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Optimization of operational parameters for performance and emissions of a diesel engine fueled with diesel and biodiesel

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Abstract : The following study attributes to optimization of operational parameters for performance and emissions of a diesel engine fueled with a blend of conventional diesel and biodiesel extracted from cotton seeds. We have used the Transesterification process for extracting the biodiesel from cotton seeds. The diesel and biodiesel mixture varies from 80-100% of Diesel and 0- 20% of Biodiesel. Experimental investigations involve varying key parameters such as fuel injection timing, air-fuel ratio, Indicated Pressure. The Compression ratio is fixed at 18:1 to identify the optimal combination that maximizes combustion efficiency and minimizes pollutant emissions. The results show that efficiency has been increased minimally (2-3%) whereas there has been a notable decrease in emissions produced by the diesel engine(in ppm). The research encourages the utilization of biodiesel derived from renewable sources as a sustainable alternative to traditional diesel fuel. Results obtained through meticulous experimentation provide valuable insights into the impact of operational parameters on engine efficiency and emissions. The findings help us to comprehend ongoing efforts to optimize diesel engine operation for improved sustainability in the diesel engine industry.

***Index Terms* - Biodiesel, Compression ratio, Energy, Blends, Efficiency.**

I.Introduction

The traditional approach of extracting diesel is burning fossil fuels at temperatures around 300 degrees Celsius results in extraction of diesel. Due to diesel fuel's higher torque and power and also for its availability, diesel fuel is one of the most preferred fuels in various industries. In recent times it has been concluded through various research and surveys that diesel engines that run with diesel fuels have been significantly contributing towards various adverse climate conditions while due to the emissions of CO,CO2, NOx and HC and various other harmful gases into the atmosphere. Hence there has been a rigorous search for the alternative of diesel fuel as we are expected to run out of fossil fuels in the future. Hence a suitable alternative along with its feedstock availability is going to be an alternative for diesel fuel in running the diesel engine.

Many alternatives such as vegetable oils, fish oils and Karanga biodiesel have been considered for this research . But keep in mind that the efficiency of the diesel engine should not be compromised in this search for new alternatives. Maintaining the efficiency of the diesel engine and also reducing the emissions are some of the main requirements to choose a biodiesel as a suitable alternative. The chosen biodiesel should also have feedstock availability as diesel fuels are used in abundant quantities. Hence choosing a biodiesel that is inedible and available in large quantities has an advantage over various other alternatives. Biodiesels extracted through cotton seeds prove to be one of the most lucrative choices as it promises both feedstock availability as well as inedible nature. Transesterification process is used to convert triglycerides react with alcohol and gives biodiesel and glycerol as its byproduct. Transesterification has also proved to increase the calorific value of the fuel hence allowing it to release more energy and also make it comfortably blend with current diesel. It also promises a high conversion rate. The biodiesel has a typical oxygenated nature as it results in more complete combustions in diesel engines and reduces the CO emissions.

It is important to keep in mind that the preferred biodiesel should be compatible with diesel engine infrastructure. Modifications cannot take place in a short time in the current diesel engine infrastructure as it promises the best efficiency. Some of the parameters such as Indicated Pressure, Injection Timing and Compression ratio have a significant effect on the diesel engine fueled with biodiesel blends. Efficiency of the engine cannot be compromised at any cost. To ensure this, A robust optimization technique should be followed. Taguchi optimization technique has been popularly regarded as parameter optimization technique in the design of experiments. Taguchi optimization technique promises robust parameters that can withstand significant variations . According to some studies, Taguchi optimization technique and its approach to design optimum operating conditions was found to maximize the efficiency of a diesel engine fueled with biodiesel. As the world seeks to reduce greenhouse gas emissions and dependence on fossil fuels, biodiesel blends present a viable solution by incorporating renewable resources such as vegetable oils, animal fats, or recycled cooking oils into the fuel mix. The seamless integration of biodiesel blends into existing diesel engine infrastructure is crucial for widespread adoption, as it ensures compatibility with engines, fuel distribution systems, and storage facilities. By maintaining engine performance and reliability while reducing emissions of harmful pollutants, biodiesel blends pave the way for a greener future in transportation, agriculture, and various industrial sectors. Thus, ensuring that biodiesel blends do not adversely affect diesel engine infrastructure is key to unlocking the environmental and economic benefits of renewable fuels. The efficiency of Internal Combustion engines depends upon the thermal efficiency and emissions which are important parameters to evaluate the performance of a diesel engine.

Experimentation is based on varying values of power and blend percentages to yield the best optimal condition that maintains the efficiency as well as reduces the emission to balance the performance and sustainability aspect of the diesel engine. Compression ratio is set at 18 which is the maximum in order as it is known that better combustion takes place at higher compression ratios. Therefore, it is important to set CR at 18 for better efficiency purposes. This study focuses on the Mult objective optimization by increasing the efficiency of a diesel engine and simultaneously reducing the emissions to improve the sustainability of the diesel engine. Experimentation through various biodiesel blends such as D100, D95B5, D90B10, D85B15, D80B20 result in the most optimal operating conditions that result in achieving the desired output.

The study mainly focuses on how varying the parameters such as CR, Power and blend percentages affect the efficiency and emission of a diesel engine. The aim of the current research is to identify the blend that results in optimal efficiency and emissions by using Taguchi optimization technique and determine the optimal values of Blend percentage and Load. This research was done in Thermal Laboratory on IC engines in Indian Institute of Information Technology Design and Manufacturing, Kurnool from August 2023 to March 2024

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II. METHODS

A. Fuel Preparation

The biodiesel was obtained from commercial sources and used without further purification. The biodiesel was obtained through a transesterification method. Methanol as an alcohol and potassium hydroxide as an catalyst were used in this method to release biodiesel as a byproduct. Transesterification produces biodiesel with properties closely resembling those of petroleum-based diesel, ensuring compatibility with existing diesel engines, fuel distribution systems, and infrastructure. Biodiesel derived from transesterification boasts favorable combustion characteristics, leading to lower emissions of harmful pollutants such as particulate matter, sulfur oxides, and carbon monoxide, thereby mitigating environmental impact and enhancing air quality.

Transesterification is a chemical process widely used in the production of biodiesel, a renewable and environmentally friendly alternative to conventional diesel fuel. During transesterification, triglycerides present in vegetable oils or animal fats react with alcohol methanol (CH_3OH) in the presence of a catalyst, such as sodium hydroxide or potassium hydroxide. This reaction results in the conversion of triglycerides into fatty acid methyl or ethyl esters, commonly known as biodiesel, and glycerol as a by-product. The process effectively separates the fatty acid esters, which have properties similar to diesel fuel, from the raw feedstock. Biodiesel produced through transesterification exhibits excellent combustion characteristics, low emissions, and biodegradability, making it a viable and sustainable alternative to petroleum-based diesel. Transesterification plays a pivotal role in the large-scale production of biodiesel, contributing to the diversification of energy sources and the reduction of greenhouse gas emissions in the transportation sector.

B. Experimental Setup

The experimental setups consist of direct injection single cylinder four stroke engine connected to an eddy current dynamometer. Eddy current dynamometers are more advantageous than other dynamometers for their durability and low maintenance requirements. They are known to last for a long time as they do not rely on friction-based components which results in reduced downtime and operation costs. The dynamometers provided a means to simulate various loads, enabling us to assess engine behavior across a range of power demands. Concurrently, IC Engine Combustion Analysis software was utilized to meticulously analyze engine emissions and efficiency at various loads and blend percentages. This software facilitated comprehensive monitoring and interpretation of data, allowing us to scrutinize factors influencing engine performance with meticulous detail.

Additionally, gas analyzers were used to scrutinize the emissions of gases such as CO, CO_2, NO_x and HC produced during engine operation, providing invaluable insights into the environmental impact of combustion processes. By leveraging this analytical approach, we were able to conduct systematic investigations into the engine's operational characteristics, exploring the interplay between load conditions, emissions, and efficiency in a controlled laboratory environment. This methodology allowed for a thorough understanding of the engine's behavior and performance, laying the groundwork for informed decision-making in the pursuit of enhancing engine efficiency and reducing environmental footprint.

No of Cylinders	1
No of Strokes	4
Stroke Length	110mm
Connecting rod length	234mm
Orifice Diameter	20mm
Dynamometer length	185mm
Fuel	Diesel
Power	3.5KW
Compression Ratio	18
Dynamometer Type	Eddy Current

TABLE I
ENGINE SPECIFICATIONS

C. Taguchi Optimization Technique

Taguchi Optimization Method is a highly renowned method for optimization of suitable parameters for optimal efficiency in a diesel engine. It involves use of Design of Experiments (DOE) to identify the optimal setting of parameters that affects the efficiency and emissions of a diesel engine. Taguchi optimization technique has emerged as a powerful methodology for optimizing product and process designs with minimal experimentation. One of its key advantages lies in its ability to achieve robust and reliable results while requiring fewer experimental runs compared to traditional optimization methods. Taguchi's approach employs orthogonal arrays and signal-to-noise ratios to identify optimal parameter settings that minimize variation and maximize performance under varying conditions. Unlike one-factor-at-a time methods, Taguchi optimization allows for the simultaneous evaluation of multiple factors, enabling researchers to efficiently explore the interaction effects among variables and identify the most influential factors affecting the outcome. Taguchi's emphasis on robustness ensures that the optimal settings are less sensitive to noise and external factors, leading to improved product or process performance over a wider range of operating conditions. Furthermore, Taguchi optimization facilitates a systematic and structured approach to experimentation, reducing the likelihood of overlooking critical factors or interactions that may impact the final outcome.

The Taguchi optimization technique uses the signal-to-noise ratio (S/N) to assess the optimal features of parameters. This study incorporates three S/N ratio types. Firstly, the ”higher is better” criterion was utilized to optimize input parameters for BTE and CO2 responses. Secondly, the ”lower is better” principle guided the optimization of input parameters for BSFC, EGT, NOx, CO, and HC responses. The Taguchi method was implemented and analyzed using Minitab-19 software.

The application of Taguchi optimization technique, particularly through the utilization of orthogonal arrays, proves instrumental in enhancing engine performance and efficiency when fueled with both diesel and biodiesel blends. Orthogonal arrays, a fundamental aspect of Taguchi methodology, allow engineers to systematically vary input parameters, such as fuel blend ratios, and varying loads, to identify the optimal combination that minimizes emissions and maximizes fuel efficiency. By conducting a series of controlled experiments using orthogonal arrays, researchers can efficiently explore the multifaceted interactions between fuel properties and engine parameters. This systematic approach enables the identification of robust engine settings that are less sensitive to variations in operating conditions, ensuring reliable performance across diverse environments. Moreover, the use of orthogonal arrays in Taguchi optimization streamlines the experimentation process, reducing the number of required tests while providing comprehensive insights into the complex relationships between fuel composition and engine performance.

III. Results and Discussion

S.No	Load	Blend	Speed	BTE (%)	BSFC (kg/kwh)
1	20	0	1300	14.467	0.61
2	20	5	1350	14.921	0.59
3	20	10	1400	15.157	0.52
4	20	15	1450	16.032	0.51
5	20	20	1500	16.724	0.5
6	40	0	1350	24.123	0.42
7	40	5	1400	23.722	0.45
8	40	10	1450	24.315	0.43
9	40	15	1500	24.511	0.41
10	40	20	1300	23.921	0.4
11	60	0	1400	28.018	0.39
12	60	5	1450	27.235	0.43
13	60	10	1500	27.891	0.4
14	60	15	1300	28.914	0.31
15	60	20	1350	29.258	0.33
16	80	0	1450	31.354	0.43
17	80	5	1500	30.565	0.37
18	80	10	1300	30.724	0.33
19	80	15	1350	31.012	0.36
20	80	20	1400	31.546	0.4
21	100	0	1500	28.574	0.51
22	100	5	1300	28.916	0.41
23	100	10	1350	29.014	0.42
24	100	15	1400	29.947	0.45
25	100	20	1450	30.015	0.49

TABLE II
Performance Results with blend percentage

S.No	Load	Blend	Speed	HC(PPM)	CO (%)	Nox(PPM)	CO2 (%)
1	20	0	1300	27	0.052	389	3.1
2	20	5	1350	28	0.054	310	3.4
3	20	10	1400	28	0.058	260	4.1
4	20	15	1450	30	0.051	436	4.2
5	20	20	1500	26	0.049	630	4.3
6	40	0	1350	28	0.056	577	4.9
7	40	5	1400	32	0.06	460	3.4
8	40	10	1450	32	0.066	450	4.4
9	40	15	1500	31	0.061	490	4.9
10	40	20	1300	30	0.038	614	5.1
11	60	0	1400	32	0.04	760	5.5
12	60	5	1450	30	0.049	670	4.8
13	60	10	1500	33	0.05	665	5.2
14	60	15	1300	31	0.038	782	4.7
15	60	20	1350	33	0.051	740	5.2
16	80	0	1450	31	0.039	930	5.8
17	80	5	1500	37	0.057	789	5.3
18	80	10	1300	32	0.056	734	6.2
19	80	15	1350	33	0.052	810	5.8
20	80	20	1400	36	0.047	910	5.3
21	100	0	1500	32	0.032	980	7.8
22	100	5	1300	34	0.063	756	5.9
23	100	10	1350	35	0.067	848	6.2
24	100	15	1400	36	0.049	1030	7.4
25	100	20	1450	37	0.041	989	6.6

TABLE III
Emissions Results with blend percentages

A. Brake Thermal Efficiency

Brake Thermal Efficiency (BTE) is an important parameter that was taken into consideration to measure the efficiency of a diesel engine in converting fuel energy into useful work. It represents the ratio of the useful work output to the heat input from the fuel. Higher BTE values indicate better fuel efficiency and reduced energy wastage, making it an essential parameter for evaluating engine performance. Optimizing BTE in diesel engines leads to lower fuel consumption, reduced emissions, and overall cost savings in various industrial and automotive applications.

Brake Thermal Efficiency has shown significant rise with the increase in blend percentage during experimentation. It has improved with increased rpm and has reached highest efficiency at D80B20 blend. Brake thermal efficiency has shown significant rise with increasing loads. This proves that Brake Thermal efficiency is directly proportional to the Increasing loads of the Diesel Engine. The highest BTE achieved during experimentation is 31.546 when experimented with D80B20. Hence it shows that the optimal blend percentage for highest BTE is 20% of biodiesel.

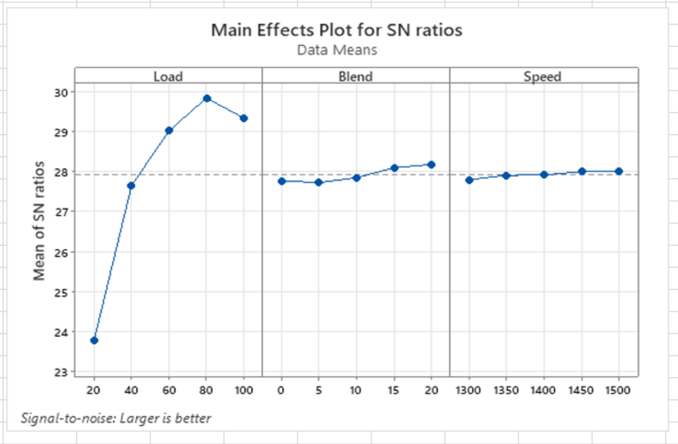

Fig. 1. Brake Thermal Efficiency Analysis.

B. Brake Specific Fuel Consumption

Brake specific fuel consumption (BSFC) is also one of the important parameters for diesel engine performance analysis. Brake Thermal Efficiency is the amount of fuel consumed per unit of power output. BSFC is typically expressed in units of mass per unit of power output (e.g., grams per kilowatt- hour) and is derived from measurements of fuel flow rate and brake power. In diesel engines, minimizing BSFC is indirectly proportional to achieving optimal fuel efficiency, as lower BSFC values indicate that the engine is utilizing fuel more effectively to generate power. With experimentation and Meticulous analysis of BSFC data, We can identify areas for improvement in engine design, combustion efficiency, and operating conditions, thereby enhancing overall fuel economy and reducing environmental impact.

Brake Specific Fuel Consumption has constantly reduced with the increase in blend percentage during experimentation. It has been reduced with increased loads and engine has reached highest efficiency at D80B20 blend. Brake Specific Fuel Consumption has shown significant rise with increasing loads. It was observed that Brake Specific Fuel Consumption is indirectly proportional to the Increasing loads of the Diesel Engine. The least BSFC achieved during experimentation is 0.31 when experimented with D85B15. Hence it shows that the optimal blend percentage for highest BTE is 20% of biodiesel. It is also known that the reduced BSFC results in higher efficiency therefore increasing BTE.

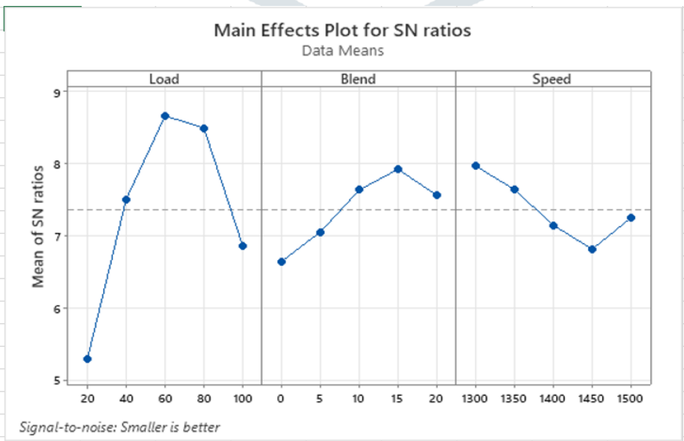

Fig. 2. Brake Specific Fuel Consumption Analysis.

C. Carbon Monoxide

Carbon monoxide (CO) emissions from diesel engines account for significant environmental concerns due to their adverse effects on air quality and human health. CO is a colorless, odorless gas produced during incomplete combustion of fossil fuels, including diesel. In diesel engines, CO is generated when there is insufficient oxygen available for complete combustion of the fuel.

CO emissions are reduced to 0.32 at D100 amongst various other blend percentages. It was also observed that CO emissions have significantly increased with increasing loads and reached highest at D90B10 at full load. This may be due to incomplete combustions but overall, it has decreased with increasing Biodiesel blend percentages.

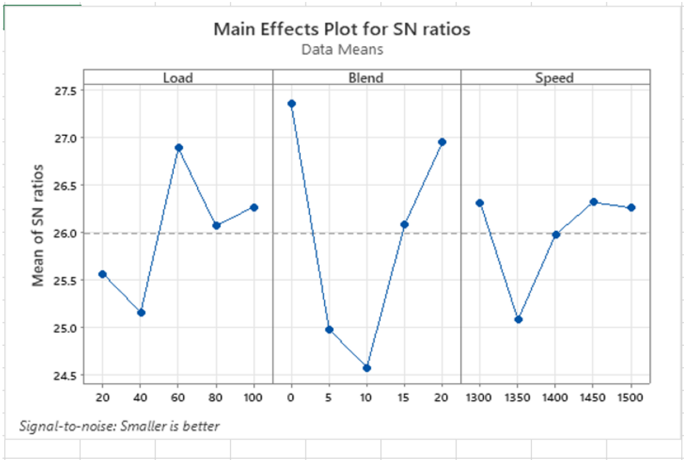

Fig. 3. Carbon Monoxide emission Analysis

D. Carbon Dioxide

Carbon dioxide (CO_2) emissions from diesel engines constitute a significant contributor to environmental degradation and climate change. When diesel fuel undergoes combustion within an engine, CO_2 is released as a byproduct, contributing to the greenhouse effect and global warming. The accumulation of CO_2 in the atmosphere traps heat, leading to rising temperatures, altered weather patterns, and adverse impacts on ecosystems and human health. Diesel engines, prevalent in transportation, industrial, and commercial sectors, are major sources of CO2 emissions globally.

CO_2 emissions have been reduced to 0.32 during D100 at full load. CO_2 emissions have constantly increased with increasing biodiesel blend percentages. This proves that there is increased combustion with increasing loads and biodiesel blend percentages.

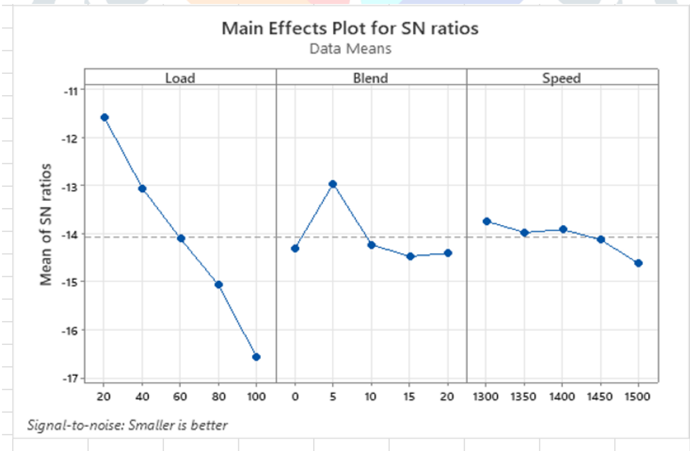

Fig. 4. Carbon Dioxide emission Analysis.

E. Nitrogen Oxide

Nitrogen oxides (NO_x) are a group of highly reactive gases composed of nitrogen and oxygen, formed primarily during the combustion process in diesel engines. These pollutants are notorious for their adverse effects on the environment and human health. NO_x emissions contribute to the formation of ground-level ozone and smog, leading to respiratory issues and exacerbating respiratory conditions such as asthma. Nitrogen oxide is also said to be one of the major contributors to acid rain. Hence it is important to mitigate the emissions in order to contribute to a green world. The reason for NO_x emissions can be high combustion temperatures and fuel compositions. To address the NO_x emissions. Many techniques such as exhaust gas recirculation(EGR) have been introduced.

NO_x was reduced to 260 ppm when experimented with D90B10 at 20% load. The emissions have been constantly rising with the increasing load. The emission reached a maximum of 1030 ppm when experimented with D15B5 at full load. The emissions are not always increasing with increased blend percentages but have shown a constant rise with increased loads.

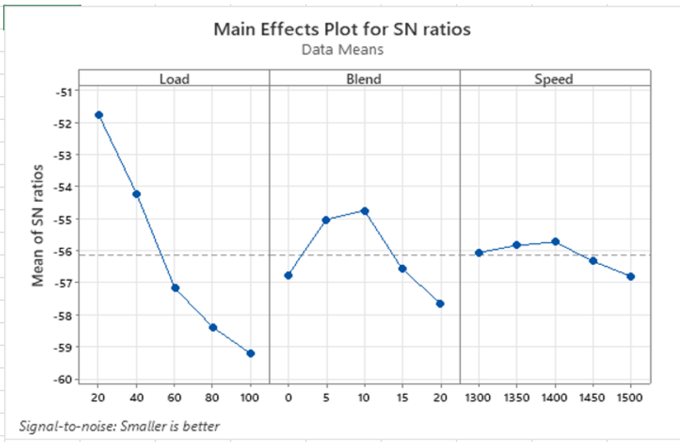

Fig. 5. Nitrogen Oxide emission Analysis.

F. Hydrocarbons

Hydrocarbons emitted from diesel engines represent a significant environmental concern due to their adverse effects on air quality and human health. These organic compounds, released as unburned fuel or partially combusted byproducts, contribute to the formation of ground-level ozone and smog, exacerbating respiratory issues and cardiovascular diseases. In addition to their direct health impacts, hydrocarbons participate in photochemical reactions in the atmosphere, leading to the formation of fine particulate matter (PM2.5) and volatile organic compounds (VOCs), which are associated with respiratory ailments and contribute to global warming.

HC emissions have shown a significant increase with increasing loads. The least recorded HC emissions from diesel engines is 26ppm when experimented with D80B20 at 20% load. Hence with increasing blend percentages HC emissions have been significantly reduced.

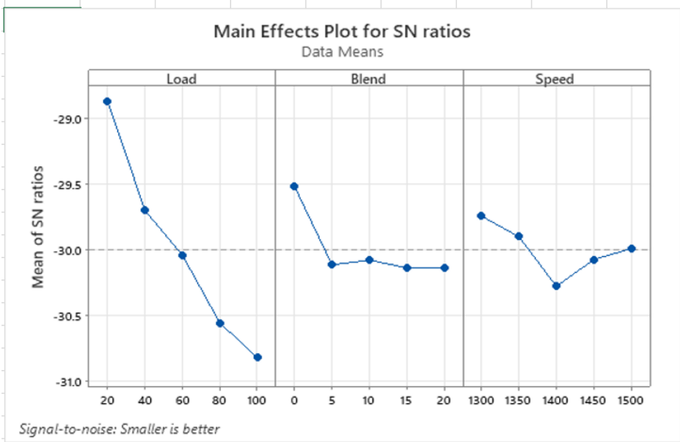

Fig. 6. Hydro Carbon emission Analysis.

G. Summary

The B20 blends have shown an increase in efficiency by 3% and significantly reduced the emissions of various harmful gases such as HC by 3 ppm, NO_x by 130 ppm , CO by 0.003%.

Performance parameters such as BTE have increased with increasing blend percentages and BSFC have reduced with increasing blend percentages. The optimal performance of the diesel engine was achieved with B20 biodiesel blend. Harmful emissions have also been reduced with an increase in blend percentages. D80B20 blend is the optimal blend percentage for performance and emissions of a diesel engine.

IV. CONCLUSIONS

- Taguchi technique of Design of Experimentation (DOE) suggested L(Orthogonal Array (OA), which has significantly optimized the experimental trials providing optimal parameters to yield highest efficiency while mitigating the emissions. Confirmation test has been carried out where parameters such as BTE, BSFC, CO and CO2 have shown a little deviation up to 10%. NOx and HC have shown a deviation of about 40%.
- The multi-objective optimization technique of gray relational analysis (GRA) was employed to determine the most optimal combination of parameters. It was determined that the ideal combination of input parameters consists of IA19, CR18, B20, and operating at 100% load. The parameters are said to yield the highest efficiency.

- The experimental analysis revealed a slight increase in Brake Thermal Efficiency (BTE) of approximately 2%, accompanied by a 3% decrease in Brake Specific Fuel Consumption (BSFC).The Exhaust Gas Temperature (EGT) increased up to 3%, while Carbon Dioxide (CO_2) emissions showed a slight increase of 0.86%.Carbon Monoxide (CO) emissions decreased by 0.029%, Nitrogen Oxide (NO_x) emissions increased by 6%, and Hydrocarbon (HC) emissions increased by 10 parts per million (PPM) compared to baseline diesel at full load.

Abbreviations

BTE, Brake Thermal Efficiency; BSFC, Brake Specific fuel consumption; EGT, Exhaust Gas Temperature; CO2, Carbon Dioxide; NOx, Nitrogen Oxides; CO, Carbon Monoxides; SFC, Specific fuel consumption; IC, Internal Combustion; CI, Combustion Ignition; CR, Compression Ratio; IT ,Injection Timing; IP, Indicated Pressure; PPM, parts per million; DOE, Design of Experiment; OA, Orthogonal array.

V. Acknowledgment

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