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Performance evaluation and emission characteristics of microalgae fuel in combustion engine

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Abstract
Biofuels derived from microalgae have potential to replace fossil fuel and other biofuels. The current study evaluated the performance and emission characteristics of microalgae fuel in agricultural tractor. Microalgae (*Desmodesmus sp.*) was treated with Hydrothermal Liquefaction (HTL) process to extract the lipids. Physical and chemical properties of microalgae oil were used to evaluate the performance and emissions characteristics in agricultural tractor's engine. With microalgae oil, two other biofuels, i.e., fossil diesel (Diesel No. 2) and Soybean Methyl Ester (SME100) were also used to provide a comparative result. A commercial software "Diesel-RK" was used to simulate selected engine (Perkins 4.236) which is widely utilized in Massey Ferguson 255. Microalgae oil showed slightly lower power (44.80 kW) and torque (164.9 N-m) compared to diesel No. 2 (54.5 kW, 200 N-m) and SME100 (51.27 kW, 188.34 N-m) at full load and maximum rated speed (2600 rpm). Specific fuel consumption of microalgae oil is higher than the other two fuels, which can be explained by the lower heating value of microalgae oil. NO_2 emissions and particulate matter formation were lowered when the engine was filled with microalgae oil.

Keywords: Microalgae, hydrothermal treatment, agricultural tractor engine, performance, emissions

Introduction
The world has been challenged with an energy crisis since resources of fossil fuel are depleting at a significant rate. It is widely accepted that the use of fossil fuel in the combustion engine is not sustainable and it accumulates greenhouse gases in the atmosphere, which contribute to global warming (Ayhan *et al*., 2010) [3]. Recent studies have mentioned that 80% of the world energy demand is provided by fossil fuel sources and will be depleted by 2030 therefore, development of safe and sustainable renewable energy resources is a top priority for all countries (Xu *et al*., 2015) [14]. According to EIA, the demand for oil from 2005 to 2030 will increase by 1.3 % annually, and it will reach 99 million barrels/day in 2015 to 116 million barrels/ day by 2030. According to Shafiee *et al*., (2007), even the demand for fossil fuel will decrease in the next 25 years compared to other sources of fuels, but in absolute terms, it will be the largest source of universal demand for energy until 2030. Over the last few decades, an increase in the supply of fossil fuel has been noticed. On the other hand, the production of energy from other hydro, nuclear and biofuel will increase rapidly. With the increasing trend in energy consumption around the world, sources of renewable energy are developing by degrees. However, renewable energy contributes only a small part of global total energy production. According to the organization for economic cooperation and development USA (OECD), renewable energy is more sustainable and environmentally friendly than fossil energy; therefore, a worldwide expansion in production of renewables should be encouraged. From the viewpoint of the World Energy Council (WEC), due to environmental problems and price of fossil fuels, many countries aim to reduce their dependency on fossil fuels sources. Furthermore, IEA reported that two modern fuels: nuclear power and biofuels/biodiesel, will supply a significant share of fuel requirements by 2030. The EIA also mentioned that the demand for biofuels for transportation would increase to 13% by 2050.

Out of some available options of renewable resources to replace fossil fuels in the combustion engine, biodiesel is considered most promising because, it can be easily mixed with fossil fuel and used in conventional engines, such as in agricultural tractor engine and other engines. The main problem associated with the production of biofuels from farm crop is the availability of land. Currently, many countries are dealing with the critical issue of food supply. In this case, diverting food crops towards the production of biofuels will be a detrimental step towards food security (Sadeghinezhad *et al*., 2013) [31].

Awareness about the environmental loading and fossil fuel depletion leads to research for an alternative and sustainable fuel source that can be used without much environmental pollution. Commonly all the bio-oil is cleaner and safe to use in CI engines. Performance and emission are the two distinct parameters we talk about in the case of biofuels. Significant work has been done about performance evaluation and emission of biodiesel obtained from different sources. However, evaluation of algal-based biodiesel in agricultural tractor engine is lacking. Table 1shows statistics of references that have studied the effect of pure biodiesel on engine performance and emission characteristics.

Table 1: Statistics of biofuel's impact on performance of IC engines

Particulars	Decreases	Similar	Increases
CO_2 emission	5	2	6
HC emission	51	3	3
CO emission	57	2	7
NO_x emission	20	4	45
PM emission	64	2	7
Power performance	19	6	2

Source: Xue *et al*., 2011

Alireza *et al*., (2013), studied about brake torque of diesel engine with biodiesel and diesel blend. Brake power (BP) decreased up to 17 % with the use of biodiesel. The result also showed that increase in engine load results to increase in BP up to 69 %. The capacity of biodiesel to reduce total emissions from the engine has been considered as a valuable property. As per the United States, Environmental Protection Agency (EPA), consolidated or durable material gathered by a suitable filter at a temperature of 52 °C or lower is called particulate discharge. It incorporates residue carbon, fuel, and derivatives of lube oil, and corrosive sulfuric mist concentrates. EPA report investigated the impacts of biodiesel emission produced from crops such as rapeseed, soybean, and animal fat. The study indicated that emitted pollutants were not affected by the model number and years of the engine. Wahlen *et al*., (2012), evaluated emissions from engines using microalgae biofuel and other fuel (yeast, bacteria, soybean and petroleum diesel) in a 2-cylinder diesel engine. The study analyzes horsepower, BSFC, torque and emissions with different speed and load conditions while analyzing the emission characteristics; the study reported that all the biofuel produced lower HC and CO as compared to pure diesel oil. Amongst all the biofuels, microalgae-based biodiesel surprisingly produced lowest NO_x than all others, even lower than petroleum diesel oil. All the emitted pollutants were collected without the application of any external load on the engine running at a constant speed of 3500 rpm. Datta and Mandal *et al*., (2016), presented a systematic approach to evaluating the effect of the addition of alcohol to diesel oil on the performance and emission of a diesel engine. Kirloskar TV1 engine with 1 cylinder was used in this study. Authors have used commercial software "Diesel-RK" for the simulation of engine with different fuels. A marginal improvement in brake thermal efficiency (BTE) was observed and BSFC increased with addition of ethanol and methanol to diesel due to lower energy density of alcohol. Combustion efficiency was enhanced with the addition of alcohol to diesel due to lower flame temperature of alcohol blend fuels. The study revealed that 15% ethanol blended fuel reduced emission of NO_x, specific PM and smoke by 39.08%, 32.63% and 27.29% respectively.

Even after a series of studies, there is a large research gap between the production of microalgae oil and its performance evaluation as a fuel in combustion engines (Biller *et al*., 2011) [4, 5]. Therefore, the overall aim of this study is to analyze the performance and emission characteristics of microalgae-based biodiesel in internal combustion engines.

Preparation of microalgae oil and its specifications

Microalgae (*Desmodesmus sp*.) biomass of known water content was provided by the microalgae cultivation center at the University of Tsukuba, Japan. Crude oil from microalgae was extracted using HTL process. Crude oil, having dark color was separated in different phases using screening and sedimentation process. Samples were prepared to examine the physical and chemical properties of microalgae oil obtained. Fatty acids of microalgae oil were analyzed using GC-MC by following all means of standard. Microalgae products obtained from HTL reactor were sent to chemistry lab. GC-MS of model Shimadzu GC-2010with column BPX70 (30m, ID 0.25 mm, 0.25 mm) was used. The split injection in the ratio of 25:1 at 250 °C, helium flow rate was 3.0 mL/minute, FID type detector was used at 70 °C. After obtaining microalgae oil, important physical and chemical properties were analyzed. Some of the properties were determined using methods/data in reference studies. Cetane number or CN is the characteristic of fuel that is used to evaluate the quality of fuels. CN indicates combustion speed of diesel or biodiesel fuel. It is similar to octane rating for petrol. The Cetane is mainly affected by the fatty acids methyl ester composition of the biodiesel (Miraboutalebi *et al*., 2016). In this study, fatty acids were used to predict CN of microalgae oil. This method was same as mentioned in Knothe *et al*., (2012).

Table 2: Prediction of Cetane number based on C16, C18 and C20 fatty acids

Number of C in fatty acid chain	Number of double bond						
	0	1	2	3	4	5	6
C16	85.9	52	32	-	-	-	-
C18	101	59.3	38.2	22.7	16	-	-
C20	-	73.2	49	36	29.6	22	18
C22	-	74.2	68	55	42	32	24.4

(Source: Knothe *et al*. 2012)

Properties of fuel or biodiesel are affected by the fatty acids composition of oils. These fuel properties such as HVV, oxidative stability, and kinematic viscosity correlate with the molecular weight and the number of double bonds in fatty acid alkyl esters (Hong, *et al*. 2015) [16]. Viscosity is an important fuel property, and it is directly related to the fuel injection process of engines. The kinematic viscosity of biodiesel at 313 K should satisfy the range specified by the international biodiesel standard (Meng *et al*., 2014) [25]. In this study, the method explained by Knothe, *et al*. (2012) to predict kinematic viscosity was followed. The fraction of C, H and O were used to predict the calorific value (HHV) of microalgae oil obtained using HTL. Delong's formula (given below) was used to predict the calorific value of microalgae oil.

Higher Heating Value (MJ/kg) = 0.3383× C + 1.442 × (H-O/8), (Delong's formula).

Where, C = fraction of carbon in microalgae oil

H = Fraction of Hydrogen in microalgae oil

O = Fraction of Oxygen in microalgae oil

The calorific value of microalgae obtained from above formula was compared with the calorific value measured using Bomb calorimeter. Bomb calorimeter was used at National Agriculture and Food Research Organization (NARO), Tsukuba, Japan. The fraction of Carbon, Hydrogen, and Oxygen was analyzed at JGC Corporation (Nikki) Minami Soma city, Fukushima, Japan. Average values of C,H and O, were taken out of three replications. C, H, and O fraction were used to predict the calorific value of microalgae oil by Delong's formula.

Engine simulation using Diesel-RK

Design of simulation software Diesel-RK is based on full cycle thermodynamic process for simulation and optimization working process of two and four stroke IC engines with all types of boosting. Thermodynamics models used in this software and database are based on the first law of thermodynamics and are used to analyze the performance of engines based on modeling. In this study, simulation has been carried out for Perkins 4.236 diesel engine, which is used in Massey Ferguson 255 agricultural tractor. The basic geometry of engine such as piston and bowl shape, connecting rod length, rated rpm, compression ratio, injection timing and other properties were used as inputs. Table 3 shows detailed specifications of the engine used in this study. After developing engine model in the software, fuel gallery was prepared based on fuel properties to be used. Properties of fossil diesel and some other fuel were set in the software's database. Three types of fuels were modeled in fuel gallery as fossil diesel (diesel No. 2), Microalgae oil and Soybean Methyl Ester (SME100).

Table 3: Specifications of agricultural tractor's engine used for simulation

1.	Manufacturer	Perkins
2.	Model	4.236
3.	Type	4 Stroke, Direct ignition
4.	No. of cylinder	4
5.	Bore (mm)	98
6.	Stroke (mm)	127
7.	Rated speed (rpm)	2600
8.	Connecting rod length (mm)	226
9.	Compression ratio	16.0:1
10.	Cooling type	Liquid
11.	Engine position	Vertical

(***Source***: Perkins)

The performance of agricultural tractor engine relies on the types of fuel being used and its thermochemical properties. Characteristic of fossil fuel and biodiesel depend on the chemical composition and the method of production of the fuel. The calorific value of fuel depends on the presence of C, H, O, and N in fuel. Diesel-RK takes all these properties to prepare fuel gallery for the evaluation of engine performance. Fuel properties of microalgae-based oil were modeled in fuel gallery as shown in table 4.

Table 4: Chemical and physical properties of fuels used in study

Properties	Microalgae oil	Soybean ME	Fossil Diesel
Carbon content (%wt.)	74.5	77.3#	87#
Hydrogen content (%wt.)	13.01	11.8#	12.6#
Oxygen content (%wt.)	12.61	10.8#	0.4#
Sulfur content (ppm wt.)	0	0	<350
Cetane number	53.58	51.3#	48#
Lower heating value (MJ/Kg)	34	36.22#	42.5#
Density at 323 K (kg/m^3)	902.3**	874#	830#
Dynamic Viscosity at 323 K (Pa. s)	0.0319**	0.00463#	0.003#

* Murriloetel., 2007.
#Diesel-RK default value verified with references.
**Tsaousis *et al*., 2014 [28].

The model developed in Diesel-RK considers the following conservation equations as described by Fivel and Assanis.

Conversion of mass

The rate of change of mass within any system, which is open, is the net flux of mass across the system boundaries and can be express as follows:

$\frac{dm}{dt} = \sum_j mj$

Conversion of energy

Fivel and Assanis have described equation for the thermodynamic system that can be written as:

$$\frac{d(mu)}{dt} = p\frac{dv}{dt} + \frac{dQ}{dt} + \sum_j mjhj$$

Where, $\frac{d(mu)}{dt}$= Rate of change of energy within the system

$p\frac{dv}{dt}$ =Rate of displacement, $\frac{dQ}{dt}$ = Heat transfer rate

$\sum_j mjhj$ Enthalpy flux

Relation between power and torque

$P = \frac{2\pi NT}{60000}$ kW

Where, P- engine power

N- Rotation of crankshaft (revolution per minute)

T- Engine's torque (N-m)

Brake Specific Fuel Consumption (BSFC)

BSCF (g/KWh) = $\frac{Fuel\ Consumption\ Rate\ gram\ per\ hour}{Power\ Produced\ in\ KW}$

Nitrogen oxide (NO_x) formation modeling

Out of all the oxides of nitrogen, NO is predominant in adiesel engine. In this study, amodel with Thermal Zeldocicn's Mechanism was followed. It was developed by Prof. V. Zvonov for conventional diesel and SI engines. Primary reactions for NO formation are as follows:

$O_2 \rightarrow 2O$

$N_2 + O \rightarrow NO + N$

$N + O_2 \rightarrow NO + O$

Atomic concentration is a major factor that influences the rate of above reaction.

During the start of combustion, the moles of different species considered include O_2, N_2 from the intake air and CO_2 and H_2O from the residual gases. Amid the beginning of ignition, the moles of various species studied, incorporates O_2, N_2 from the admission air and CO_2 and H_2O from the lingering gasses. The general burning condition taken into account for the fuel with C-H-O-N is:

$(1-\lambda).\ Cn_1Hm_1 + \lambda.\ Cn_2Hm_2OZ + X\ [O_2 + 3.76N_2] \rightarrow \upsilon_1CO_2 + \upsilon\ 2H_2O + \upsilon 3N_2 + \upsilon\ 4O$

Where, λ is mole ratio of biodiesel added, n_1, m_2 number of carbon and hydrogen atoms for diesel fuels correspondingly. N_2,m_2, z is number of carbon, hydrogen, and oxygen for biodiesel fuel correspondingly, υ mole fraction of product species, X number of moles of oxygen per one mole of fuel and its equal to:

$$X = (1/\varphi).\ [n_1\ (1-\lambda) + n_2\ \lambda] + \frac{[m1(1-\lambda)+m2\lambda]}{4} - 0.5z.\ \lambda$$

Where φ equivalent ratio

The total number of reactants and products during the start of combustion as well as every degree crank angle was calculated from the equation:

$N_r = 1 + X * 4.76$

$Np = (\lambda.\ n_1 + (1-\lambda).\ n_2) + 0.5(\lambda.m_1 + (1-\lambda).m_2) + 3.76{*}X + (\varphi-1) \times [n_1\ (1-\lambda) + n_2\lambda] + \frac{[m1(1-\lambda)+m2\lambda]}{4} - 0.5z.\lambda$ (Mohamed *et al*., 2013)

Summary emission (SE) of PM and NO_x calculated as:

$SE = C_{PM}\ (PM/0.15) + C_{NO}\ (NO_x/7)$

Where C_{PM} is an empirical line factor for particulate matter emission (0.5)

C_{NO} is an empiric line factor for Nitrogen Oxides emissions (1.0)

Soot and Particulate Matter Emission model setting:

The formation of microparticles (<10 microns) is a major issue from the viewpoint of the environment. These microparticles form due to incomplete combustion of ahydrocarbon in fuels. Calculation of PM emission is carried out based on acalculation of soot emission. The concentration of soot particles was calculated by Razleytsev's phenomenological model, and then on its basis PM emission calculated by Alkidas formula, which is given as:

$\left(\frac{d(C)}{dt}\right)_k = 0.004 \frac{qc}{V} \frac{dx}{dt}$ (Datta and Mandal *et al*., 2016)

WhereV is thepresent volume of cylinder

q_c - is a cylinder fuel mass

dx/dt - is a heat release rate

Alkidas also proposed aformula to calculate PM regarding Bosch Smoke number, which is given as:

$$PM = 565 \left(\text{In} \frac{10}{10-\text{Bosch}}\right)^{1.206}$$

Result and discussion

Validation of simulated results

Performance and emission characteristics of microalgae oil were evaluated using simulation software "Diesel-RK." When an experiment is conducted using software, validation of the obtained results is a musttoentirelyrely on the results. In this section, results obtained by simulation were validated with a reference case conducted by Nebraska tractor testing center, US (Liljedahl *et al*., 1979: Tractor and their power units). Performance of fossil diesel was evaluated assuming that diesel oil used have a similar characteristic as in reference study. It was also presumed that validation result with fossil diesel would work as a representative for other two types of fuels used in this study, i.e., Microalgae oil and SME100. Validation has been carried out for engine power and torque at full load and different engine speed. Engine type and operating conditions were setidentical as mentioned in reference study.

Figure 3.1 presents the comparison between simulated result and experimental result taken from reference study. It is observed that Diesel-RK predict a lower engine torque at lower engine speed, but this gap between experimental and simulated results decreased at higher engine speed. At 1000 rpm, the engine produces 223.64 N-m torque while experimental torque value is 254 N-m at same engine speed. At maximum rated engine speed (2600 rpm), simulated torque is 200 N-m while experimental toque value is 206 N-m (SAE net) and 218 N-m (SAE gross).

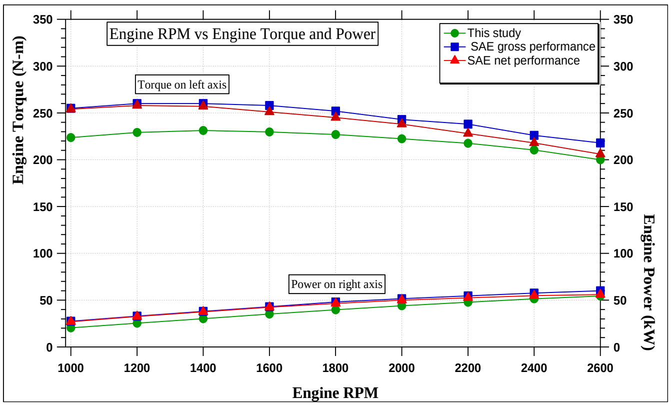

Fig 1: Validation of engine power and torque with reference study

In case of engine power, asimilar trend can be observed as in engine torque. At 1000 rpm, simulated engine power is 20.38 kW while 27 kW in the experimental result. This difference is maintained until 2200 rpm but at 2400 rpm and 2600 rpm values of simulated and experimental engine power is quite close as 51.38 kW and 54.80 kW (SAE net), 60 kW (SAE gross) respectively. The differences between the simulated and experimental results can be explained based on various assumptions made for Diesel-RK. Apart from little differences in simulated and experimental results, a good agreement can be noticed for engine torque and power. This is very encouraging for the validity of the model, given that model's constants were selected only for fossil diesel to measure engine torque and power.

Engine Power and torque

Engine torque and power were obtained at a broad range of engine speed and full load condition. Full load condition was selected because most of the time tractor engine is subjected to a heavy load condition in the agricultural operations. It is observed (Fig. 3.2) that the microalgae oil produces lower torque compared to SME100 and Diesel No. 2. The engine produced 165.06, 184.57 and 223.64 N-m at 1000 rpm for microalgae oil, SME100 and diesel No. 2 respectively. Because of lower heating value and lower energy density, microalgae oil produces less power as compared to other two fuels.

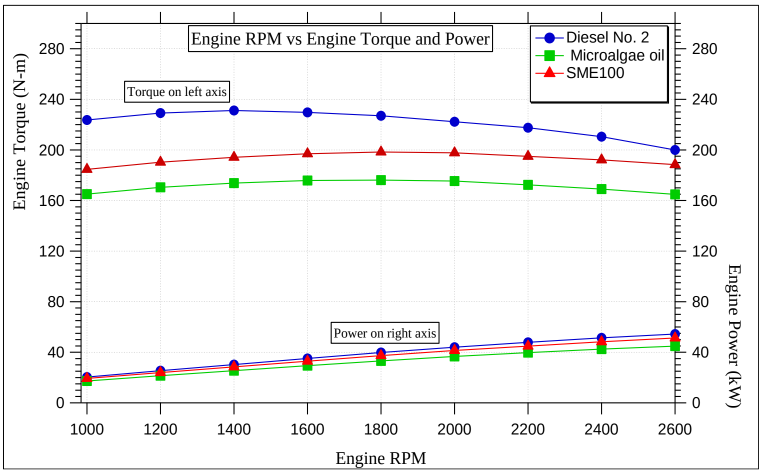

Fig 2: Relation between engine torque and speed with selected fuels

Engine torque increases with increase in engine speed up to 1800 rpm and then starts decreasing. At high speed, time for burning the fuel inside the chamber is not sufficient, and fuel does not burn completely. In case of engine power, the engine produced lower power compared to SME100 and diesel No.2. Again, this can be explained by the lower heating value of raw algae oil than SME100 and diesel No. 2.The power curve is maintained based on calorific values of three fuels used. Diesel No. 2 had higher heating value than other two fuels and showed highest power value. SME100 have a heating value of 37 MJ/kg, which is greater than microalgae oil (34 MJ/kg), and power is accordingly. Power of the engine increased throughout the engine speed range and attained amaximum value of 44.9, 51.27 and 54.44 for microalgae oil, SME100 and diesel No. 2 respectively. Wahlen *et al*., (2012), observed the similar trend for engine torque power while comparing different biodiesels (Soybean, microalgae, yeast) with fossil diesel. The author compared the engine torque and power with maximum torque and power obtained for fossil diesel at 3500 rpm. Soybean biodiesel showed a power output of 96.5 % of the value obtained for diesel fuel. Power output for microalgae biodiesel was 96% of the outputs for diesel fuel. A similar trend was observed in case of engine torque.

Specific Fuel Consumption (SFC)

Specific fuel consumption is an indicator of the amount of fuel consumed to produce a certain degree of power for a period. Microalgae oil demonstrated significantly higher specific fuel consumption (SFC) followed by SME100 and diesel No. 2. Engine consumed 310.87 g of microalgae oil to maintain 1 kW power for an hour while 292.67 g and 241.60 g of SME100 and diesel No. 2 respectively at 1000 rpm (Fig. 3.3). SFC decreased as increased in engine speed and attained a lower value at the medium speed of the engine. The result indicates that medium range of engine speed is better at full load condition for all three types of fuels being used. After 1800 rpm of engine speed, SFC started increasing for all three fuels because engine fuel pump delivers more quantity of fuel to engine nozzle per unit time and another mass of fuel delivery into the combustion chamber before complete combustion of the previous mass of fuel. Fuel consumption is higher in case of microalgae because microalgae oil has lower energy density compared to SME100 and diesel No. 2 necessitated an increase for oil to retain same power output, which causes anincrease in SFC of microalgae oil compared to SME100 and diesel No. 2 (Tsaousis *et al*., 2014) [28].

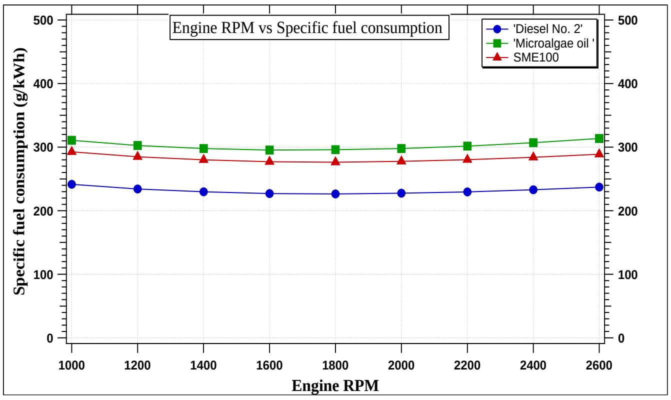

Fig 3: Specific fuel consumptions with engine rpm

Graboski *et al*., (1996) [13] also found a good correlation between Brake Specific Fuel Consumption (BSFC) and oxygen content of biodiesel used. Rakopoulos *et al*., (2004) [29], presented a review and stated an increase in BSFC comes from the fuel having more oxygen, but not from the intake air. Turrio *et al*., (2004) [36], found an increase in BSFC of 2.95% with 95% confidence level. Last *et al*., (1995) [21], tested another heavy-duty diesel engine with pure soybean-oil. Author observed a linear increase in BSFC as the blend of biodiesel increases. BSFC was higher by 12.4% with pure soybean-oil. Alam *et al*., (2004) [1], also found an increase in BSFC in selected heavy-duty engine with 20% soybean-oil biodiesel blends. Lapuerta *et al*., (2007), examined a 2.21 engine in five modes with biodiesel fuels derived from differently stressed waste oils. Increase in BSFC was similar in all cases as the loss in heating value.

Specific CO_2 emission

Complete combustion of fuel inside the combustion chamber is responsible in increasing CO_2 emission. However, is it not necessity of complete combustion inside combustion chamber, there may be a nearly complete combustion that may depends upon the type of engine used and operating conditions but nature of combustion is mainly govern by composition and physical properties of fuel used to operate the engine (Datta *et al*., 2016). All the differences in emissions in this study are only because of composition and physical properties of fuels since environmental conditions and geometry of engine were modelled in software. Microalgae oil showed higher CO_2 emission than SME100 and diesel No. 2 throughout the engine speed. Microalgae oil emitted 838 g/kWh of CO_2 at 1000 rpm while SME100 and diesel No. 2 emitted 795.6 g/kWh and 777.5 g/kWh of CO_2 respectively at same engine speed (Fig. 3.4). This can be explained with the fact that presence of oxygen molecules in fuels helps in better combustion increases CO_2emission but in case of diesel No.2, oxygen content is very low compared to microalgae oil and SME100. CO_2 emission starts decreasing with increase in engine speed and after 1800 rpm its again starts increasing. This behavior can be explained with the pressure rise phenomenon in engine cylinder.

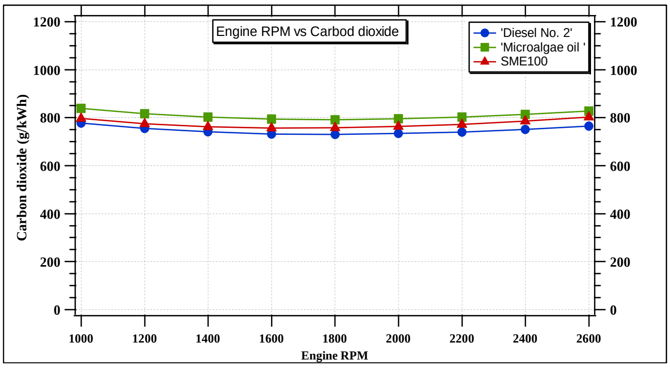

Fig 4: Specific CO_2 emissions of selected fuels

Wahlen *et al.*, (2012), reported similar CO_2 emission of microalgae with fossil diesel and even lower than other three biodiesels used. Alizera, (2013), found overall lower CO_2 emission when the engine was fueled with biodiesel. More amount of CO_2 in exhaust gas indicates that combustion of fuel inside combustion chamber was more complete. Similarly, Lenin *et al.*, 2012, found that at full load, the CO_2 emission of B75 and B100 was significantly lower compared to fossil diesel. The author explained that the variations of CO_2 highly depend on the oxygen content of biodiesel.

NO_2 and particulate matter (PM) emissions

Microalgae oil emitted lower NO_2 compared to diesel No. 2 and SME100 (fig. 3.5). Engine emitted 3.236 g/kWh of NO_2 at 1000 rpm while diesel No. 2 and SME100 19.52 and 9.24 g/kWh of NO_2 at same engine speed. NO_2 emission decreased with increase in engine speed and showed 1.14, 13.25 and 3.87 g/kWh of NO_2 emission at full engine speed (2600 rpm). Three conditions, which favor the NO_2 emission, are (i) higher combustion temperature (ii) higher oxygen content in fuel and (iii) faster reaction rate (Dawood and Bhatti, 2014). Results showed that temperature of exhaust gas is lower in case of microalgae oil than diesel No. 2 and SME100. At 1000 rpm, the temperature of exhaust gas is 614.9 K whereas 656.62 and 669.9 K for SME100 and diesel No. 2 respectively. The percentage of reduction in exhaust temperature with microalgae oil compared to SME100, diesel No. 2 is 6 and 8.9% respectively, and reduction in NO_2 is 64 and 84% for SME100 and diesel No.2 respectively.

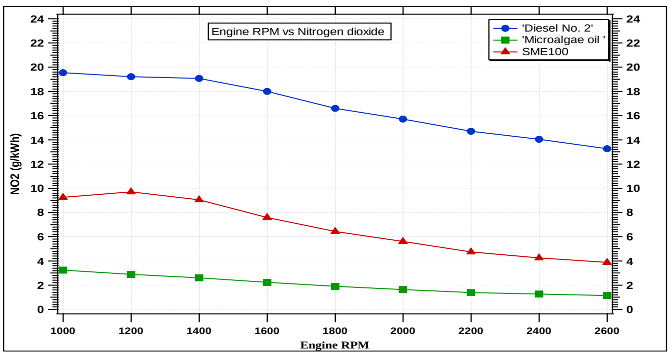

Fig 5: NO_2 emissions of selected fuels

At the maximum rated engine speed, the reduction in NO_2 with microalgae compared to SME100 and diesel No. 2 is 70.5 and 91.37% respectively. The higher Cetane number of algal oil is responsible for lower NO_2 emission. Fuel shows less ignition delay with a higher Cetane number and results in lower temperature and hence NO_2 emission. Smoke opacity is an indication of dry soot emission, which is responsible for the formation of Particulate Matter (PM).

Wahlen *et al.*, (2012), also found asimilar trend in NO_x emissions while experimenting with a naturally aspired indirect injection combustion ignition engine (Kubota Z482-ESO4, Lincolnshire, IL). McCormick *et al.*, (2005), reported that NO_x emissions were lower when theenginewas fueled with 20% blend of soybean-oil biodiesel. Nabi *et al.*, (2006), tested a single-cylinder 9.8 kW diesel engine with different EGR rates. The study found anincrease in NOx emissions without EGR. No significant differences were found with EGR rates between 5% and 35% when theenginewas fueled neem-oil biodiesel. Two arguments that are widespread, which were made by many authors regarding NO_xemissions, are: (1) the increase Cetane number of biodiesel and (2) thehigher oxygen content of biodiesel. Higher Cetane number of biodiesel could be a reason for thevariation in NO_x emissions.

Particulate matter (PM)

The variations of the specific PM and smoke emission with engine speed is presented in figure 3.6. Particulate matter formation is higher in case of diesel No. 2 compared to SME100 and microalgae oil. Microalgae oil and SME100 showed significantly lower PM emission than diesel No. 2. At 1000 rpm, diesel No. 2 emitted 1.929 g/kWh of PM whereas SME 100 and microalgae oil emitted0.0697 and 0.1868 g/kWh of PM respectively. Because of similar properties, the differences of PM emissions are low in the case of SME100 and microalgae oil throughout the engine speed. Diesel No. 2 showed a higher value of PM at low engine speed, then starts decreasing with increase in engine speed, and showed a lower value of 0.5533 g /kWh of PM at maximum rated engine speed (2600 rpm).

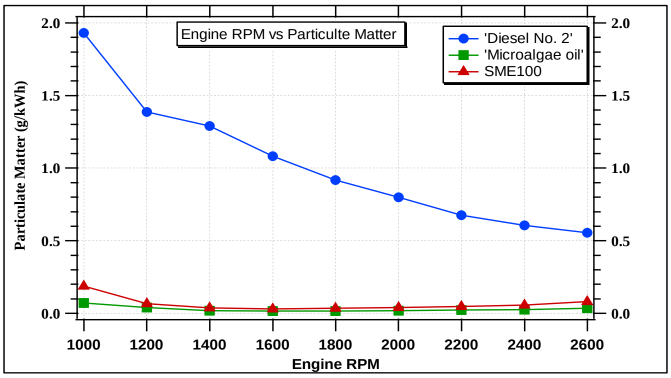

Fig 6: Specific Particulate Matter emissions of selected fuels

The primary reason for the particulate matter formation from CI engine is improper ignition and burning of heavy lubricating oil; smoke formation occurs primarily in the fuel-rich zone of the cylinder at high temperature and pressure (Saying*et al.*, 2010).Although some authors had reported some increase in PM emissions when fossil diesel was substituted by biodiesels (Durbin *et al.*, 2000, Munack *et al.*, 2001, and Alfuso *et al*., 1993), a significant decrease in PM emissions could be considered as a popular trend (Grabski and McCormick, 1998, Lapuerta *et al*, 2002, Monyen and Gerpen, 2001, Staat and Gateau, 1995, Wang *et al*., 2000, and Cardone *et al*., 2002). Many authors have reported areduction in PM of the same order, either from PM measurement from smoke opacity measurement (Hansen *et al*., 1997, Hamasaki *et al*., 2001). Canakci and Gerpen, (2001), observed 65% reduction in PM when theenginewas fueled with soybean biodiesel and waste-oil biodiesel.

Exhaust gas temperature

It can be observed that exhaust gas temperature of microalgae oil is lower than Diesel No. 2 and SME100 (Fig. 3.7). At 1000 rpm, exhaust temperatures are 614.90, 656.62 and 670 K for microalgae oil, SME100 and diesel No. 2 respectively. As the speed of the engine increases, the temperature of exhaust gas also increases almost linearly. Amaximum rated engine speed of 2600 rpm, EGT rose by 8%, 13.56% and 14.17% for microalgae oil, SME100 and diesel No.2 respectively. These can be explained by the Cetane Number of these fuels. These differences in theexhaust can be credited to the increase in the combustion temperatures. The expansion in thermal efficiency implies that a greater part of heat has been changed over into work and along these lines lower exhaust temperature can be expected. Also, the lower combustion temperatures portraying the oxygenated mixes are relied upon to results in lower exhaust temperatures (Agrawal *et al*. 2007).

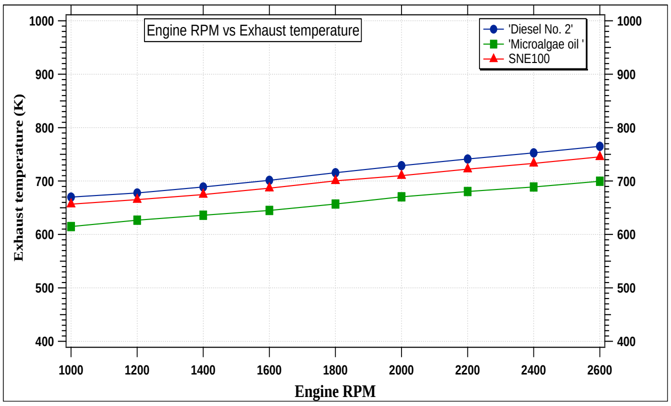

Fig 7: Exhaust temperature vs engine rpm

Wahlen *et al*., (2012), presented engine exhaust gas temperature as a function of engine speed with different biodiesels including microalgae biodiesel. Exhaust gas temperature was collected for each fuel throughout the engine rpm. The trend of exhaust gas temperature was similar as shown in figure 3.7. Exhaust gas temperatures were highest for fossil diesel followed by soybean and microalgae biodiesels. In contrast, exhaust gas temperature of each fuel used decreased as the rpm of theengine increased.

Conclusions

The microalgae oil revealed a negative influence on engine power, torque, and specific fuel consumption. As expected, due to lower energy density, thepower output of microalgae oil lowered by 17% and 12% compared to petroleum diesel and soybean methyl ester respectively. Some emissions characteristics (NO_2 and PM) of microalgae oil are better compared to fossil diesel. At full load and maximum engine rpm, emissions of CO_2, NO_2, and PM were 5% (higher), 70% (lower) and 54% (lower) respectively compared to fossil diesel. It can be concluded that the power and torque performance of microalgae oil were lower as compared to fossil fuels. However, the use of microalgae oil in a combustion engine is more eco-friendly. In summarizing the performance evaluation, the performance data presented in the results and discussion section indicated that oil derived from microalgae could adequatelyreplace both petroleum diesel and other biodiesel derived from terrestrial plants or plant oil.

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