

Experimental Investigation of CI Engine Fuelled With Waste Agricultural Biodiesel at Higher Compression Ratios



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Abstract: In this study, the performance, combustion and emissions characteristics of compression ignition engine were calculated and analysed using a waste agricultural biodiesel. The tests were performed at steady state conditions for a four-stroke single cylinder diesel engine loaded at engine speed of 1500 rpm. The present experimental investigation evaluates the effects of using BD20 blend of biodiesel. During experimental testing of CI engine using biofuel blend, the engine was maintained at various compression ratio i.e., 18, 19 and 20 respectively. Engine load is varied from zero to full load condition. Design of experiment is done with Taguchi method. The main objective is to check the optimum compression ratio and to obtain minimum specific fuel consumption, better efficiency and lesser emission with higher compression ratio. Results shows that Brake thermal efficiency and cylinder pressure of CI engine increases with increase in compression ratio and load. Specific fuel consumption, emission of hydrocarbon and carbon monoxide decreases as we increase compression ratio. Nitrogen oxide follows the reverse trend and found to be increased as we increase compression ratio and load on engine. The analysis shows optimum performance with lower emission at a CR of 20 and load 100%.

Keywords: biodiesel, compression ratio, emission, load, Taguchi.

I. INTRODUCTION

The growth and economy of any country mainly depend on its energy resources. Industrialization and economic greed lead to tremendous amount of rise in demand and consumption of fuel throughout the world. The world is currently facing severe crisis of fuel depletion as well as environmental degradation. This limits the use of fuels for industries which eventually limits the chances of growth. The search for alternate fuels for diesel engines has been increased from last

few decades as alternative to fossil fuels. As economy of India is mainly dependent on agriculture and due to huge amount of resources, we can try to partially replace fossil fuels with biofuels extracted from agricultural waste. It is the need of time to reduce emissions of CO, NO_x, CO₂ to minimize environmental damage which causes problems such as global warming, acid rain and air pollution. It is proved that by blending biodiesel in diesel fuel, the harmful gas emission can be reduced due to high percentage of oxygen contents in biodiesel [1-4]. The biodiesel blend BD20 is found to be the best blend [1]. Thus, BD20 is selected for experimental study.

The experiment is to be study performance characteristics namely Brake thermal efficiency, Brake specific fuel consumption, emissions of CO, HC and NO_x and to check combustion characteristic like Cylinder Pressure. The actual testing experiment is conducted on single stroke four-cylinder CI engine. The engine speed is maintained at 1500 RPM throughout the experiment. The performance, combustion and emission characteristics are tested and compared according to compression ratio and load. Taguchi method is used for designing the experiment and "Minitab 19" software is used for analysis purpose. In the present study an orthogonal array (L9) was with 2 control factors and 3 levels. Taguchi method is applied to select the 2 control factors (Compression ratio, Load) with 3 levels (18, 19, 20 & 0%, 50%, 100%). Therefore, total number of experiments conducted was 9. The objective of this research is to investigate the usage of biodiesel blended in order to reduce the emissions of pollutants from diesel engine and to increase engine performance.

II. EXPERIMENTAL WORK

A. Experimental Setup

The experimental setup consists of single cylinder four stroke diesel engine. The pressure sensor is mounted on cylinder head which is exposed to combustion chamber for measurement of in-cylinder combustion pressure with respect to crank angle. The crank angle encoder was mounted on crank shaft to measure the crank angle. The eddy current dynamometer was used for loading the engine. The data acquisition system was used for acquiring the pressure-crank angle data and for further analysis. The engine speed (1500 rpm) and static injection timing were maintained as constant throughout tests. Exhaust gas analysis is done by sampling directly from the exhaust line without affecting the back pressure with a specially designed arrangement by the multi gas analyzer. The concentrations of CO, HC and NO_x in the engine exhaust are recorded continuously.

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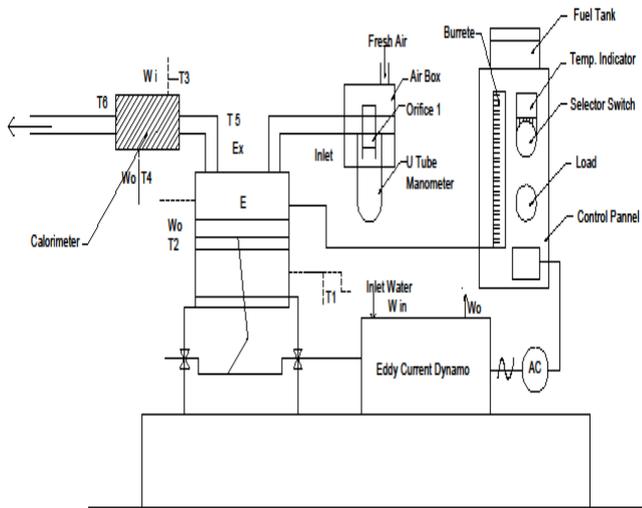


Fig.1: Schematic diagram of engine set-up

Table I: Technical specifications of the test engine

Description	Specification
Engine Manufacturer	Apex Innovations (Research Engine test set up)
No of cylinders	1
No of strokes	4
Type of cooling	Water cooling
Cylinder diameter	87.5mm
Stroke length	110mm
Connecting rod length	234mm
Orifice diameter	20mm
Swept volume	661.45cc
Dynamometer arm length	185mm
Fuel	Diesel
Power	3.5kW
Speed	1500 RPM



Fig.2: Engine Testing Rig

Properties testing of biodiesel is done in “Ashwamedh Engineers and Consultants, Nashik”. Properties are mentioned in Table II.

Table II: Properties of biodiesel

Properties	Biodiesel
Density (g/cubic cm)	0.8389
Viscosity (cSt)	2.93
Calorific Value (kj/ kg)	44296
Fire Point(°C)	55
Flash Point(°C)	62
Cetane Number	51
Ash percent by mass, Max	0.01
Carbon residue (Ramsbottom), Max	0.3
Total Sulphur, (mg/kg), Max	50
Water content, (m/kg), Max	200
Oxidation stability, (g/m3), Max	25
Oxygen content, percent by mass, Max	0.6



Fig.3: Waste agricultural biodiesel Sample

III. RESULTS AND DISCUSSION

Minitab software provides several analytical and graphing tools to help understand the results. The experimental results are transferred into SN ratio. There are three categories of quality characteristics in analysis of SN ratio namely “smaller is better”, “larger is better” and “nominal is better”. The SN ratio for optimal BTE and cylinder pressure are coming under “larger is better” characteristic. The category “lower is better” was used to calculate the SN ratio for SFC and emissions of NO, CO, HC. In response table of SN ratios, level 1 is for the average of SN ratios of three experiments of respective factors like CR (18) and load (0%). Similarly, level 2 and level 3 shows average of SN ratios of three experiments each with factors like CR (19,20) and load (50%, 100%). Delta is the difference between highest and lowest reading from all levels for a specific factor. According to these delta values, the ranks are given from highest delta to lowest delta. In SN ratio plot, if the line for a particular parameter is nearly horizontal, the parameter has less significant effect on response. On the other hand, a parameter for which the line has the highest inclination will have the most significant effect.

Table III: Observation Table

Ex No	CR	Load (%)	BTE (%)	SFC (kg/kWh)	Cylinder Pressure (bar)	HC (ppm)	CO (%vol)	NOx (ppm)
1	18	0	0.72	11.80	52.88	13	0.11	61
2	18	50	17.16	0.49	63.93	30	0.15	359
3	18	100	22.86	0.37	73.14	52	0.30	635
4	19	0	0.32	26.34	56.04	13	0.08	79
5	19	50	17.44	0.49	67.01	32	0.16	432
6	19	100	21.84	0.39	77.03	55	0.36	690
7	20	0	1.75	4.84	57.21	8	0.08	88
8	20	50	17.70	0.48	71.41	26	0.11	510
9	20	100	22.81	0.37	79.50	57	0.31	681

A. Brake Thermal Efficiency (BTE)

Brake thermal efficiency gives an idea of the output generated by the engine with respect to the heat supplied in the form of fuel. In BTE analysis, rank 1 is given to load factor with maximum delta and it had been also observed from the SN plot that parameter load had the most significant effect than CR. In SN ratio calculation and interpretation of graph, we have considered “larger is better” criteria for obtaining maximum BTE. So, SN curve will show highest priority to the condition with highest BTE.

Larger is better

Table IV: Response Table for Signal to Noise Ratios of BTE

Level	CR	LOAD
1	16.340	-2.630
2	13.906	24.827
3	18.994	27.043
Delta	5.088	29.673
Rank	2	1

In response Table IV, we get highest value of SN ratio for load 100% which is 27.043. We get lowest value of SN ratio for load 0% which is -2.630. From Fig.4 and SN ratios, it is also clear that optimal load condition for highest BTE is at 100% load. Average BTE at 100% load is 22.5033% and at 0% load is 0.93%. BTE of the engine was low at part loads as compared to the engine running on full load. Improvement in the BTE with the load is because of the fact that relatively less portion of the power is lost with increasing load. At full load conditions BTE varies less than at part loads between CR’s. This could be due to the increased temperatures inside the cylinder due to more amount of fuel burning at higher loads. We get highest value of SN ratio for CR 20 which is 18.994. We get lowest value of SN ratio for CR 19 which is 13.906. From Fig.4 and SN ratios, it is also clear that optimal condition for highest BTE is at CR 20. Thus, increasing the CR improved the efficiency of the engine. Improvement in the BTE with the increased CR is because of the reduced ignition delay.

The main effects plot of SN ratios for BTE is shown in Fig.4

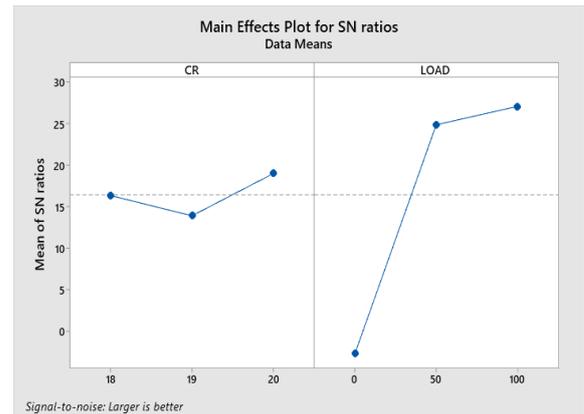


Fig.4: SN plot for BTE

The variation of BTE obtained in this study is shown in Fig.5 as a function of load for compression ratios of 18, 19, 20, respectively.

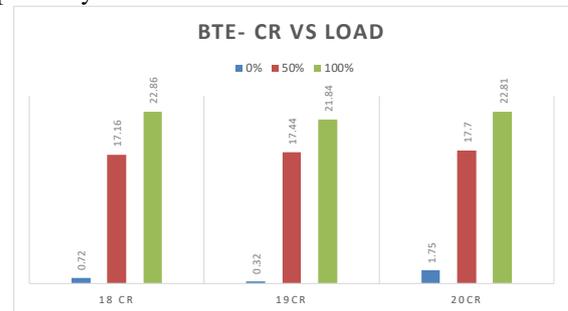


Fig.5: Variation of BTE

Optimized condition for BTE:

Optimize set for maximum BTE is at CR 20 and at load 100%. The BTE value predicted from Minitab at this condition is 22.9678%. Experimental value at this condition is 22.81% which is nearer our predicted value. So, the analysis is correct.

B. Specific Fuel Consumption (SFC)

The specific fuel consumption is an important parameter to measure the engine performance. It is defined as the mass of fuel required to produce unit brake power. In SFC analysis, rank 1 is given to load factor with maximum delta and it had been also observed from the SN plot that parameter load had the most significant effect than CR. In SN ratio calculation and interpretation of graph, we have considered “smaller is better” criteria for obtaining minimum SFC. So, SN curve will show highest priority to the condition with lowest SFC.

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Table V: Response Table for Signal to Noise Ratios of SFC

Level	CR	LOAD
1	-2.201 9	-21.182 3
2	-4.679 2	6.2558
3	0.4381	8.4835
Delta	5.1173	29.6658
Rank	2	1

In response Table V, we get highest value of SN ratio for load 100% which is 8.4835. We get lowest value of SN ratio for load 0% which is -21.1823. From Fig.6 and SN ratios, it is also clear that optimal load condition for lowest SFC is at 100% load. Average SFC at 100% load is 0.3766 kg/kWh and at 0% load is 14.32 kg/kWh. SFC decreases sharply with increase in load at any CR. The main reason for this could be that percent increase in fuel required to operate the engine is less than the percent increase in brake power due to relatively less portion of the heat losses at higher loads.

The highest value of SN ratio for CR 20 is 0.4381. We get lowest value of SN ratio for CR 19 which is -4.6792. From Fig.6 and SN ratios, it is also clear that optimal condition for lowest SFC is at CR 20. Average SFC at CR 19 is 9.07 kg/kWh and at CR 20 is 1.89 kg/kWh. Thus, increasing the CR improved the efficiency of the engine. Low volatility and higher viscosity allow biodiesel to performing relatively better at higher compression ratios. When CR increases, the maximum cylinder pressure increases due to the fuel injected in hotter combustion chamber and this leads to higher effective power. Therefore, fuel consumption per output power decreases. The main effects plot of SN ratios for SFC is shown in Fig.6

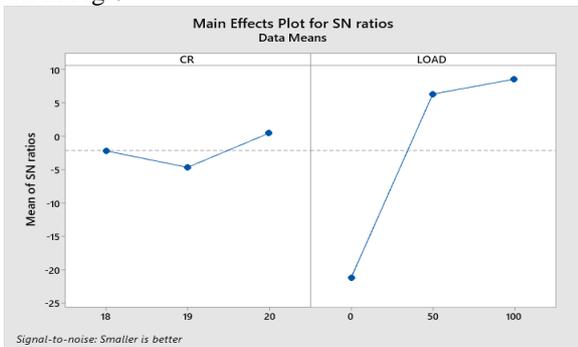


Fig.6: SN plot for SFC

The variation of SFC obtained in this study is shown in Fig.7 as a function of load for compression ratios of 18, 19, 20, respectively.

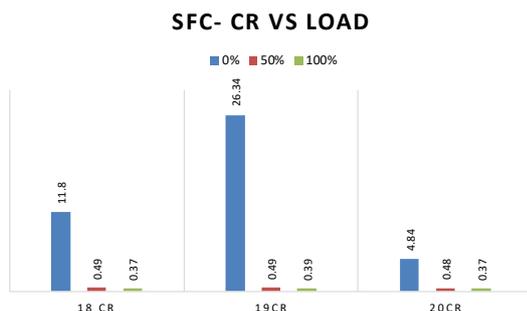


Fig.7: Variation of SFC

Optimized condition for SFC:

Optimize set for minimum SFC is at CR 20 and at load 100%. The SFC value predicted from Minitab at this condition is 0.33 kg/kWh. Experimental value at this condition is 0.37 kg/kWh which is nearer our predicted value. So, the analysis is correct.

C. Cylinder Pressure

Cylinder Pressure is the pressure in the engine cylinder during the 4 strokes of engine operation (intake, compression, combustion and expansion, exhaust). The higher the cylinder pressure during the intake stroke, the less work the engine has to do to "suck in" the intake air and fuel. The more pressure during compression stroke helps to easily vaporize the fuel. During combustion stroke, high cylinder pressure is created which gives power to engine as it forces the piston down. As the piston goes down, the cylinder volume increases which reduces the cylinder pressure. In expansion stroke the cylinder pressure is higher than atmospheric pressure. Intensity of cylinder pressure during exhaust stroke decides the amount of work the engine has to do. The combustion of diesel engine is partially premixed and partially diffusive. The major part of the combustion of biofuel blend occurs at the premixed stage and a small part of the combustion occurs in diffusive stage. In cylinder pressure analysis, rank 1 is given to load factor with maximum delta and it had been also observed from the SN plot that parameter load had the most significant effect than CR. In SN ratio calculation and interpretation of graph, we have considered "larger is better" criteria for obtaining maximum cylinder pressure. So, SN curve will show highest priority to the condition with highest pressure

Table VI: Response Table for Signal to Noise Ratios of cylinder pressure

Level	CR	LOAD
1	36.1 1	35.02
2	36.4 1	36.57
3	36.7 4	37.67
Delta	0.63	2.65
Rank	2	1

We get highest value of SN ratio for load 100% which is 37.67 and lowest value of SN ratio for load 0% is 35.02. From Fig.8 and SN ratios, it is also clear that optimal load condition for highest cylinder pressure is at 100% load. Average pressure at 100% load is 76.55 bar and at 0% load is 55.37 bar. As the quantity of fuel burned increases with engine load, it leads to increase in the heat energy released. Thus, cylinder pressure increases with increase in load. The highest value of SN ratio for CR 20 is 36.74 while the lowest value of SN ratio for CR 19 is 36.11. From Fig.8 and SN ratios, it is also clear that optimal load condition for highest pressure is at CR 20. Thus, Cylinder pressure increases with increase in CR. At higher CR, fuel gets easily mixed and temperature also increases during compression stroke.

This causes ignition delay to reduce and the combustion occurs near the TDC. During this period, the fuel reaction rate is faster and causes a rapid increase in pressure in the engine cylinder. As the compression ratio is higher than the normal range of the diesel fuel engine misfired, high knocking occurs with high pressure oscillation. This adversely affects and narrows the expected rise in fuel conversion efficiency. The fuel conversion efficiency will be effective at a high compression ratio. This leads to reduced ignition delay. The longer ignition delay at lower CR results in diffusive end burning and drops in cylinder pressure.

The main effects plot of SN ratios for cylinder pressure is shown in Fig.8

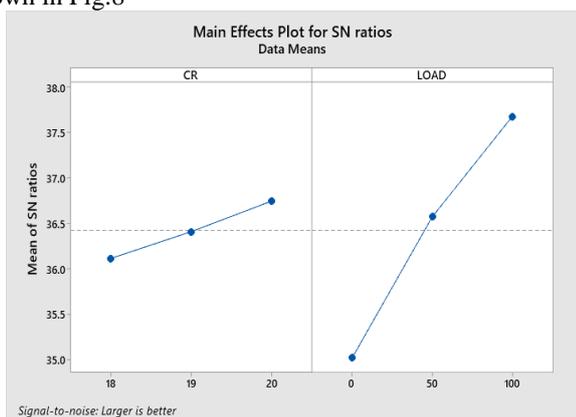


Fig.8: SN plot for Cylinder Pressure

The variation of cylinder pressure obtained in this study is shown in Fig.9 as a function of load for compression ratios of 18, 19, 20, respectively

CYLINDER PRESSURE- CR VS LOAD

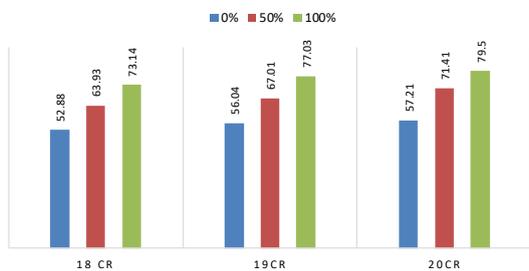


Fig.9: Variation of Cylinder Pressure

Optimized condition for cylinder pressure:

Optimize set for minimum cylinder pressure is at CR 20 and at load 100%. The cylinder pressure value predicted from Minitab at this condition is 79.1356 bar. Experimental value at this condition is 79.5 bar nearer our predicted value. So, the analysis is correct.

D. Hydrocarbon (HC) Emission

HC emission takes place when fuel particles fails to ignite completely in the combustion chamber. It happens due to incomplete combustion. It also appears in the inner layers during the diffusion flame where there is more fuel than air. In HC emission analysis, rank 1 is given to load factor with maximum delta and it had been also observed from the SN plot that parameter load had the most significant effect than CR. In SN ratio calculation and interpretation of graph, we have considered “smaller is better” criteria for obtaining minimum emission. So, SN curve will show highest priority to the condition with lowest HC emission

Table VII: Response Table for Signal to Noise Ratios of HC

Level	CR	LOAD
1	-28.71	-20.87
2	-29.06	-29.31
3	-27.16	-34.75
Delta	1.90	13.88
Rank	2	1

Highest value of SN ratio for load 0% is -20.87 and lowest value of SN ratio for load 100% is -34.75. From Fig.10 and SN ratios, it is also clear that optimal load condition for lowest HC emission is at 0% load. Average HC emission at 0% load is 11.33 ppm volume and at 100% load is 54.66 ppm volume. Thus, when load is high, HC emissions increased largely because of reduced in-cylinder temperature and pressure. There exists high deficiency of O₂ leading the rich fuel inside the combustion chamber. In short biofuel particles do not combust entirely and result in increased HC emissions at higher loads. We get highest value of SN ratio for CR 20 which is -27.16. We get lowest value of SN ratio for CR 19 which is -29.06. From Fig.10 and SN ratios, it is also clear that optimal condition for lowest HC emission is at CR 20. Thus, HC emissions are more at lower CR because the insufficient heat of compression delays ignition. Emissions are much lesser at high CR as during the end of the compression stroke, the air temperature gets higher, this enhance the complete burning which leads to efficient combustion, and reduced HC emission for biodiesel. The main effects plot of SN ratios for HC emission is shown in Fig.10

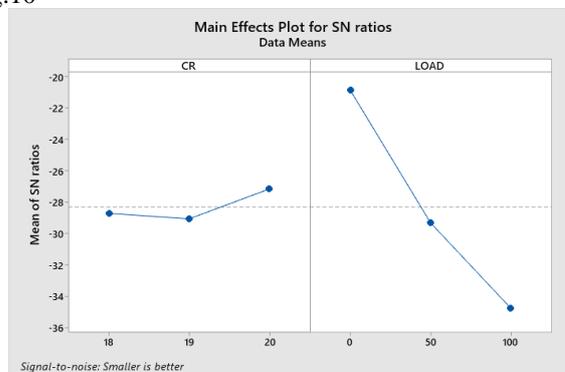


Fig.10: SN plot for HC emission

Variations of unburned HC emission with respect to the CR 18,19,20 and load conditions is given in Fig.11.

HC- CR VS LOAD

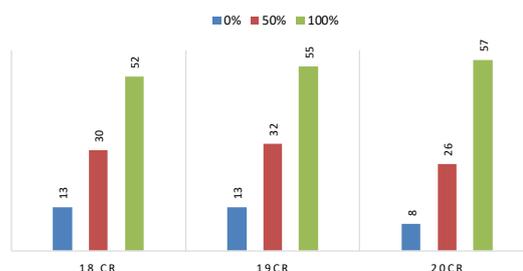


Fig.11: Variation of HC emission

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Optimized condition for HC emissions:

Optimize set for minimum HC emissions is at CR 20 and at load 0%. The HC emissions predicted from Minitab at this condition is 9.889 ppm volume. Experimental value at this condition is 8 ppm volume which is nearer our predicted value. So, the analysis is correct.

E. Carbon Monoxide (CO) Emission

CO emission causing due to incomplete combustion of fuel particles is hazardous to human health. Thus, needs to be minimized. In CO emission analysis, rank 1 is given to load factor with maximum delta and it had been also observed from the SN plot that parameter load had the most significant effect than CR. In SN ratio calculation and interpretation of graph, we have considered “smaller is better” criteria for obtaining minimum emission. So, SN curve will show highest priority to the condition with lowest CO emission.

Table VIII: Response Table for Signal to Noise Ratios of CO

Level	CR	LOAD
1	15.36 9	21.016
2	15.57 7	17.189
3	17.09 4	9.835
Delta	1.725	11.181
Rank	2	1

Highest value of SN ratio for load 0% is 21.016. We get lowest value of SN ratio for load 100% which is 9.835. From Fig.12 and SN ratios, it is also clear that optimal load condition for lowest CO emission is at 0% load. Average CO emission at 0% load is 0.09% volume, at 50% load is 0.14% volume and at 100% load is 0.32% volume. Thus, CO emissions are comparatively lesser at lower loads. We get highest value of SN ratio for CR 20 which is 17.094 and lowest value of SN ratio for CR 18 which is 15.369. From Fig.12 and SN ratios, it is also clear that optimal condition for lowest CO emission is at CR 20. Insufficient heat of compression delays ignition which leads to CO emissions increase at lower CR. The increased CR actually increases the air temperature inside the cylinder which reduces the ignition lag causes better and more complete burning of the fuel. Thus, lesser CO emissions at higher CR. The main effects plot of SN ratios for CO emission is shown in Fig.12

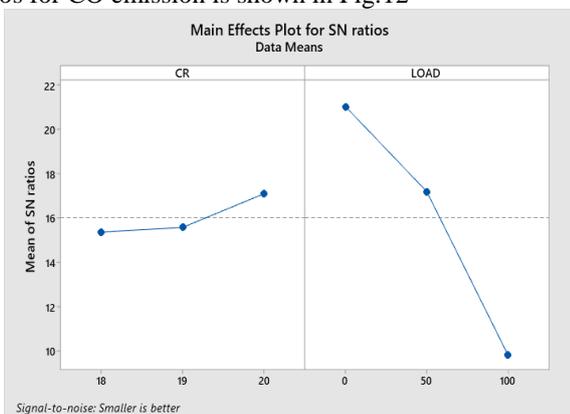


Fig.12: SN plot for CO emission

Variation of CO emissions at various compression ratios 18,19,20 and load condition is given in Fig.13.

CO- CR VS LOAD

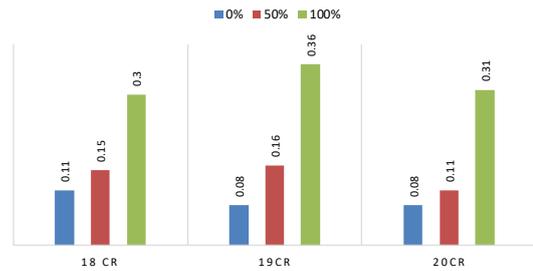


Fig.13: Variation of CO emission

Optimized condition for CO emissions:

Optimize set for minimum CO emissions is at CR 20 and at load 0%. The CO emissions predicted from Minitab at this condition is 0.0722 % volume. Experimental value at this condition is 0.08 % volume which is nearer our predicted value. So, the analysis is correct.

F. Oxides of Nitrogen (NOx) Emission

Nitrogen is present in air at high percentage of about 78%. NOx formation involves reaction of N₂ and O₂ at high temperatures in the combustion process. NOx must have been formed mainly in the premixed combustion and in the outer layers of the diffusion flame, where the temperature is high and there is a lot of O₂ presents that is contained in the B20. NOx emission is one of the precarious emissions from the diesel engine due to high in-cylinder temperature which must be reduced by some technical treatment.

In NOx emission analysis, rank 1 is given to load factor with maximum delta and it had been also observed from the SN plot that parameter load had the most significant effect than CR. In SN ratio calculation and interpretation of graph, we have considered “smaller is better” criteria for obtaining minimum emission. So, SN curve will show highest priority to the condition with lowest NOx emission.

Table IX: Response Table for Signal to Noise Ratios of NOx

Level	CR	LOAD
1	-47.62	-36.31
2	-49.15	-52.65
3	-48.69	-56.50
Delta	1.53	20.19
Rank	2	1

Here we get highest value of SN ratio for load 0% which is -36.31. We get lowest value of SN ratio for load 100% which is -56.50. From Fig.14 and SN ratios, it is also clear that optimal load condition for lowest NO emission is at 0% load. Average NO emission at 0% load is 76 ppm volume and at 100% load is 668.67 ppm volume. At higher load condition during combustion, temperature inside the engine exceeds a particular limit and nitrogen reacts with oxygen to create NOx. Thus, as load increases, NOx emission increases and reach at peak value at load 100%. We get highest value of SN ratio for CR 18 which is -47.62. We get lowest value of SN ratio for CR 19 which is -49.15. From Fig.14 and SN ratios, it is also clear that optimal condition for lowest NOx emission is at CR 18.

The most important factor for NOx emission is high combustion temperature which increases with increase in compression ratio. Reduced CR causes reduction in the in-cylinder temperatures, and thus flame temperatures suppress NOx emissions during the combustion process. Thus, as CR increases, NOx emission increases. The main effects plot of SN ratios for NOx emission is shown in Fig.14

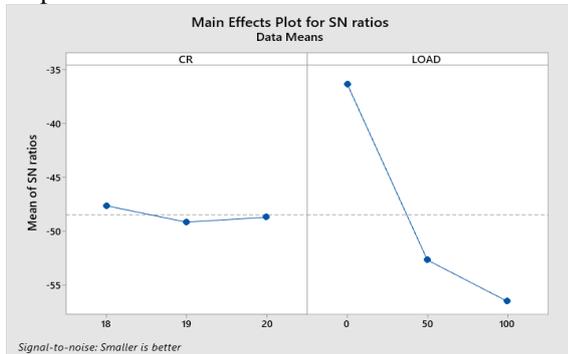


Fig.14: SN plot for NOx emission

Variation of NOx emissions at various compression ratios 18,19,20 and load condition is given in Fig.15.

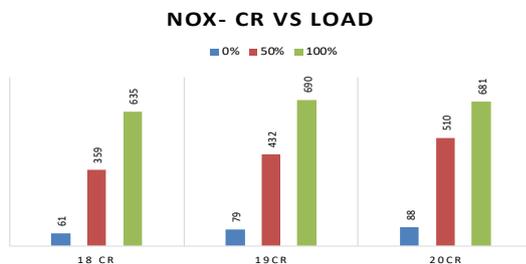


Fig.15: Variation of NOx emission

Optimized condition for NOx emissions:

Optimize set for minimum NOx emissions is at CR 18 and at load 0%. The NOx emissions predicted from Minitab at this condition is 28.22 ppm volume. Experimental value at this condition is 61 ppm volume which is also much lesser than the values at other CR and load conditions. So, the analysis of predicting combination of 18 CR and 0% load is correct.

IV. CONCLUSION

The impacts of higher compression ratios on CI engine fuelled with waste agricultural biodiesel were systematically investigated with Taguchi method at various load conditions and following conclusions can be made:

- Analysis by SN plots shows that Load is the most impacting factor on engine performance than CR.
- Brake thermal efficiency of CI engine increases with increase in compression ratio and load. BTE is found to be highest at CR 20 and load 100%.
- Specific fuel consumption of CI engine decreases as we increase compression ratio. Minimum SFC is obtained at CR 20 and load 100%.
- Cylinder pressure is directly proportional to the compression ratio and load. Thus, it is maximum at CR 20 and load 100%.
- Emission of hydrocarbon increases with load and found to be reduced as we go from CR 18 to CR 20. Thus, minimum HC emission is obtained at CR 20 and load 0%.
- Carbon monoxide emission follows the same trend as HC emission and is minimum at high compression ratio i.e. CR 20.

- Nitrogen oxide emission mainly depends on in-cylinder combustion temperature. Thus NOx emission follows the reverse trend and found to be increased as we increase compression ratio and load on engine. NOx emission is least at CR 18 and load 0%.

Main objective of the study was to check impact of higher compression ratio on engine performance and experiments shows that compression ratio 20 gives optimum results except in case of NOx emissions. Thus, we can use waste agricultural biofuel in CI engine at higher compression ratio up to 20 for maximum efficiency.

FUTURE SCOPE

Experimental study has proved that 20 compression ratio has exhibited superior engine performance with minimum exhaust emissions. However, increased NOx emissions are obtained at higher compression ratio. Hence, future work of this project will include various methods to reduce NOx emissions for improved results.

Methods used for diesel engine NOx emissions reduction can be divided into following 2 categories:

1. Primary methods-

Primary methods are used to reduce the amount of NOx formed during combustion. The basic aim of most of these methods is to lower the maximum temperature in the cylinder, since this result inherently in a lower NOx emission. Primary methods can be categorized as follows:

- Altered fuel injection- Fuel nozzle modification, Retarded fuel injection, High pressure fuel injection
- Water addition- Direct water injection, Water emulsified fuel, Stratified water injection, Intake air Humidification
- Combustion air treatment- Exhaust gas recirculation, Adjustment of inlet /exhaust valve
- Change of engine process- Compression ratio

2. Secondary methods

Secondary methods are used to remove NOx from the exhaust gas by downstream treatment. Various catalytic converters are used in this method.

The Selective Catalytic Reduction (SCR) is the most well-known method.

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