satisfactory results and could be used as a good substitute for petrodiesel fuel.

Keywords: *Algae Biofuel, Performance, Combustion, Emission*

INTRODUCTION

Finding adequate supplies of renewable and eco-friendly energy for the long run is closely connected with world security, economic prosperity and enhanced the quality of life. Among the available renewable energies, the most crucial energy sources in nearby future are biomass [1]. Use of algae can be a promising substitute because algae are the ultimate competent biological producers of oil on the earth and become resourceful biomass. Algae are considered to be one of the oldest living organisms and fastest growing plants on our planet.

Table 1. Physico-chemical properties of Algae biofuel blends and Standard diesel

Sr. No.	Property	Unit	Ref. Std. ASTM 6751	Diesel	AOME 05	AOME 10	AOME 20	AOME 30
1	Density	gm/cc	D1448	0.83	0.834	0.838	0.841	0.847
2	Calorific Value	kJ/kg	D6751	42500	42520	42600	42640	41690
3	Cetane Number	--	D613	49.5	49.32	49.21	49.11	48.93
4	Viscosity	mm^2/s	D445	2.7	2.79	2.86	2.92	3.1
5	Flash Point	^0C	D93	64	67	70	73	75
6	Fire Point	^0C	D93	71	73	78	80	82

Algae comprise an enormous and diverse group of fastest growing photosynthesizing microscopic aquatic organism ranging from unicellular to multicellular forms with simplistic structure. There are more than 300,000 species of algae, diversity of which is much greater than plants. Depending on the species, algae can produce different types of lipids, carbohydrates, and other complex oils with varying proportions in large amounts over a

This paper was recommended for publication in revised form by Regional Editor Sandip Kale
[1]Research Scholar, Symbiosis International University, Pune, India
[2]Department of Mechanical Engineering, MIT AOE, Pune, India
[3] Automotive Research Association of India, Pune, India
**E-mail address: them2712@gmail.com*
Orcid id: 0000-0002-8284-4535, 0000-0003-2714-9262
Manuscript Received 15 January 2018, Accepted 25 April 2018

short time [2–4]. A biofuel produced from chlorella algae oil through a transesterification process was used in this study, whereas, the biofuel-diesel blends were done on percent volumetric basis of diesel and algae biofuel for net unit volume. The properties of these fuels presented in Table 1, depicts the visual comparison of diesel and algae oil methyl ester (AOME) blends respectively.

METHODOLOGY

The setup comprised a single cylinder, four stroke, water cooled, direct injection, and variable compression ratio diesel engine. Eddy current dynamometer is used for loading purpose. It is equipped with essential instruments like in-cylinder pressure transducer, crank angle encoder, fuel flow measurement, thermocouples and strain gauge load cell which are interfaced to computer through prompt high speed data acquisition device. Rotameters are provided for cooling water and calorimeter water flow measurement. EngineSoft is Labview based software package developed by Apex Innovations Pvt. Ltd. for engine performance monitoring system. The detailed specification of the engine and schematic diagram of the experimental set up are shown in Table 2 and Fig. 1.

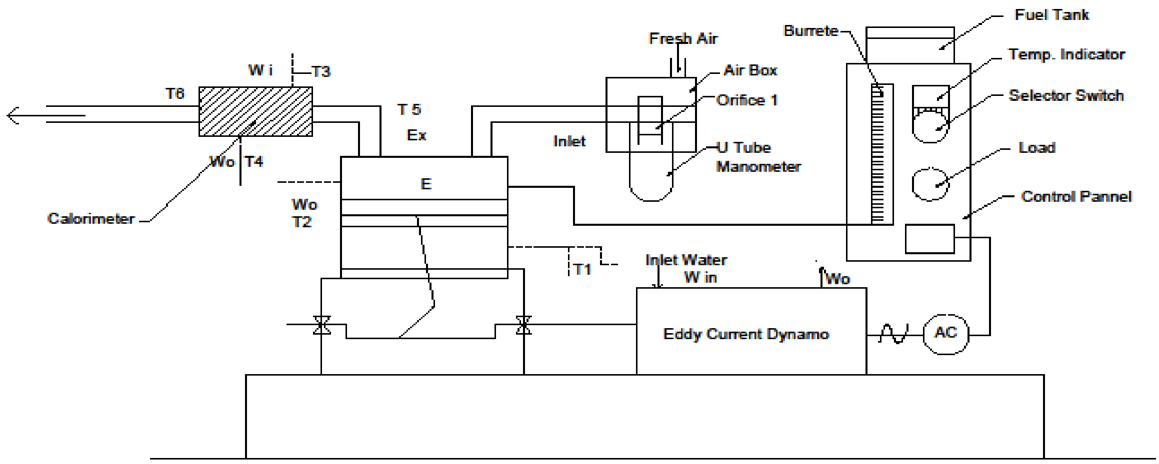


Figure 1. Schematic of engine set-up

Performance tests were conducted in a diesel engine using standard diesel and blends of algae biofuel (B5, B10, B20, and B30) following the Indian standard (IS) 10000: part 8. Standard diesel was used to start the engine and for sufficient warm up. The engine was run at constant speed 1500 rpm by varying the engine load from no load to full load in steps of 25%. Moreover, all tests were performed and parameters were measured under steady state condition. The tests were conducted for 1 hour and 15 minutes for each test fuel, and the readings were recorded at an interval of 15 min for a particular engine load.

Table 2. Engine Specification

Make	Kirloskar TA1
Orientation	Vertical
Type	DI, Single cylinder, 4-Stroke
Arrangement of valves	Overhead
Bore & Stroke (mm)	87.5 & 110
Compression ratio	18:1
Engine capacity	0.661 lit
Rated power	3.5 kW
Rated speed	1500 rpm
Start of injection	23^{O}bTDC
Dynamometer	Eddy current
Cooling system	Water cooling
Injection pressure	200 bar

During this test, performance parameters such as brake thermal efficiency (BTE), specific fuel consumption (SFC), and exhaust gas temperature (EGT) were determined by measuring fuel consumption, engine torque, and exhaust gas temperature. The pressure sensor was mounted on the cylinder head at the middle to reduce any error; also its output was amplified and regenerates to digital signals and recorded for every 1O crank angle. In order to eradicate the effect of cycle-to-cycle variations, the in-cylinder pressure data were recorded for ten consecutive cycles and then the mean was used for analysis. Hence the combustion parameters like in-cylinder pressure, net heat release, ignition delay were measured with an accuracy of 0.1[5-6]. Furthermore, exhaust emissions such as carbon monoxide (CO), hydrocarbon (HC), carbon dioxide (CO_2), and oxides of nitrogen (NOx) were also measured using an exhaust gas analyzer.

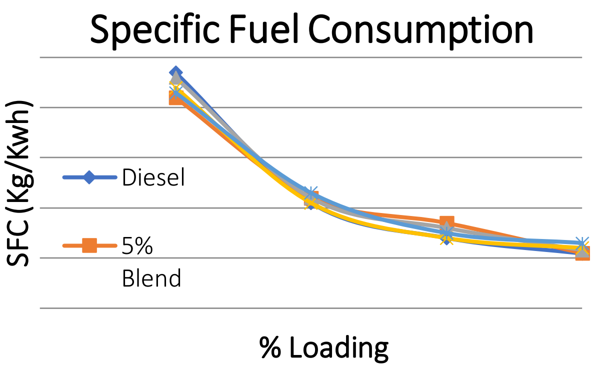
RESULTS AND DISCUSSION PERFORMANCE ANALYSIS

Brake thermal efficiency

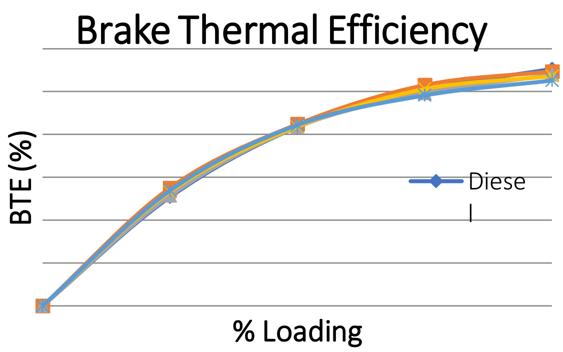
Brake thermal efficiency evaluates how capable the engines convert the chemical energy of the fuel into useful work [7]. The change in BTE percentage for different blends with different loading condition is shown in Fig. 3a. The brake thermal efficiency shows increasing trend for all the tested fuel types while increasing the engine load. It happened due to the reduction in heat loss and an increase in power developed while increasing the load. BTE was slightly lower for all algae biofuel blends compared to diesel, however, the difference was found to be below 5%, at all loading conditions. The maximum BTE obtained for diesel, B5, B10, B20, and B30 are 27.65%, 27.36%, 26.96%, 26.81%, and 26.30% at full load respectively. Also, brake thermal efficiency shows gradual decrement with increasing fraction of algae oil because of its unsatisfactory combustion and spray atomization characteristics due to their high viscosity and density along with lower heating value [8].

Specific fuel consumption

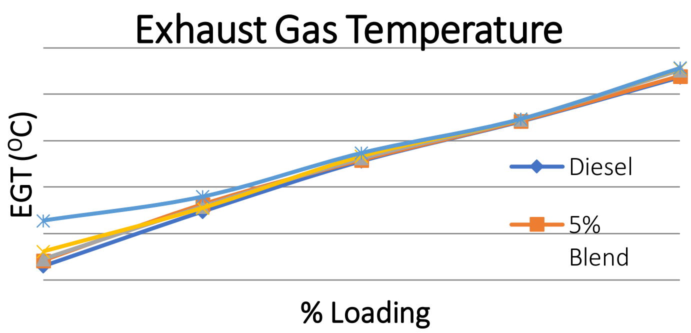
Fig. 3b exhibits variations in the specific fuel consumption for various blends under various loading conditions. The figure indicates that when the load increases, the SFC of all types of fuel will maintain a gradual decrement, however, decreases of BSFC slowed with increased engine loads for all fuels. SFC increased with an increase in biofuel fractions in the blend. The SFC of the blends B5, B10, B20, and B30 at full load is 0.310 kg/kWh, 0.316 kg/kWh, 0.320 kg/kWh, and 0.331 kg/kWh respectively, whereas for diesel it is 0.309 kg/kWh. It was noted that the SFC of the algae biofuel blends was higher than the diesel by up to 7% at all loading conditions. This was due to the effect of volumetric fuel injection rate, lower calorific value and higher density as well as the viscosity of the biofuel. Generally, at lower loads, the SFC of the CI engine is higher and then decreases linearly because of gradual increment in brake power than the fuel consumption [9].



(a) BTE



(b) SFC



(c) EGT

Figure 3. Variation of performance parameters for different blends with different engine loads

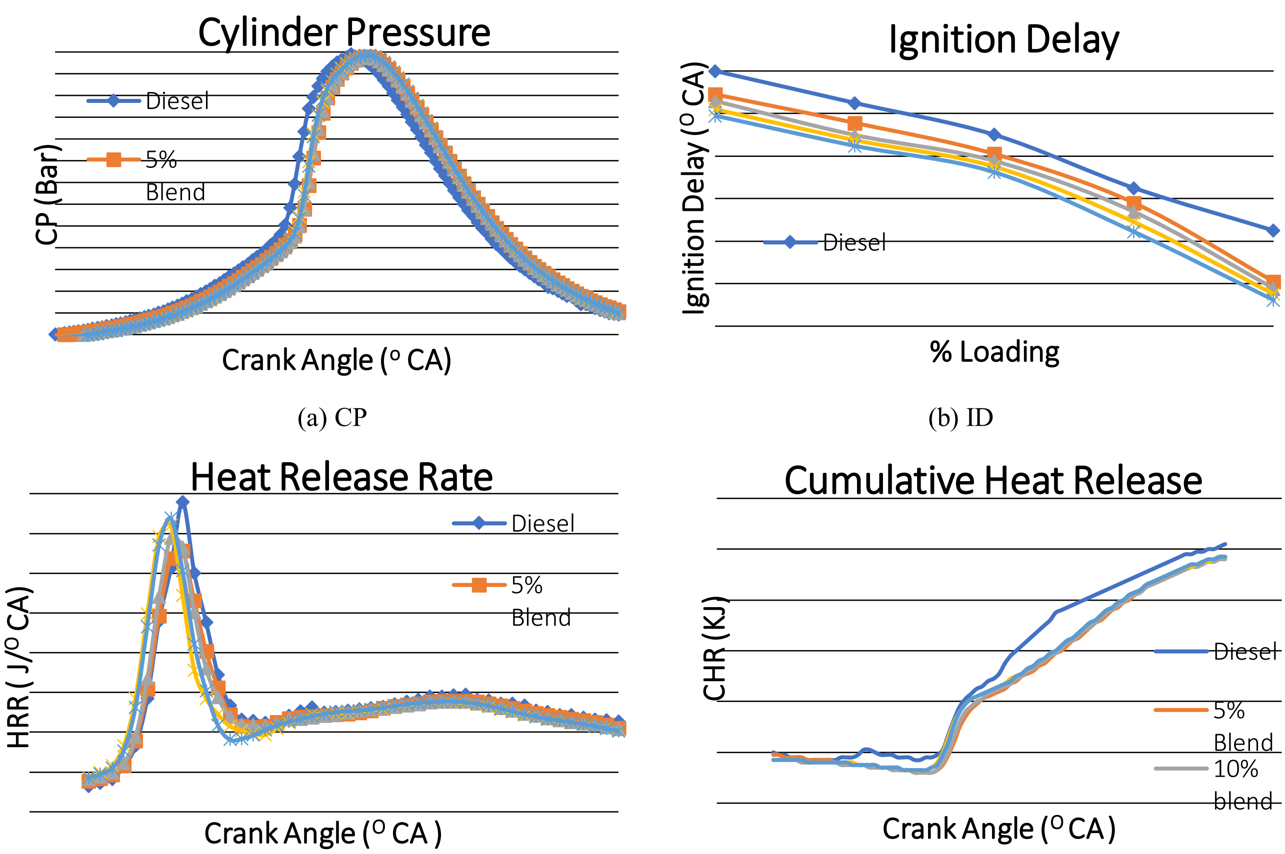
Exhaust gas temperature

The variations of exhaust gas temperature with different engine loads and for different blends are shown in Fig. 3c. Slightly increasing exhaust gas temperatures (≤ 3%) while increasing the proportion of algae oil in the blends and engine load were noted. The exhaust gas temperature for diesel, B5, B10, B20, and B30 are 318.390C, 319.90C, 326.10C, 327.89 0C and 328.360C respectively, at full load condition. Due to the lower compressibility of biofuel (higher bulk modulus) than diesel, the sudden rise in pressure created by the pump and moreover it's higher density and viscosity helps to increase the injection line pressure. This opens the injector needle valve sooner than diesel which results in the earlier start of combustion and elevated combustion temperature ultimately causes slightly higher exhaust gas temperature [6].

COMBUSTION ANALYSIS

Cylinder pressure

In-cylinder pressure measurement is the most significant tool used for analyzing the combustion process as it characterizes the ability of the fuel to mix well with air and burn [10-11]. Variation of cylinder pressure with respect to the crank angle for full load condition and for the different blends is shown in Fig. 4a. It is noted that the peak pressure was higher for diesel compared with blends at all loading conditions. The peak pressure has been observed to be 69.53 bar, 69.03 bar, 68.18 bar, 68 bar, and 67.27 bar for standard diesel and algae biofuel blends B5, B10, B20, and B30 respectively at full load. The high viscosity and low volatility of the algae biofuel led to unsatisfactory atomisation and the formation of a mixture with air. Thus, a slight decreasing trend of cylinder pressure was observed with increasing the biofuel fraction in the blends [12].



(a) CP (b) ID

(c) HRR (d) CHR

Figure 4. Variation of combustion parameters for different blends

Ignition delay

Ignition delay is the most significant parameter used in combustion analysis. Fig. 4b shows the variation of ignition delay of algae biofuel blends compared with that of diesel under various loads. At full load condition, the ignition delay periods for B5, B10, B20, and B30 are 6.1, 5.78, 5.51, and 5.23/°CA respectively that are lower than diesel (8.5°CA). It was found that the delay period for all tested fuel shows decreasing trend while increasing the load due to increased in-cylinder gas temperature. Also, ignition delay slightly decreased with the use of biofuel blends due to its comparable cetane number, higher unsaturated fatty acids, excess oxygen and diglycerides content, which helps to auto-ignite resulting in shortened ignition delay [13].

Net heat release

The heat release curve exhibits the potential availability of heat energy during combustion, which can be transformed into useful work and used to differentiate the combustion rates of fuels [12]. The net heat release rate at full load condition with respect to the crank angle for different biofuel blends is presented in Fig. 4c. After the completion of the premixed combustion, the algae biofuel blend possessed combustion stages almost comparable to that of diesel fuel. The maximum heat release rate for biofuel blends B5, B10, B20, B30, and diesel was 55.58, 58.88, 62.08, 63.78, and 67.75 J/°CA. The overall heat release rate is higher for diesel than algae biofuel blends due to its higher volatility, longer ignition delay period and superior spray formation. However, the heat release during the late combustion phase for biofuel blends did not show any significant difference than that of diesel. Excess amount of oxygen ensured the complete combustion of the fuel that is residual during the controlled combustion phase but continues to burn in the late combustion phase [14].

Cumulative heat release

Figure 4d shows the cumulative heat release for all test fuels at full load engine operating condition. Due to heat absorbed by the injected fuel for vaporization and heating from the cylinder, the heat release rate is somewhat negative during the delay period, afterward, the heat release values become positive [15]. The figure shows the tendency of an earlier release of fuel energy for biofuel blends, which becomes less important at higher engine loads [16]. Combustion for diesel starts later on but quickly it exceeds the cumulative heat released for biodiesel blends, signifying a quicker burn rate of diesel. Cumulative heat release rate shows the slightly decreasing trend as the fraction of biofuel increases in the blend, due to the lower calorific value of the biofuel.

EMISSION ANALYSIS

Hydrocarbon

The variation in hydrocarbon emissions under various engine loads for the various blends is displayed in Fig. 5a. The hydrocarbon emission shows increasing trend while increasing the load of the engine for all the fuel type tested. It was noted that the hydrocarbon emission reduced linearly with the addition of biofuel fraction in the blends. The measured HC emissions of algae biofuel blends were found to be on an average of 28% lower than that of diesel fuel respectively. Due to the presence of excess oxygen, comparable cetane number, longer chain length and higher saturation level of algae biofuel led to complete combustion results in the reduction of HC emissions [17].

Carbon Monoxide

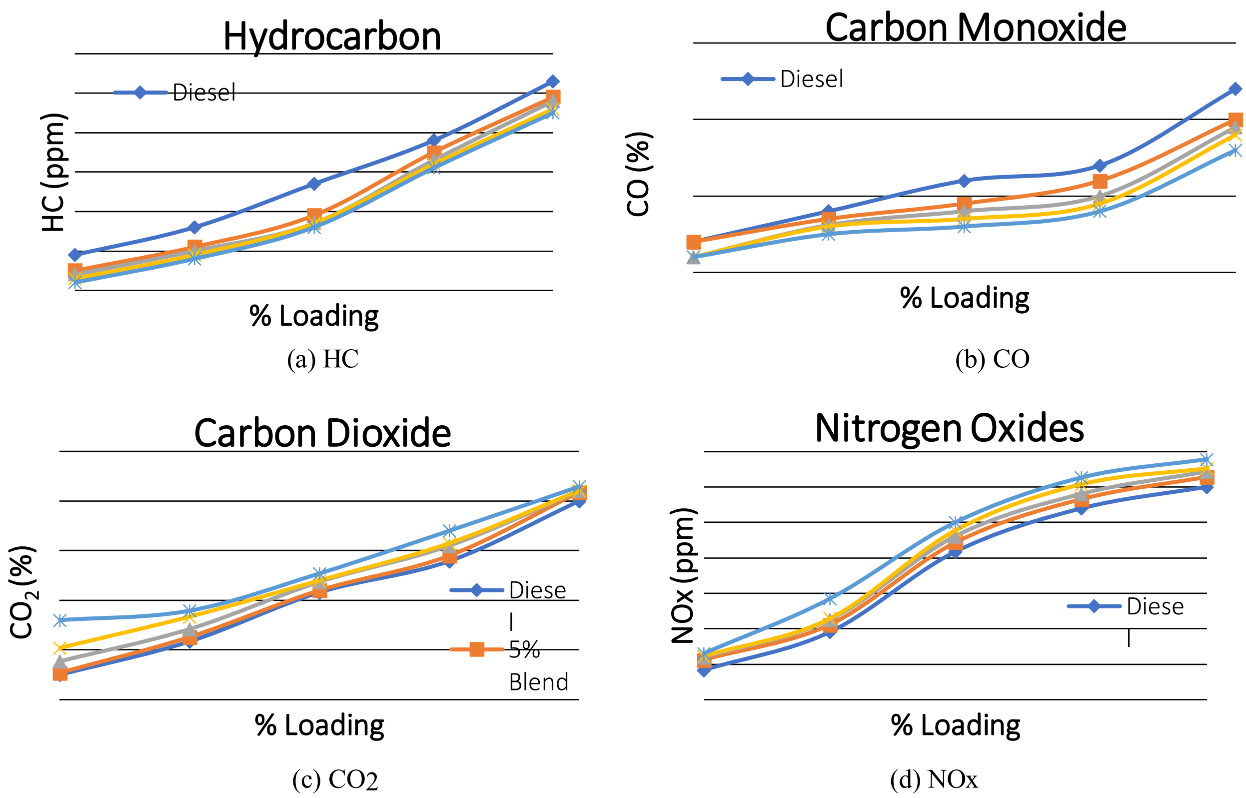
The variation of carbon monoxide for different loading condition for different blends is as shown in Fig. 5b. The carbon monoxide emission shows increasing trend while increasing the load of the engine for all the fuel type tested due to the reducing trend of the air-fuel ratio. At higher engine load, burning of richer air-fuel mixture generally produced higher CO emissions [18]. The measured CO emissions of algae biofuel blends were found to be an average of 22% lower than that of diesel fuel. CO is mainly produced due to the lack of oxygen for complete combustion. Since algae biofuel is an oxygenated fuel with lower carbon content, it leads to complete combustion of biofuel results in decreasing carbon monoxide emission.

Carbon dioxide

Fig. 5c illustrates the variation in CO_2 emissions under various loads for various blends. The carbon dioxide emission shows increasing trend (upto 4.83) while increasing the load of the engine for all the fuel type tested. The complete combustion of biofuel blends in the combustion chamber leads to the increased emission of carbon dioxide. It is evident that CO_2 emission increases with increased biofuel blends due to the availability of more oxygen molecules for complete conversion of CO to O_2 during combustion [19].

Nitrogen Oxide

NOx emission is a common term used for nitric oxide (NO) and nitrogen dioxide (NO_2), which is produced due to the reaction of nitrogen and oxygen gasses in the air at elevated temperature, during the combustion process [20]. Fig. 5d exhibits the variation in NOx emissions under various engine loads for the various blends. It was noted that the NOx emissions increased linearly with the increase in both engine load and biofuel proportion in the blends. It was observed that the NOx emissions with algae biofuel blends were higher at an average of 13% than diesel due to comparable cetane number, excess oxygen content, longer carbon chain length, lower oxidation stability, higher engine exhaust temperature and higher peak combustion temperature.



(a) HC (b) CO

(c) CO2 (d) NOx

Figure 5. Variation of emission parameters for different blends with different engine loads

CONCLUSION

Performance, emission, and combustion analysis of a CI engine fuelled with algae biofuel blends (5%, 10%, 20%, and 30%) were experimentally investigated. It can be concluded that the blends of algae biofuel with small content by volume (20%) could partly displace conventional petrodiesel for controlling air pollution, encouraging the rich lipid content algae oil to produce biofuel and reducing the stress on scant resources without any modifications and notably sacrificing engine performance.

The performance parameters like brake thermal efficiency showed decreasing trend (upto 5%) whereas specific fuel consumption (upto 7%) and exhaust gas temperature (upto 3%) showed increasing trend for algae biofuel blends compared to diesel. On the other hand reduction in hydrocarbon (upto 28%) and carbon monoxide (upto 22%) emission was noted for algae biofuel blends along with a marginal increase in carbon dioxide (upto 4.83%) and oxides of nitrogen (upto 13%) emissions. Also, combustion characteristics of all algae biofuel blends showed almost comparable results when compared to that of conventional diesel. Comparable cetane number and oxygenated nature of algae biofuel lead to an earlier start of combustion with shortened ignition delay. In addition, it was also noted that the net and cumulative heat release rate of algae biofuel blends is somewhat inferior to diesel due to its lower heating value, lower volatility, shortened ignition delay and higher viscosity. The overall experimental analysis reveals that the 20% algae oil methyl ester blend operates quite similar to diesel with respect to thermal performance, emission and combustion characteristics and could be used as a good substitute to petrodiesel fuel.

Furthermore, research on several new combustion technologies with emission control methods of modern diesel engines is also needed for comprehensive combustion and emission optimization. Also, there is the need to establish models that accurately correlate the engine operating variables and combustion-emission characteristics of algae biofuel with a minimal number of input parameters.

NOMENCLATURE

CI engine	Compression Ignition engine
AOME 20%	Algae oil methyl ester biofuel (80:20 wt%)
SFC	Specific fuel consumption
BTE	Brake thermal efficiency
EGT	Exhaust Gas Temperature
HC	Hydrocarbon
CO	Carbon monoxide

CO_2	Carbon dioxide
NOx	Nitrogen oxides

REFERENCES

[1] Demirbas A. (2010). Use of algae as biofuel sources. Energy conversion and management, 51, 2738-2749.
[2] Kleinova A et al,. (2012). Biofuels from algae. Procedia Engineering, 42, 231 – 238.
[3] Singh J and Gu S. (2010). Commercialization potential of microalgae for biofuels production. Renewable and sustainable energy reviews, 14, 2596-2610.
[4] Schlagermann P. (2012). Composition of algal oil and its potential as biofuel. Journal of combustion, 2012, 1-14.
[5] Islam M A Rahman M M Heimann K and Ristovski Z D. (2015). Combustion analysis of microalgae methyl ester in a common rail direct injection diesel engine. Fuel, 143, 351-360.
[6] Saravanan S Nagarajan G Lakshmi Narayana Rao G and Sampath S. (2010). Combustion characteristics of a stationary diesel engine fuelled with a blend of crude rice bran oil methyl ester and diesel. Energy, 35, 94-100.
[7] An H W M Yang S K Chou and K J Chua. (2012). Combustion and emissions characteristics of diesel engine fueled by biodiesel at partial load conditions. Applied Energy, 99, 363-371.
[8] Devan P K and Mahalakshmi N V. (2009). Performance, emission and combustion characteristics of poon oil and its diesel blends in a DI diesel engine. Fuel, 88, 861–867.
[9] Tesfa Belachew Mishra Rakesh Gu Fengshou and Ball Andrew. (2013). Combustion and Performance Characteristics of CI Engine Running with Biodiesel. Energy, 51 (1), 101-115.
[10] Shailendra Sinha. (2009). Rice bran oil methyl ester fuelled medium-duty transportation engine: long-term durability and combustion investigations. International Journal of Vehicle Design, 50.
[11] Mei Deqing Shan Yue Xiaodong Zhao Klaus Hielscher and Roland Baar. (2016). Combustion features under different center of heat release of a diesel engine using dimethyl carbonate/diesel blend. International Journal of Green Energy, 13, 1120-1128.
[12] Gopinath Anantharaman Krishnamurthy Sairam and Ramalingam Velraj. (2015). Combustion Analysis of Polanga (Calophyllum inophyllum) Biodiesel. Applied Mechanics and Materials, 812, 51-59.
[13] Xue Jinlin. (2013). Combustion characteristics, engine performances and emissions of waste edible oil biodiesel in diesel engine. Renewable and Sustainable Energy Reviews, 23, 350-365.
[14] Sahoo P and Das L. (2009). Combustion analysis of Jatropha, Karanja and Polanga based biodiesel as fuel in a diesel engine. Fuel, 88(6), 994–999.
[15] Rajasekar E and Selvi S. (2014). Review of combustion characteristics of CI engines fueled with biodiesel. Renewable and Sustainable Energy Reviews, 35, 390-399.
[16] Sinha S. (2007). Experimental investigation of the combustion characteristics of a biodiesel (rice- bran oil methyl ester)-fuelled direct-injection transportation diesel engine. Proceedings of the Institution of Mechanical Engineers Part D Journal of Automobile Engineering, 221, 921-932.
[17] Lapuerta M and ArmasO Rodrı´guez-Ferna´ndez J. (2008). Effect of biodiesel fuels on diesel engine emissions. Progress in Energy and Combustion Science, 34(2), 198–223.
[18] Monirul I M Masjuki H H Kalam M A Mosarof M H Zulkifli N W M Teoh Y H and How H G. (2016). Assessment of performance, emission and combustion characteristics of palm, jatropha and Calophyllum inophyllum biodiesel blends. Fuel, 181, 985-995.
[19] Mohamed F Al_Dawody and Bhatti S K. (2014). Experimental and Computational Investigations for Combustion, Performance and Emission Parameters of a Diesel Engine Fueled with Soybean Biodiesel-Diesel Blends. Energy Procedia, 52, 421 – 430.
[20] Datta Ambarish and Bijan Kumar Mandal. (2016). A comprehensive review of biodiesel as an alternative fuel for compression ignition engine. Renewable and Sustainable Energy Reviews, 57, 799-821.