Asian Journal of Convergence in Technology **Volume 4 Issue III**
ISSN No.:2350-1146, I.F-5.11

COMPARATIVE STUDIES OF COMBUSTION, PERFORMANCE AND EMISSION PARAMETERS OF DIESEL ENGINE USING CASTOR BIODIESEL BLENDS

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Abstract**—**The experimental studies for combustion, performance and emission characteristics of the variable compression ratio (VCR) diesel engine of rated power 3.5 kW at rated speed of 1500 rpm at two compression ratios of CR-16:1 and CR-18:1 was done using castor biodiesel-diesel blends (B10, B20 and B30) as a substitute fuel. The results revealed that Start of combustion (SOC) advanced, End of combustion (EOC) delayed, Ignition delay (ID), Maximum Rate of Pressure Rise (MRPR) decreased while Combustion duration (CD), Premix Combustion Phase Duration (PCD) increased with biodiesel blends concentration. Increase in CR resulted in reduction in ID, CD, while MRPR and PCD increased as compared to plain diesel. Brake thermal efficiency (BTE) decreased with increase in blending percentage for both compression ratios (CR's), while higher CR resulted in increase in BTE. Carbon monoxide (CO) and unburned Hydrocarbon (HC) emissions decreased, while Carbon dioxide (CO_2) and Nitrogen oxides (NO_X) emissions increased with biodiesel contents for both CR's. Increase in CR resulted in reduction in CO and HC emissions while CO_2 and NO_X emissions increased. The castor biodiesel may be used as a substitute fuel by blending it partially with plain diesel in diesel engine

Keywords— ***Diesel Engine, Compression ratio, Castor biodiesel***

I. INTRODUCTION

Ever since the Industrial Revolution that took place in 1800 century, energy is required for economic development of country and enhancing the standard of living of citizens. The primary energy is derived mostly from fossil resources like Coal, Natural gas and Petroleum oil. In 2017, primary energy consumption rose by 2.2% globally and for India by 4.6%, taking its share of global primary energy to 5.6%. Coal was the dominant fuel accounting for 56% of India's primary energy mix. The petroleum oil imports rose by 0.7% to 4.9 Mb/d, its indigenous production rose by 1.1%, while its consumption increased by 2.9% which amounted for 29% share in India's primary energy mix [1]. Today, world is facing the dual crisis of depletion of fossil reserves and environmental degradation due to pollution. Increasing industrialization and motorization has led to exponential utilization of finite fossil resources, resulting in rapid price rise. Indian economy is always stressed due to imports of over 80% of its crude oil. Thus it's the need of time to go for renewable, sustainable biofuels as substitute for fossil fuels. Edible and non-edible oils are such options to produce biodiesel to be used in diesel engines.

Dwivedi et al. [2] analysed various straight vegetable oils based on fatty acids contents. Oxidation tendency and cold flow properties are analysed for edible and non-edible oils. Oxidation stability and cold flow properties of castor oil was found to be better than other oils and recommended for biodiesel production. Valente et al. [3] studied the physico-chemical properties of castor oil biodiesel -diesel blends. Fuel blends up to 35 vol% concentration is found to meet various specifications for biodiesel. Lubricity, wear scar, cold-filter plugging point of up to 40 vol% of castor blends is also found to meet most of European (EN 590) specifications for biodiesel [4].

Biodiesel as substitute fuel for diesel engines is investigated by many researchers. Panwar et al. [5] analyzed the performance of castor biodiesel-diesel blends, and reported that low percentage blends (B10) increased the brake thermal efficiency and reduced the fuel consumption, however NO_X emissions were found to be slightly higher than plain diesel. The emission studies reported that CO, CO_2, NO_X and smoke opacity increase with blending ratio. B20 was found to be highest for these values. It could be seen that castor biodiesel can be treated as a viable alternative fuel for CI engines for various agricultural and transportation purposes [6].

The injection and spray characteristic plays a vital role in performance, emission and combustion of a diesel engine. The fuel injection pressure and injection duration increases while the dynamic injection timing advances causing higher NO_X emissions with use of biodiesel-diesel blends. Sauter mean diameter and spray penetration distance increases with blending percentage resulting in deteriorated performance and durability issues of diesel engine [7-10]. The problem of fuel striking on piston-bowl can be well addressed by modifying the geometry of injector nozzle. The reduction in nozzle hole diameter can decrease the spray length inside cylinder owing to low spray momentum, decreases the fuel droplet size and improves the diesel spray atomization thus improving combustion [11].

Since properties of plain diesel and biodiesel are different, the combustion parameters of diesel engine are found to be different at varying loads. At lighter loads on engine, the maximum cylinder pressure, maximum rate of pressure rise and the heat release rate are found to be more for biodiesel. Whereas at heavier loads the maximum cylinder pressures are comparable, but the maximum rate of pressure rise and maximum heat release rate are lesser with biodiesel. Reduced ignition delay owing to advanced injection timing results in earlier start of combustion with biodiesel at all loads on engine [12]. Sahoo et al. [13] studied effects of neat jatropha, karanja and polanga esters and their blends on combustion parameters of diesel engine. The ignition delay was found to reduce in a range of 5.9^0 and 4.2^0 crank angles with neat jatropha biodiesel compared to plain diesel. Similarly ignition delay was shorter for polanga and karanja biodiesel (B100) when compared with base diesel.

From the literature it is observed that the Performance, Emission and Combustion parameters of diesel engine need to be studied in order to improve the general performance and reduce the emission of diesel engine for using blends of castor biodiesel in specific and from other feedstock in general. The objective of the current work is to conduct experimentation for using blends of castor-biodiesel to analyze the various performance, emission and combustion parameters of the diesel engine.

II. EXPERIMMENT DETAILS

The experiment was performed on four strokes, single cylinder diesel engine with provision to change compression ratio. Loading was done using eddy current dynamometer. Engine was provided with sensors for measurement of in-cylinder pressure and corresponding crank angle. Instrumentation was also provided for measuring temperature, air, fuel and water flow rates. All signals are interfaced to the computer for automatic measurements. The specifications of the engine are given in Table 1 and the snap of the setup is shown in Fig. 1.

Table 1: Specifications of the engine

Parameter	**Specifications**
Make/Model	M/s Kirloskar oil engines/TV1
General details	1 Cylinder, 4 Stroke, VCR, naturally aspirated, water cooled, compression ignition
Rated power	3.5 kW @ 1500 rpm
Bore × Stroke	87.5 mm × 110 mm
Volume	661 cc
Compression Ratio	17.5:1 (range 12-18:1)
Combustion Chamber	Open Hemispherical
Start of Injection	23 deg. BTDC (range 0-30 deg. BTDC)
Injection Pressure	~ 220 bar
Type of Injection	direct injection

The castor oil was esterified to produce its biodiesel and the blends of 10% (B10), 20% (B20) and 30% (B30) by volume were prepared with commercially available plain diesel. The various properties were measured as listed in Table 2.

Table 2: Properties of diesel, castor biodiesel and blends

Property	**Diesel**	**B10**	**B20**	**B30**	**B100**
Density (kg/m3)	825	830	835	838	870
Calorific Value (MJ/kg)	42.50	42.09	41.50	41	37.50
Cetane No.	49.50	-	-	-	50.10
Acid Value	0.01	-	-	-	0.41
Viscosity (mm^2/sec)	2.7	-	-	-	5.40
Flash Point (^{0}C)	64	-	-	-	167
Fire Point (^{0}C)	71	-	-	-	176

Fig. 1: Experimental engine test setup

III. RESULT AND DISCUSSION

Ignition delay(ID), combustion duration(CD), maximum rate of pressure rise (MRPR) and three phases of diesel engine combustion viz. premixed (rapid combustion), diffusion (mixing-controlled combustion) and after-burning (late burning) phases need to be investigated for understanding combustion characteristics of diesel engine. The delay between start of injection and actual start of combustion of fuel in the engine cylinder is called ignition delay period. The comparison of ignition delay for diesel and biodiesel blends (B10, B20 and B30) at two compression ratios of CR-16 and CR-18 is depicted in Fig. 2. The ignition delay period for castor biodiesel blends decreased consistently from 23.7^0 CA to 17.2^0 CA at CR-16 and 12.8^0 CA to 9^0 CA at CR-18 for diesel and B30 respectively. It could be due to higher cetane number and lesser chemical ignition delay of castor biodiesel than that of plain diesel fuel. At higher compression ratio, the operating in-cylinder pressures and temperatures increases, resulting in acceleration of pre-combustion chemical reactions thus reducing ignition delay for all fuels. Lower ignition delay is beneficial since it results in lower rate of pressure rise and smooth operation of the diesel engine.

The start of combustion advanced from 360.7^0 CA to 354.2^0 CA at CR-16 and from 349.8^0 CA to 346^0 CA at CR-18 for diesel and B30 fuels respectively as shown in Fig. 3. This is because biodiesel have higher bulk modulus that results in advancement in dynamic injection timing and has higher cetane number causing lesser ignition delay [10-11]. As compression ratio increases, the start of combustion advances due to higher in-cylinder pressure and temperature resulting in faster pre-combustion chemical reactions.The cylinder pressure and crank angle (p-θ) data is shown in Fig. 4. It is an important parameter to calculate various combustion characteristics. The maximum in-cylinder pressure increased from 42.75 bar to 44.49 bar at CR-16 and from 53.93 bar to 54.14 bar at CR-18 for diesel and B30 blend respectively. The rise in compression ratio and blending percentage increases the in-cylinder pressures in the cycle, and it will influence the premixed combustion phase and associated NO_X emission which is discussed in latter section.

The maximum rate of pressure rise decreased with blending percentage (at CR-16, Diesel: 2.67 bar/CA to B30: 2.07 bar/CA, and at CR-18, Diesel: 2.86 bar/CA to B30: 2.36 bar/CA) as compared to plain diesel and results in smooth operation of engine. The reduction in rate of pressure rise can be attributed to higher cetane number and lesser ignition delay of biodiesel blends. However at higher compression ratio the magnitude of rate of pressure rise increases as shown in Fig. 5.

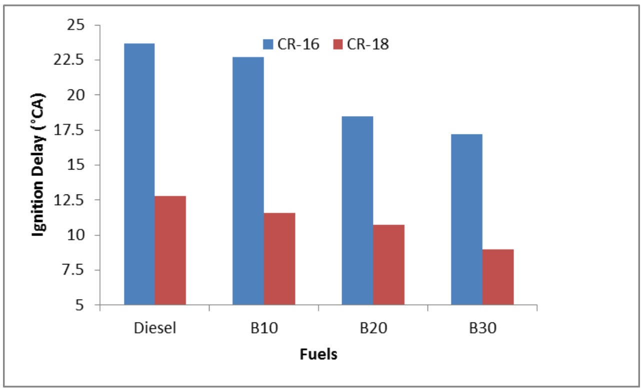

Fig. 2: Ignition Delay for Fuel Samples

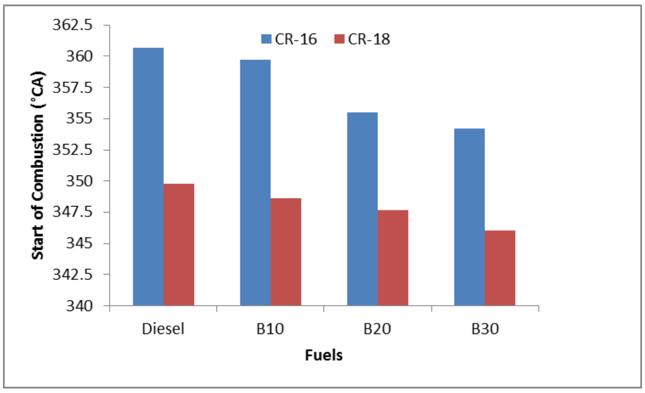

Fig. 3: Start of Combustion for Fuel Samples

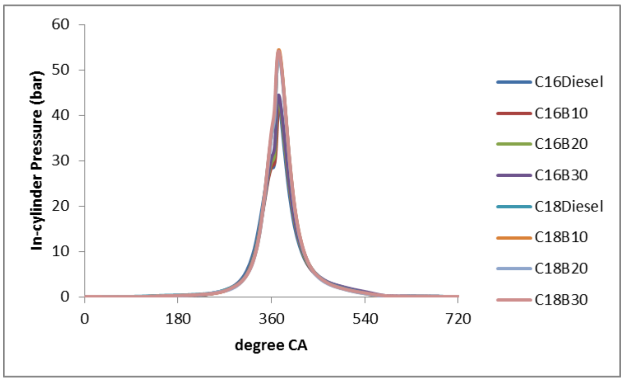

Fig. 4: In-cylinder Pressure for Fuel Samples

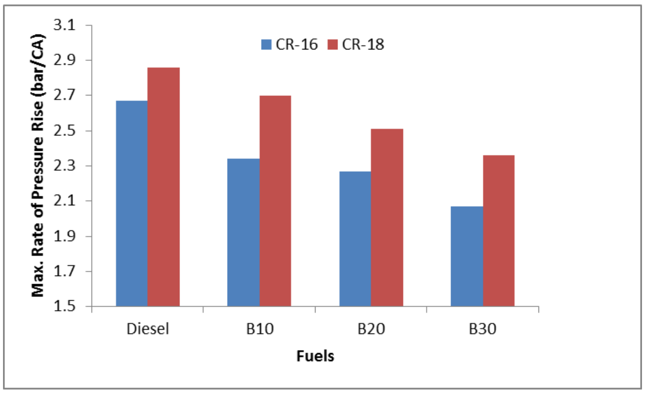

Fig. 5: Maximum Rate of Pressure Rise for Fuel Samples

The heat release rate for fuel samples is shown in Fig. 6. Just before the combustion begins and heat is released, endothermic chemical reactions of fuel-air mixture takes place absorbing activation energy of fuel to break the chemical bonds results in negative heat release rate initially [11]. On the onset of combustion, heat release rate becomes positive and it is an important tool for optimizing the diesel engine parameters. The cumulated heat release rate decreased with biodiesel-diesel blends so that it reduces brake thermal efficiency as discussed later. The three combustion phases (viz. Premixed, diffusion and after burning) were calculated from heat release diagram as shown in Fig. 7 (a & b). Premixed combustion duration increases with blending percentage for both compression ratios (at CR-16, Diesel= 14.3 ^{0}CA to B30= 19.8 ^{0}CA and at CR-18, Diesel= 23.2 ^{0}CA to B30= 27 ^{0}CA) as compared to plain diesel. Enhancement in compression ratio increases premixed combustion phase duration owing to higher in-cylinder temperatures.

The end of combustion is delayed with biodiesel samples resulting in longer combustion duration (Fig. 8-9). Combustion duration signifies the reaction rate and plays a vital role in optimizing the engine. Since calorific energy value for biodiesel is on lower side, the injection duration is more resulting in increase in combustion duration [10-11]. At higher compression ratio the temperatures are more, thus reduces the combustion duration. Specific fuel consumption is seen to increase with biodiesel samples resulting in lowering of brake thermal efficiency (BTE) as shown in Fig. 10. Poor atomization and mixing with in-cylinder air with biodiesel samples can be attributed to viscosity-density-surface tension being on higher side resulting in retarded combustion and reduced BTE [11]. Higher compression ratio results in improvement in combustion process and increase in Brake Power (BP) produced thus increases the brake thermal efficiency.

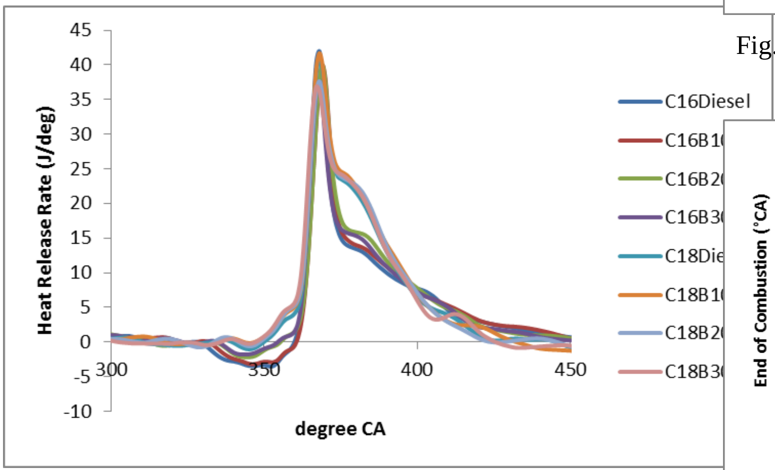

Fig. 6: Heat Release Rate for Fuel Samples

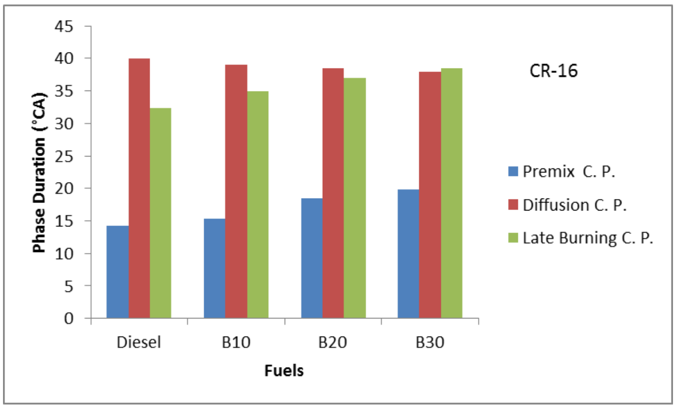

Fig. 7(a): Combustion Phases for Fuel Samples at CR-16

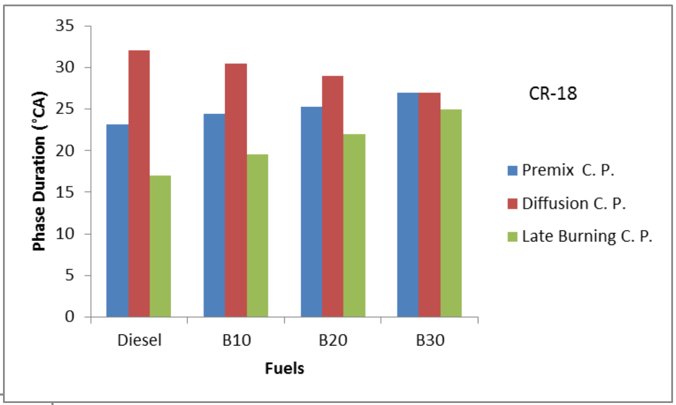

Fig. 7(b): Combustion Phases for Fuel Samples at CR-18

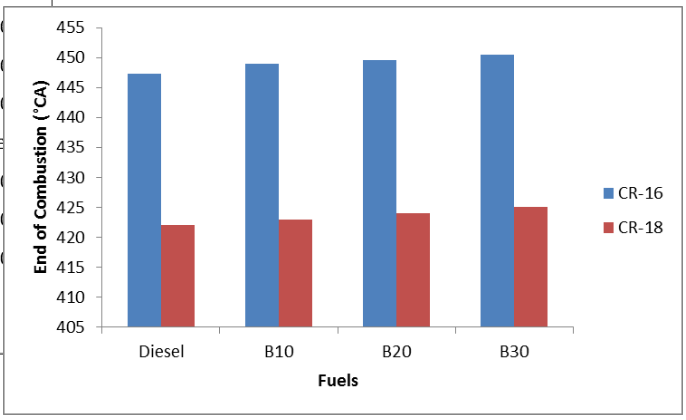

Fig. 8: End of Combustion for Fuel Samples

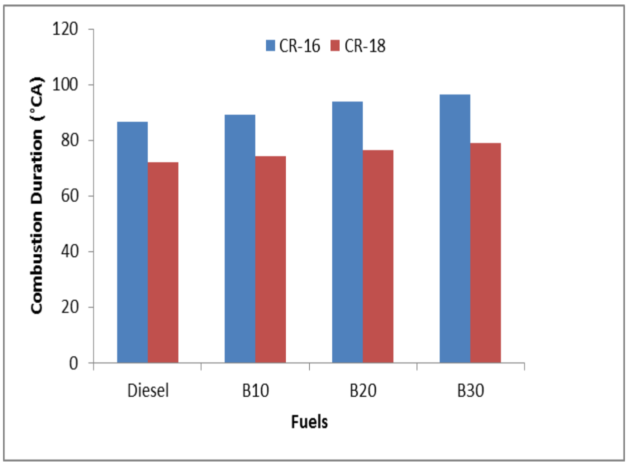

Fig. 9: Combustion Duration for Fuel Samples

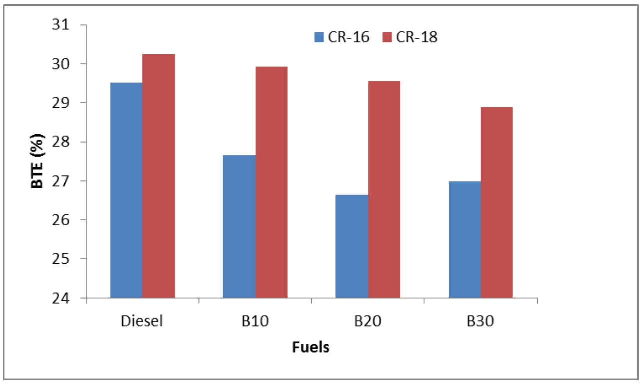

Fig. 10: Brake Thermal Efficiency for Fuel Samples

The carbon monoxide (CO) emissions is found to decrease with increase in blending percentage (at CR-16, Diesel= 0.04% Vol. to B30= 0.014% Vol. and at CR-18 Diesel= 0.02% Vol. to B30= 0.01% Vol.) at both compression ratios. Similarly unburned hydrocarbon (HC) emission decreased with biodiesel-diesel blends (at CR-16, Diesel= 28.67ppm to B30= 19.5ppm and at CR-18, Diesel= 15.9 to B30= 10.3ppm). This could be attributed to additional oxygen content, higher in-cylinder pressure and temperature with biodiesel samples favoring complete combustion [10-11]. Increase in compression ratio reduces CO & HC emissions due to better combustion (Fig. 11 & 12).

The CO_2 and NO_X emissions are seen to increase with blending samples (Fig. 13 & 14). The increment in NO_X emission can be attributed to additional oxygen content, advancement in injection timing and longer spray length with biodiesel samples favoring increased temperatures in cylinder and enhancement in premixed phase of combustion. Higher compression ratio obviously results in higher in-cylinder temperatures causing better combustion leading to increase in CO_2 and NO_X emissions. The higher NO_X emissions of castor biodiesel problem could be solved by water-diesel emulsion technology [14]. The increment in CO_2 emissions cannot be considered as negative impact as they are reused in plants in photosynthesis process from which biofuels are produced.

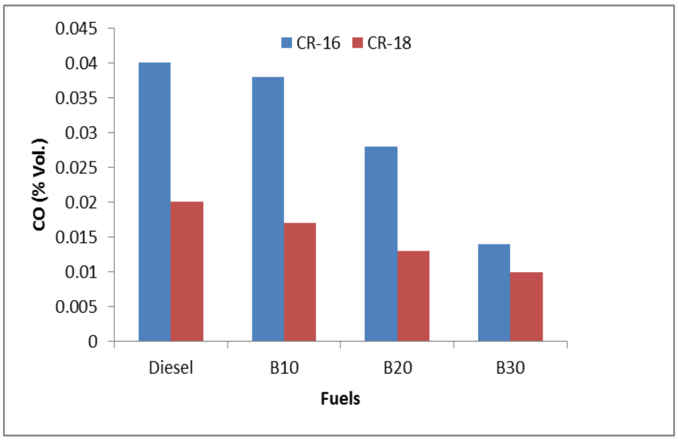

Fig. 11: CO Emissions for Fuel Samples

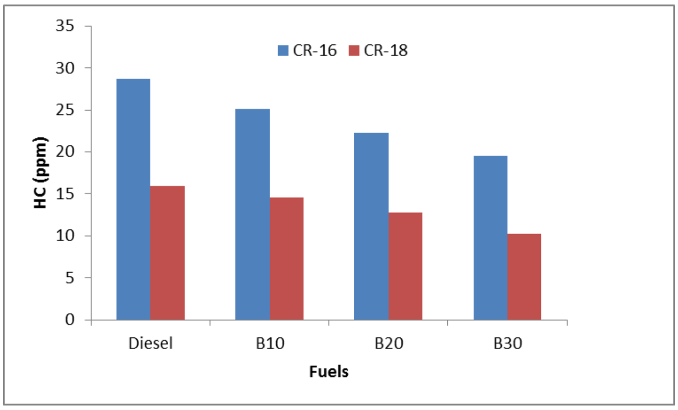

Fig. 12: HC Emissions for Fuel Samples

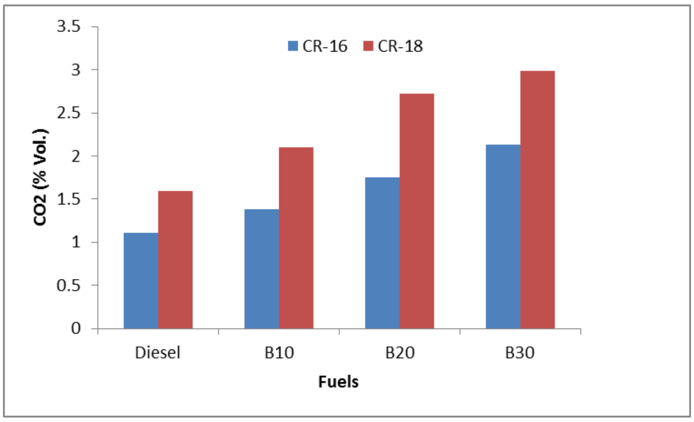

Fig. 13: CO_2 Emissions for Fuel Samples

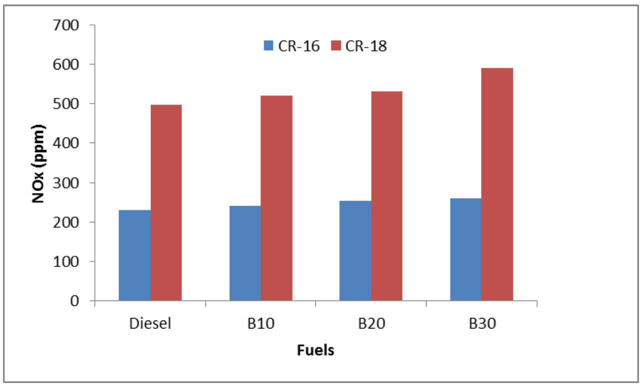

Fig. 14: NO_X Emissions for Fuel Samples

IV. CONLUSIONS

The following conclusions for diesel engine operating on castor biodiesel fuel samples (B10, B20 and B30) at two compression ratios (CR-16 & CR-18) when compared to base diesel are drawn:

- The duration of ignition delay decreases with castor biodiesel fuel samples (Diesel: 23.7 ^{0}CA to B30: 17.2 ^{0}CA at CR-16 and Diesel: 12.8 ^{0}CA to B30: 9 ^{0}CA at CR-18) as compared to plain diesel for both compression ratios.
- The peak in-cylinder pressure increases with blending percentage of biodiesel when compared with plain diesel; also it logically increases with increment in compression ratio. Whereas the rapid pressure rise got reduced with biodiesel samples and increased with compression ratio.
- The premixed combustion phase duration increases with blending percentage as well as with increment in compression ratio. Diffusion combustion phase is found to remain unchanged with blending percentage. The combustion duration increases with increase in biodiesel contents and it decreases with higher compression ratio.
- BTE decreased with increase in blending percentage of blends, and it increased with compression ratio.
- CO and HC emissions are found to reduce with increase in biodiesel percentage and compression ratio.
- CO_2 and NO_X increased with blending percentage and also with increment in compression ratio.

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