Performance enhancement of CRDI Diesel Engine by chlorella vulgaris microalgae - derived methyl ester with high pressure fuel injection

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Abstract
Most of the recent researches focus on alternative fuels because fossil petroleum resources reduce with time and also fossil fuels have the most adverse impact on environmental pollution. There are many researches that point out the importance of biodiesel fuel as an alternative to diesel fuel. The main objective of this work is to produce biodiesel from Chlorella vulgaris microalgae and utilize it through the high fuel injection pressure on a diesel engine in order to meet future emission legislation.

Fuel injection pressure plays a significant job in atomization of injected Chlorella vulgaris biofuel and consent to for complete burning and tends reduce pollutants. The fuel injection pressure varies 22 to 42 MPa through CRDI fuel injection system. Based on the results, B25 Chlorella vulgaris fuel blend at 42 MPa of fuel injection pressure exhibits high thermal efficiency, better combustion and emission characteristics.

Keywords: Chlorella vulgaris, Transesterification, High pressure injection, Diesel engine, Combustion.

Introduction

Consumption of conventional fossil fuels has vastly enhanced and the utilization of these conventional energy sources has a key ecological impact as well. The fossil energy resources are inadequate and are declining at a faster rate. Herein point of view, different non-edible vegetable oils are considered as the potential substitute to supply as fuel in diesel engines [1-3]. Global warming and stringent emission laws enforced by the governments have led to investigate more proficient engines with satisfactory emissions intensity. In this perspective, biofuel can be shown as a potential solution as a result of its similar properties with fossil fuel [4].

Most traditional bio fuels, such as biofuel from vegetable seeds, are generated from the agricultural crops that necessitate agricultural land for cultivation. The increased requirement for vegetable oils for the making of biofuel has created pressure on the oil market[5]. In reality, India's biodiesel trade is currently functioning far below by reason of a need of large source. The fatty acid contour of macro-algal is appropriate for the production of methyl ester. Second-generation microalgae are progressively more envisaged by professionals and policy-makers to play an important role in a uncontaminated and sustainable outlook.[6-8]

Generally, microalgae can be pertained as microscopic organisms which can cultivate by the use of photosynthesis. The photosynthetic capability of microalgae is comparable to other plants, because of their uncomplicated cellular configuration[9]. Microalgae are immersed in aqueous environment where they have capable contact to water, nutrients and CO_2. Microalgae are very proficient in absorb the solar energy and transferring into biomass compared with other plants.[10,11]

Biofuel from microalgae designate the best alternative fuel that has the capable to be a better substitute for petroleum-derived fossil fuels without concerning of harvest products, since they do not require farm land for cultivation [12]. India has an appropriate climate for the cultivation of Chlorella vulgaris. The development of Chlorella vulgaris in waste lands and ponds reduces the soil erosion and directs to enhancement of rainwater.[13,14]

The high pressure fuel injection system used in a diesel engine is to achieve a high level of fuel atomization for better penetration with the aim of make use of the maximum quantity of air and to persuade the fuel evaporation in a short period.[15,16] Different microalgae species have been previously studied for the production of biofuel. The present work is carried out to describe the biofuel production, property analysis and working characteristics in a CRDI diesel engine with high pressure fuel injection.

Extraction of fatty acids from microalgae

The Chlorella vulgaris microalgae were collected from the marine system. It was dried at oven for 10 hours to get rid of the moisture content. After drying, Chlorella vulgaris was powdered into micron size. One kilogram of the dehydrated Chlorella vulgaris was placed in the Soxhlet apparatus. The thimble of Soxhlet extractor is made up of from substantial filter paper, which is packed in the primary part of Soxhlet apparatus. The Soxhlet apparatus is sited on a flask which containing the solvent. The extractor is then attached with a condenser part. Soxhlet extractor was used for convert the complex lipid content to low-volume lipid content with the use of *iso*-propanal and *n*-hexane solvents.

The solvents form vapour, which travels to distillation unit and the thimble. The condenser cools solvent vapour which drips into the chamber containing the solid CV biomass. When the thimble is approximately filled, the chamber is by design deflated and hexane returned to the distillation flask. Figure 1 shows the process flow plan of extraction of methyl ester from microalgae and figure 2 shows the diagram of Soxhlet apparatus.

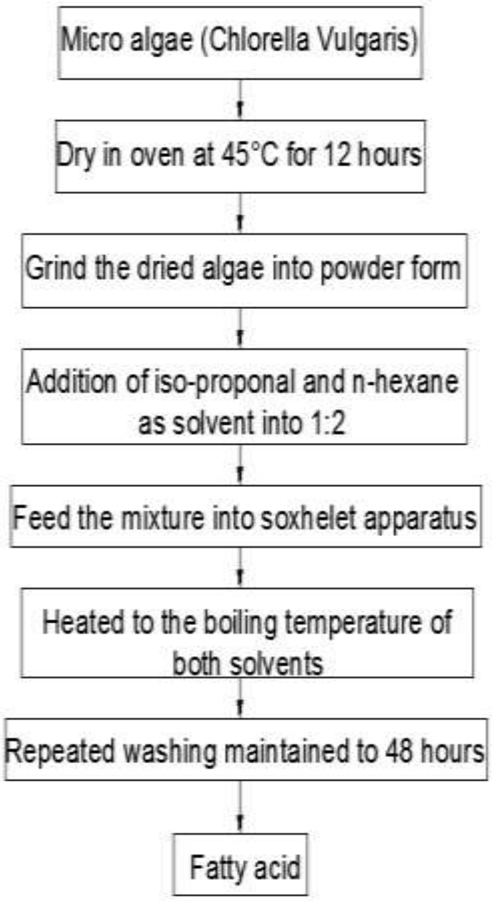

Figure 1: Process flow chart of extraction of methyl ester from microalgae

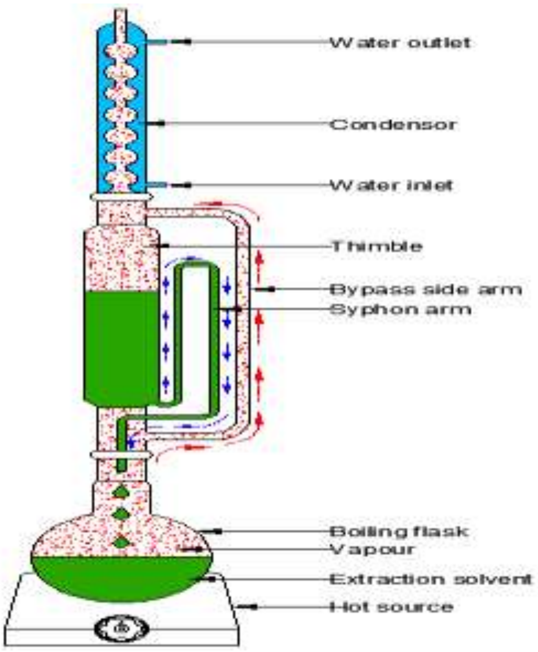

Figure 2: Schematic diagram of Soxhlet apparatus

Extraction of biodiesel

The Chlorella vulgaris microalgal biofuel was extracted through the transesterification process using methanol and catalyzed by potassium hydroxide (KOH). Titration process was accomplished to find the quantity of catalyst necessitated to break the hydrocarbons with long chain present in the Chlorella vulgaris microalgal oil. The quantity of KOH required as catalyst to boost the process for every litre of Chlorella vulgaris microalgal (CVM) oil was found as 7g.

In favour of the transesterification process, 220 ml of methanol was added for every litre of CVM oil. One litre of CVM oil is first subjected to 60°C and then 7g of catalyst, which is suspended in 210ml of methanol, is dispensed and stirred for 50 minutes. The crude glycerine was taken apart at the bottom and the biofuel on the top. The washing process using water is achieved by a sprinkler which sprays the water into the oil flask. The water-biofuel mixture was then gradually stirred for 15 minutes and allowing the water to drain out. Schematic diagram of transesterification plant is shown in Figure 3 and the properties of the Chlorella vulgaris microalgal biofuel and diesel are shown in table 1.

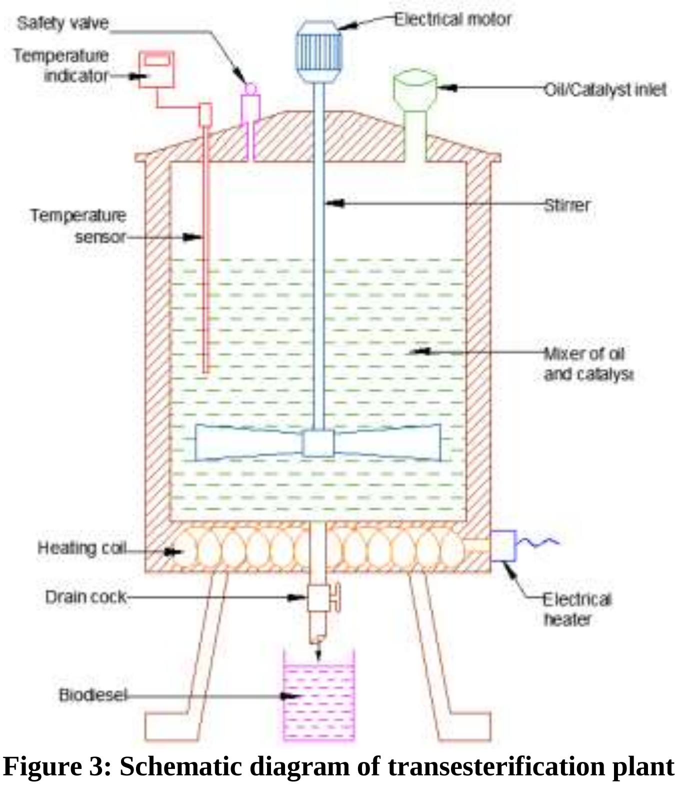

Figure 3: Schematic diagram of transesterification plant

Fourier transform infrared (FTIR) analyzer Spectrography

The FTIR spectrum of Chlorella vulgaris microalgal (CVM) methyl ester (B100) and its blend (B25) is shown in figures 4 and 5. An exploration of the FTIR spectrum showed the important composition stages, which exposes the presence of these five different absorption bonds. The functional group and absorption characteristics were tabulated in table 2.

Table 1
Properties of the fuel blends

Properties	ASTM Measurement Standards	Diesel fuel	CVME100	CVME25
Kinematic viscosity at 40°C (CSt)	ASTM D445	2.57	3.82	2.91
Fire Point (°C)	ASTM D92	75	89	82
Flash Point (°C)	ASTM D92	56	78	63
Density at15°C (g/cc)	ASTM D1298	0.8072	0.8355	0.8134
Cetane index	ASTM D976	50	53.5	52

Table 2
FTIR analysis - characteristics absorption

Functional faction	Nature of vibration	Absorption Characteristics (cm^{-1})	Intensity Characteristics
C-O-C	Stretch	800 - 1200	Strong
-C-H	Bending	2800 - 2950	Variable
C=O	Stretch	1700 - 1740	Strong
H_2O	Stretch	1100 - 1750	Strong

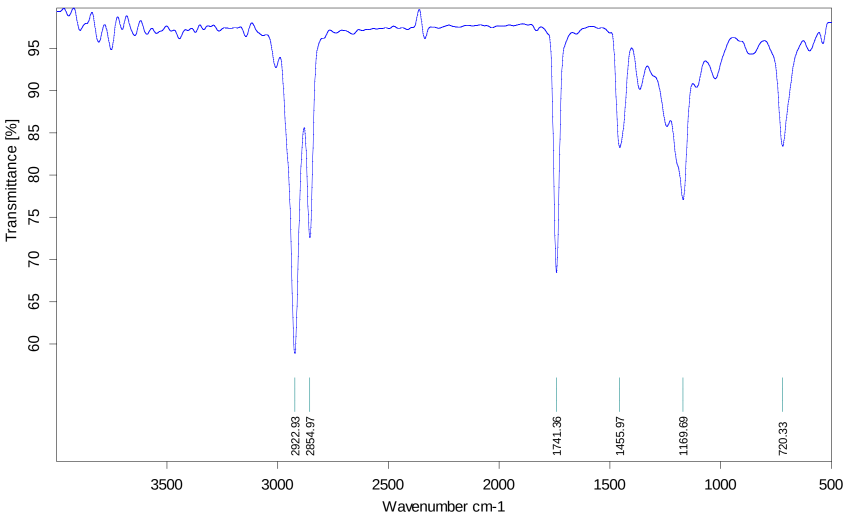

Figure 4: FTIR spectrum of CVME100

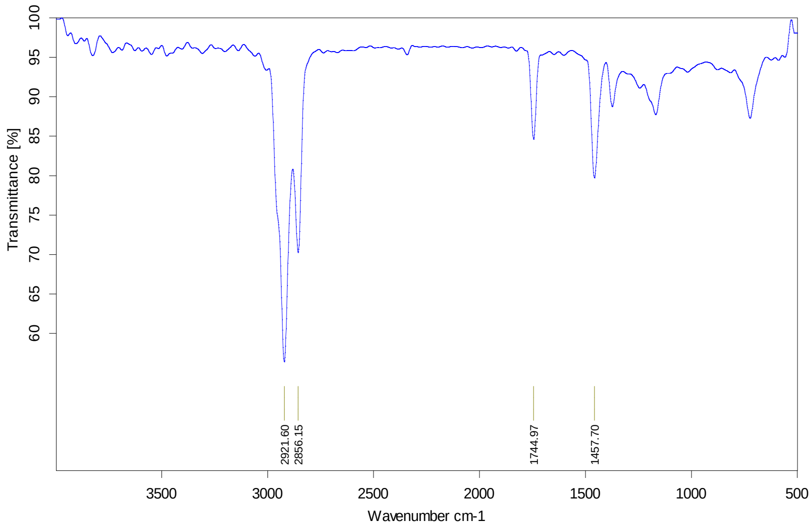

Figure 5: FTIR spectrum of CVME25

- Absorption band 2922cm^{-1} represents the asymmetric vibrational mode of methyl groups and 2851cm^{-1} represents the asymmetric vibrational mode of methylene groups.
- CO_2 produces weak bands in between 2700 and 2000 cm^{-1} as well as in the 750 cm^{-1} region.
- Carbonylic compounds are the strong C=O stretching absorption band in the region of 1700-1740 cm^{-1}.
- The adsorption bands of water (H_2O) can be observed in the range of 1100-1750 cm^{-1}.
- Ethers (C-O-C) stretching vibrations produce a strong band in the 800-1200 cm^{-1} region.

From the FTIR spectrum, it is clear that the CVM methyl ester blend is having characteristics related to diesel fuel.

Gas Chromotograph (GC) Analysis

Gas chromatograph spectrography is used to identify the chemical components present in the CVM methyl ester (B100) and its blend (B25). Figure 6 and 7 shows the chromatographic spectrums of B100 and B25, respectively. The chromatogram shows a number of compounds at various retention periods. The GC-MS results specify the existence of various groups of hydrocarbons which consist of nitriles, aromatic amines, alkenes and alkane. The lauric acid is the main fatty acid subsequently myristic acid and palmitic acid. Stearic, oleic caprylic, caproic and capric acids are present as minor constituents. This is an indication that the CVM methyl ester is contained mainly of saturated fatty acids. The components with corresponding retention time were tabulated in table 3.

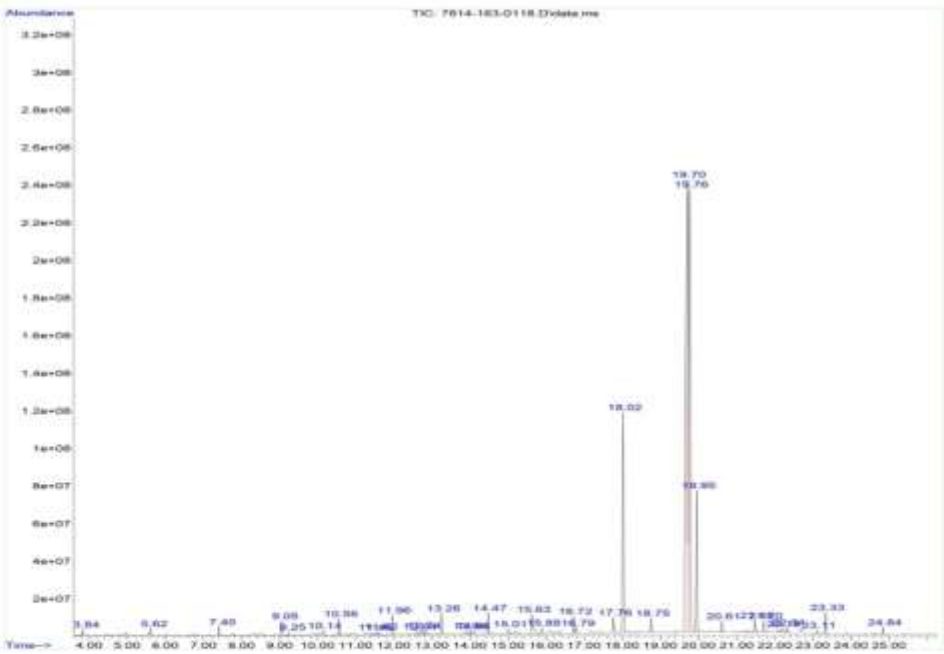

Figure 6: GC spectrum of B100

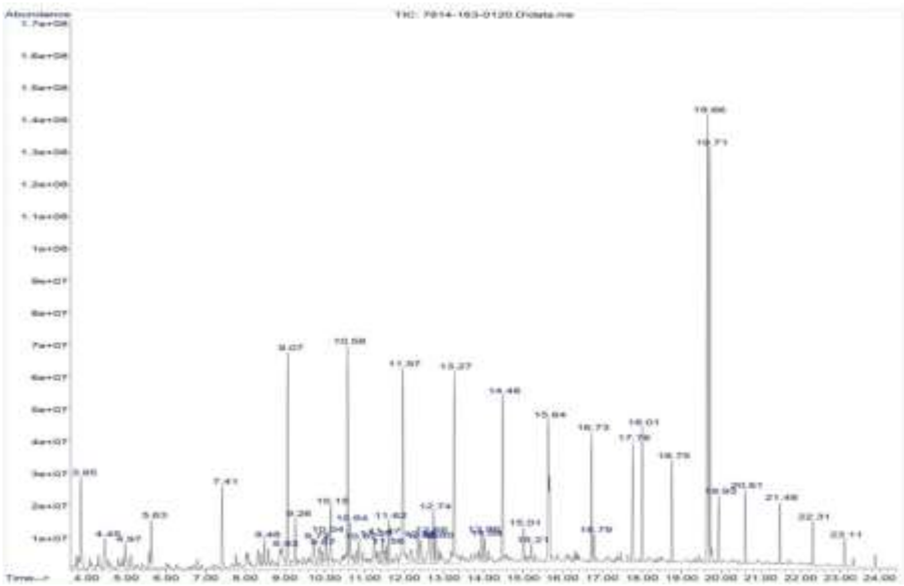

Figure 7: GC spectrum of B25

Table 3
GC analysis

S.N.	Name of compounds	Retention Time
1	Caproic (Hexanoic) acid, C6:0	7.41
2	Caprylic (Octanoic) acid, C8:0	9.07
3	Capric (Decanoic) acid, C10:0	10.58
4	Lauric (Dodecanoic) acid, C12:0	33.27
5	Myrystic (Tetradecanoic) acid, C14:0	15.64
6	Palmitic (Hexadecanoic) acid, C16:0	18.01
7	Stearic (Octadecanoic) acid, C18:0	19.66
8	Oleic acid (C18:1)	19.71

Thermo-Gravimetric Analysis (TGA)

Figure 8 shows the TGA of Chlorella vulgaris microalgal (CVM) methyl ester blend (B25) at optimum conditions. From the TGA curves, a huge difference between the weight loss temperatures was found and this lets us to determine the conversion rate. The mass of the CVM methyl ester starts to reduce approximately at 115 °C and it lasts to decrease until all the methyl ester present in the given sample is vaporized at about 350 ºC. Figure 8 shows the degradation temperature of the CVM methyl ester blend as the set point of degradation is at 203 °C. Similarly, evaporation of CVM methyl ester blend starts at approximately 350 °C.

Experimental Setup

The performance of biodiesel derived from Chlorella vulgaris microalgal oil was studied and compared with neat diesel. A four stroke, single cylinder, constant speed (1500 rpm), direct fuel injection Kirloskar TV-I diesel engine was used for this study. The specifications of the engine are given in table 4. The schematic of experimental setup is shown in figure 9. The Kirloskar TV-I test engine was paired with an eddy current dynamometer.

In-cylinder pressure in combustion chamber was acquired by an AVL piezoelectric pressure transducer which is mounted into the cylinder head. An AVL make charge amplifier is used to convert the charge yield into electric signals. A personal computer was interfaced with an AVL make Indimeter hardware and “Test engine express 2014” data acquisition system to get combustion parameters, such as peak heat release rate and in-cylinder pressure. Engine speed was assessed by a magnetic pickup sensor. The common rail fuel injection system is used in this test was made by Bosch. This is a linear accumulator with providing of four injector ports and maximum capacity of injection pressure up to 1000 bar and a volume of 18 cm^3.

A high pressure sensor is fitted on the one side of the accumulator for pressure measurement. The pressure data was sent to the ECU for closed-loop control of the injection pressure and for the calculation of injection flow-rate and timing. The DELPHI made six holes nozzle piezo electric injector was used to inject the fuel at high injection pressure depend upon the signal getting from ECU. Engine exhaust emissions like smoke was measured by an AVL made smoke meter and oxides of nitrogen (NO_x), carbon monoxide (CO) and hydrocarbon (HC) emissions were analysed by an AVL made DI gas analyzer. The various measurement systems used in this work have an accuracy of 2 % over a maximum of 8 hours and a linearity of the signals of +/-1 %.

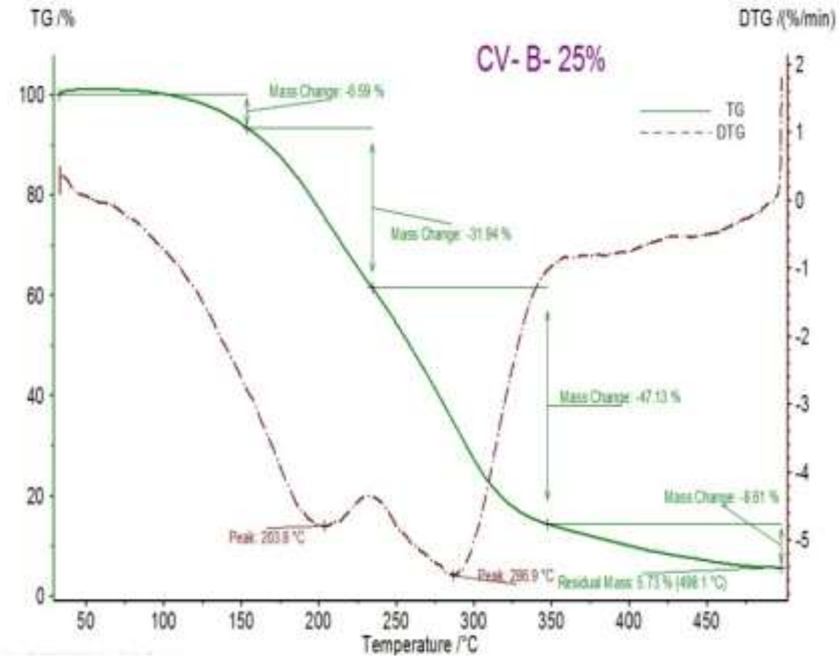

Figure 8: TGA curve of B25

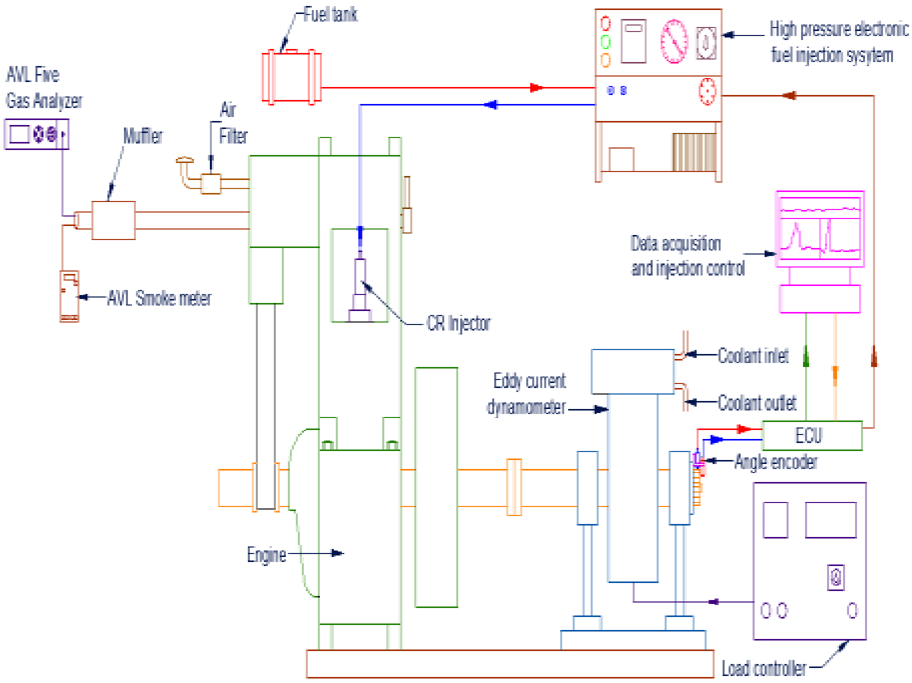

Figure 9: CRDI engine setup

Table 4
CRDI diesel engine specification

Make	**VCR - Kirlosar-TV 1**
General details	Four stroke, variable speed, vertical, common rail direct injection
Number of cylinder	One
Bore	87.5 mm
Stroke	110 mm
Compression ratio	17.5:1
Rated output power	5.2 kW
Injection pressure	Variable injection pressure
Fuel injection dwell time	23º bTDC

Results and Discussion

Impact of CVM fuel blend (B25) on combustion characteristics: Figure 10 depicts the variation in peak in-cylinder pressure with crank angle for Chlorella vulgaris microalgal biofuel blend (B25) with different injection pressures and varies from 22 MPa to 44 MPa. From the figure, it is obvious that the in-cylinder pressure is considerably decreased in the case CVM-B25. The cylinder pressure is fully depends on the quantity of fuel ensues in ignition delay period and the speed of combustion in early phases of premixed fuel combustion[3].

The basis for the reduction of in-cylinder pressure for B25 may be due to poor evaporation and improper mixing of fuel with air. If fuel is injected at higher fuel injection pressure, smaller fuel droplets are produced due to better atomization. Though, the combustion of CVM-B25 fuel is comparable and consisting of premixed combustion. Premixed combustion part is controlled by means of the fuel atomization and ignition delay duration. From the results, it is clear that the in-cylinder pressure of CVM-B25 increased with the enhance in fuel injection pressure. The cylinder pressure of the CVM-B25 fuel blend at 22MPa was 6.15MPa, whereas it was 6.58 and 7.2MPa for 32 and 42MPa of fuel injection pressures, respectively.

Figure 11 depicts the impact of CVM biofuel blend (CVM-B25) in peak heat release rate with crank angle for diesel with different fuel injection pressures. The ignition feature of a CVM biofuel is mainly dependent upon its cetane index and a higher cetane index may be results in a shorter ignition delay [16]. This causes a negative heat release for the duration of the ignition delay period. From the figure, it is obvious that the peak heat release rate of B25 is lower than that of reference diesel fuel. This may due to higher cetane index of CVM biofuel blend (B25) decreasing the premixed combustion and it lead to softer pressure and temperature gradients. When the injection pressure increases, heat release rate gradually increases. This is mainly due to higher level of atomization at maximum fuel injection pressure

(42MPa). The amount of heat release rate for B25 of CVM blend at 22MPa was 125 kJ/m^3deg, whereas it was 130, 132 kJ/m^3deg for 32 and 42 MPa of fuel injection pressures, correspondingly.

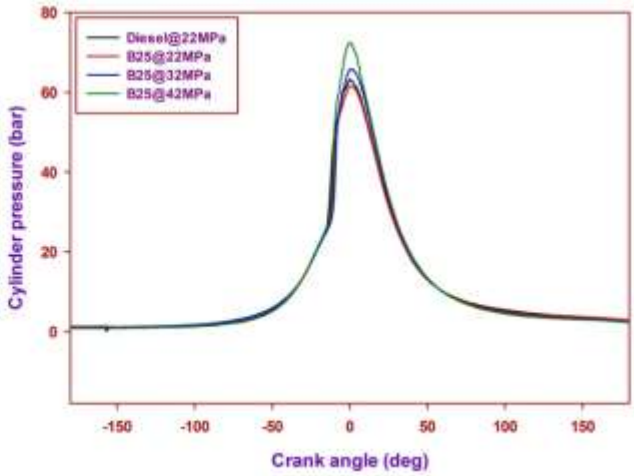

Figure 10: Impact of CVM fuel blend (B25) on cylinder pressure

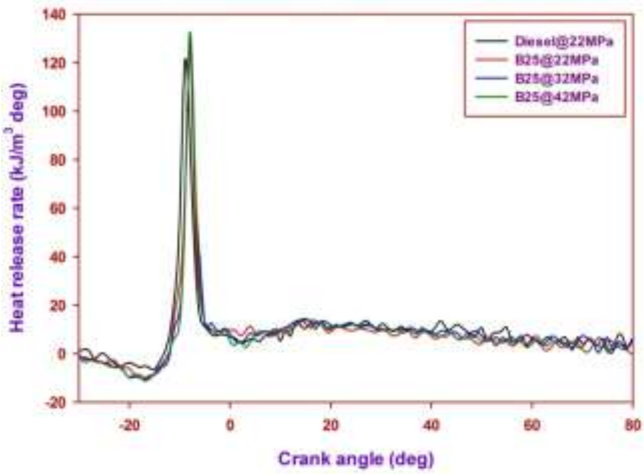

Figure 11: Impact of CVM fuel blend (B25) on heat release rate

Impact of CVM blend (B25) on performance characteristics: The engine performance with CVM blend (B25) at different fuel injection pressures was calculated in terms of brake thermal efficiency at different engine load conditions. Figure 12 shows the dissimilarity in brake thermal efficiency with respect to brake power. From the figure, it is clear that BTE slightly decreased with the blending of CVM biofuel in diesel fuel.

It is mainly attributed by reason of the mixed effects of the higher kinematic viscosity and higher density of CVM biofuel blend. BTE value of diesel fuel was 26.6%, whereas it was 25.5% for B25 fuel blend. This deficiency of B25 could be overcome using higher fuel injection pressure as of 22 to 42MPa. From the figure, it is clear that the BTE increases from 25.5% to 28% when the fuel injection pressure enhanced as of 22 to 42 MPa.

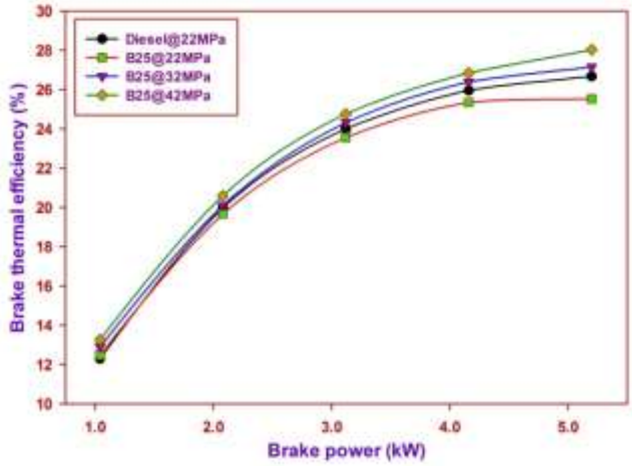

Figure 12: Impact of CVM fuel blend (B25) on Brake thermal efficiency

Impact of CVM fuel blend (B25) on emission characteristics: Figure 13 depicts the variation of hydrocarbon emission with brake power. From the figure, it was clear that the HC emission increased with CVM fuel blend (B25). This is caused by the properties of CVM fuel blend for instance density and viscosity. Higher viscosity and density may lead to larger fuel droplet size for CVM biofuel blend, contrasted with that of diesel fuel. High pressure injection helps to reduce the fuel droplet size and it leads to a better combustion of biofuel blend. The HC emission for B25 at full load was 119ppm, whereas it was 116ppm for diesel. When the fuel injection pressure enhanced from 22MPa to 42MPa, the HC emission reduced to 83ppm.

Figure 14 shows the variation of CO emission with brake power for CVM fuel blend at different injection pressures. It is found that CO emission enhances with the CVM biofuel blend. This is attributable to poor viscosity and higher density. High pressure injection improves the air-fuel mixing and it leads to a better combustion of CVM fuel blend. Due to high pressure injection, more of carbon combines with O_2 forming CO_2 resulting in reduced CO emission. When the fuel injection pressure is enhanced from 22MPa to 42MPa, the CO emission reduces up to 15%. The CO emission for B25 at 22MPa was 0.33% by volume whereas it was 0.25 and 0.21% for 32 and 42MPa injection pressures.

Figure 15 shows the impact of CVM-B25 on NO_x emission with brake power for B25 fuel blend at different fuel injection pressures. From the figure, it was found that the NOx emission of the test engine significantly decreased with B25 fuel blend. Combustion temperature plays a vital role in NO_x formation [15]. The NO_x emission was found to be low for B25 fuel blend when compared with diesel fuel. When the fuel injection pressure increases, the NO_x emission significantly increased. An increase in NO_x is probably because of the high pressure injection and better combustion of fuel and as a result, the combustion temperature increases. The NO_x emission for B25 is 8.76 % lower than that for neat diesel at an injection pressure of 22MPa. As the fuel injection pressure enhances as of 22MPa to 42MPa, the NO_x emissions increased by about 16.6%.

Smoke emission is the major problem in DI diesel engines. The variations of smoke emission as regards brake power are depicted in figure 16. Smoke emission of B25 fuel blend was observed and it was higher than diesel fuel for all load conditions. The smoke emission was found to be 77.6HSU for B25 and 74.3HSU for diesel at 1500 rpm at 22MPa of fuel injection pressure. The formation of smoke emission is mainly caused by incomplete combustion of the hydrocarbon and carbon present in the fuel[12]. The smoke emission of CVM methyl ester blend is high when match up to with diesel fuel, which is caused by the higher viscosity of CVM-B25 fuel blend (Table 1).The smoke emission decreases from 74HSU to 67HSU, when the fuel injection pressure increases as of 22MPa to 42MPa.

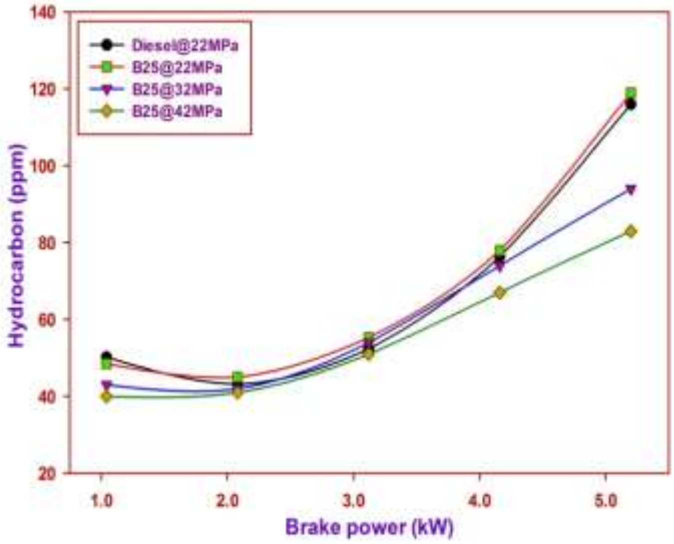

Figure 13: Impact of CVM fuel blend (B25) on hydrocarbon emission

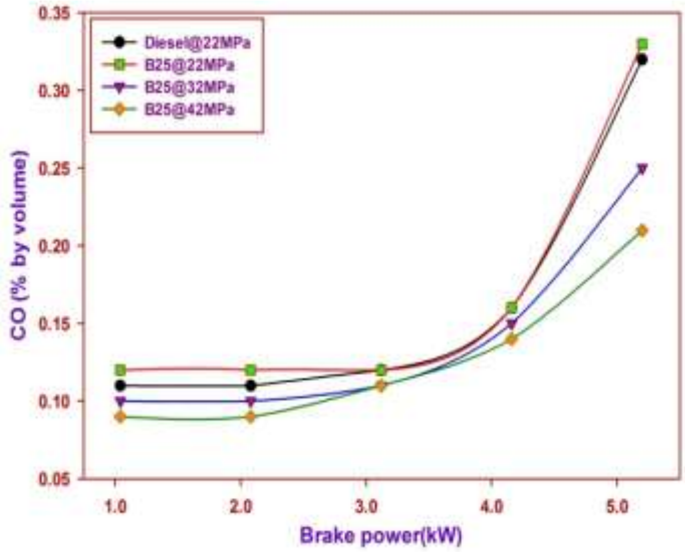

Figure 14: Impact of CVM fuel blend (B25) on carbon monoxide emission

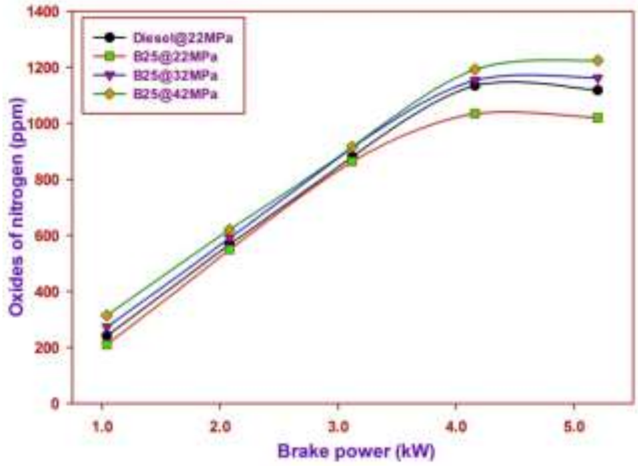

Figure 15: Impact of CVM fuel blend (B25) on oxides of nitrogen emission

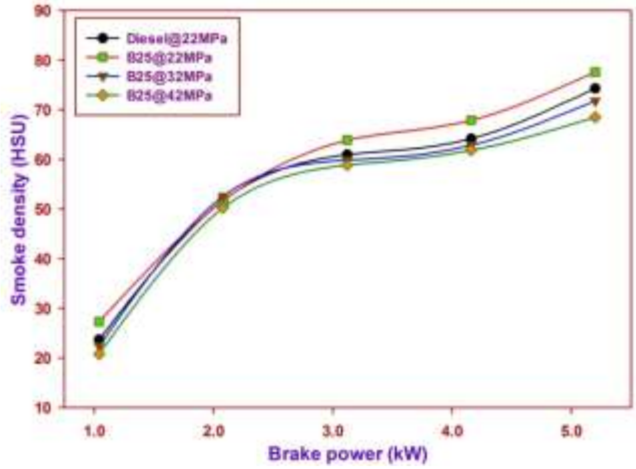

Figure 16: Impact of CVM fuel blend (B25) on smoke density

Conclusion

A successful function of CRDI diesel engine fuelled by CVM biofuel blend (B25) over various loads and different fuel injection pressures (22-42MPa) without any major modification in components. The experiment has been conducted as a function of CRDI engine in-cylinder pressure, heat release rate brake thermal efficiency and exhaust emissions. The following results have been concluded.

1) The in-cylinder pressure and the peak heat release rate for CVM methyl ester blend (B25) was gradually decreased when compared to single-fuel mode. When the CVM biofuel injection pressure increases from 22 to 42MPa, the in-cylinder pressure and HRR were improved due to better atomization and combustion.
2) The brake thermal efficiency for neat diesel and CVM-B25fuels are arranged in descending order in accordance with their viscosity/density and heating values. The BTE was improved when the injection pressure varied from 22 to 42 MPa.
3) HC and CO emissions increased with CVM methyl ester (B25), whereas significant NO_x reduction in correspondence to blend at standard injection pressure (22MPa). HC and CO emissions were mitigated and

NO_x emission was slightly enhanced for all higher fuel injection pressures (32 and 42MPa) with respect to B25 at standard (22MPa) injection pressure. The Higher injection pressures of fuel reduced smoke significantly.

Higher fuel injection pressures improved the performance as well as emission characteristics of CRDI diesel engine in correspondence to their respective B25 at standard injection pressure. Therefore, higher injection pressure (42MPa) can be considered as a promising way to use CVM methyl ester blend at the optimum operating condition in CRDI diesel engine.

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