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Parametric Optimization of Emission and Performace Characteristics of Ci Engine Fueled with Hydrogen-Enriched Microalgae Biodiesel Using Taguchi

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Abstract: CI engine combustion, performance, and emissions are impacted significantly by injection parameters such as Injection Angle, EGR, and Load. The emission and performance characteristics of a single four-stroke cylinder CRD engine fueled with micro algae biodiesel blends of 30% (MA30H2) and flow rate of hydrogen 7lpm. The investigation is carried out for three distinct injection advance angle 15°, 20°, 25°, EGR 0%, 10%, 20% and applied loads on engine 0N, 6N, 12N, 18N, 21N, 24N. From the results of experimentation, input parameters are optimized using Taguchi method. The analytical results indicates that Injection Angle has major impact on minimizing CO, HC and BSFC, Load has significant impact on minimizing NOx, CO_2 and maximizing BTE. EGR has minimal impact on the emission and performance characteristics. The optimal parameters Injection Angle, Load and EGR vary for all the characteristics.

Keywords: - Diesel engine · Microalgae Biodiesel · Hydrogen · Injection angle, Taguchi

1. Introduction

Alternate fuels are crucial for several reasons, especially as we confront environmental and energy challenges. The key points highlighting their importance are Environmental Impact, Energy Security, Sustainability, Economic Benefits, Health Benefits, Technological Advancement, and Global Responsibility. In summary, alternate fuels play a pivotal role in creating a more sustainable, secure, and healthy energy future [1-2]. Their adoption is crucial for addressing the pressing environmental and economic challenges of our time. Hydrogen-enriched microalgae biodiesel is a fascinating and innovative area in biofuel research [5-7]. Researchers are exploring various methods to make hydrogen-enriched microalgae biodiesel more viable, focusing on optimizing the growth of microalgae, improving hydrogen production methods, and enhancing the overall efficiency of the process. Hydrogen-enriched microalgae biodiesel represents a cuttingedge approach to creating more sustainable and efficient biofuels. While there are significant potential benefits, ongoing research and development are crucial for addressing current challenges and making this technology commercially feasible [9-11].

The Taguchi method is a robust approach developed by Japanese engineer and statistician Genichi Taguchi for improving quality and performance in manufacturing and other processes. In practice, the Taguchi method involves using statistical techniques to identify the best settings for a process, leading to improved quality and reduced costs. It's widely used in various industries, including manufacturing, engineering, and product development [13-14].

2. Literature Review

S. H. Al-lwayzy etal [3]. This work investigates the use of microalgae biodiesel from *Chlorella Protothecoides* (MCP-B) as alternative fuel for Compression Ignitions (CI) engines. The results showed that MCP-B100 produces less emission compared to PD.

F. M. Hossain *et al.*,[4] This research used five different chemical groups found in microalgae HTL biocrude to design a surrogate fuel.. Experimental results showed that without significantly deteriorating engine performance, lower particulate mass, particulate number and CO emissions were observed with a penalty in NOx emissions for all surrogate blends compared to those of the reference diesel.

G. Tüccar etal [6] Microalgae biodiesel was blended with diesel fuel with the volumetric ratio of 5%, 10%, 20% and 50%. The results showed that, although microalgae biodiesel caused a slight reduction in torque and brake power values, the emission values of the engine using microalgae biodiesel were improved.

B. D. Wahlen *et al.*,[8] Analysis of exhaust emissions (hydrocarbon, CO, CO_2, O_2, and NOx) revealed that all biofuels produced significantly less CO and hydrocarbon than petroleum diesel. Surprisingly, microalgae biodiesel was found to have the lowest NOx output, even lower than petroleum diesel. The results are discussed in the context of the fatty acid composition of the fuels and the technical viability of microbial biofuels as replacements for petroleum diesel.

Kanth S, etal [10] The biodiesel is derived from the honge oil and mixed with diesel fuel by 20% (v/v). Thereafter, hydrogen at different volume flow rates (10 and 13 lpm) is introduced into the intake manifold. Compare to diesel, the BTE increased by 2.2% and 6% less fuel consumption for the HB20 + $13H_2$ blend. Further, reduction in the emission of exhausts gases like CO and HC by 21% and 24%, respectively, are obtained.

Rajak U, etal [12] The results showed that with the addition of hydrogen (15%), NO_X emission increased by 21.3%, BSN emission decreased by 22.89%, specific fuel consumption decreased by 18.3% and BTE improved by 0.95% at higher engine loads. Moreover, with the addition of hydrogen energy, increases in PM, NO_X, and the summary of emission were observed.

Kanth S, etal [15] Results indicate that the sample 'RB10+H_2' provides 3.32% higher BTE and reduces the fuel consumption by 13% as diesel fuel. The blend RB10+H_2 attributes a maximum cylinder pressure of

68.7 bar and a peak HRR value of 49 J/ºCA. Further, compared to diesel, RB10+H_2 blend emits lower CO, HC, and smoke opacity by 17%, 22%, and 16%, respectively. However, an almost 12% increase of nitrogen oxides for the RB10+H_2 blend is observed. However, with advanced injection timing and higher opening injection pressure, NOx emissions is slightly increased.

3. Experimentation

In the current research work, experiments are performed on a single four-stroke cylinder CRDI engine fueled with micro algae biodiesel blends of 30% (MA30H2) and flow rate of hydrogen 7lpm. The investigation is carried out for three distinct injection advance angle 15°, 20°, 25°, EGR 0%, 10%, 20% and applied loads on engine 0N, 6N, 12N, 18N, 21N, 24N. The emission and performance characteristics are determined.

Table 1: Physio-chemical properties of Microalgae Biodiesel

Fuel Property	Biodiesel ASTM(D6751)	Diesel Fuel ASTM(D975)	Mahua Methyl Ester (MME)
Density (Kg /m3)	860–900	820–860	876
Cetane Number	Min.47	40–55	46
Calorific Value(Kj/Kg)	-----	42,000–46,000	38,945
Kinematic Viscosity @ 40°C (mm^2 /S)	1.9–6.0	2.6–5.7	5.32
Flash Point (°C)	Min.130	60–80	178

Table 2: Specifications of the Test Rig

S.No	Description	Specifications
1	Make	Mahindra and Mahindra
2	Engine Capacity (cc)	625
3	Number of cylinders	1
4	Application	Automotive (Multi-speed)
5	Number of Strokes	4
6	Compression Ratio	18:1
7	Bore (mm)	93.0 to 93.018
8	Stroke Length (mm)	92
9	Ignition	Compression Ignition
10	Max. Power @ RPM	9 HP @ 3000 RPM
11	Max. Torque @ RPM	30 NM @ 1800 RPM
12	Cooling System	Water Cooled

CRDI engines constitutes of high-pressure fuel pump, common piping, rail pressure sensor, pressure regulator, and common piping. The pressure sensor connects to the electronic control unit (ECU). Charging is managed by a water-cooled eddy current dynamometer, while a crankshaft angle sensor tracks crankshaft rotation. Cylinder pressure is monitored using a piezoelectric pressure transducer mounted on the cylinder head. A data acquisition system gathers pressure signals to analyze combustion parameters like the heat release rate. Temperatures of inlet and outlet water, fuel, engine oil, intake air, and exhaust gases are measured with type K thermocouples. Exhaust gas temperature (EGT) is measured with a pair of thermoelectric sensors near the cylinder exhaust pipe and a smoke meter. Additionally, hydrogen supply components consist of pressure regulators, flow meters, hydrogen cylinders, flow control valves, flame arresters, and fire traps.

Figure 1. Experimental Setup of CRDI duel fuel Engine

4. Results And Discussions

Emissions such as carbon monoxide (CO), carbon di oxide (CO_2), nitrogen oxides (NOx) and hydrocarbons (HC) are found using an AVL analyser. Performance characteristics such as Brake Thermal Efficiency (BTE) and Brake Specific Fuel Consumptions (BSFC) are also determined.

The input parameters Injection Angle, EGR and Load are optimized for lesser emissions of CO, CO_2, HC, NOx, lesser BSFC and larger BTE using Taguchi Method.

Table 3: Taguchi Design Summary

Taguchi Array	L9(3^3)
Factors	3
Runs	9

4.1 Optimization of Parameters using Taguchi Analysis

Smaller is better

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the smaller-is-better S/N ratio using base 10 log is:

$S/N = -10*\log(\Sigma(Y^2)/n)$

where Y = responses for the given factor level combination and n = number of responses in the factor level combination.

Larger is better

The signal-to-noise (S/N) ratio is calculated for each factor level combination. The formula for the larger-is-better S/N ratio using base 10 log is:

$S/N = -10*\log(\Sigma(1/Y^2)/n)$

where Y = responses for the given factor level combination and n = number of responses in the factor level combination.

4.2 Emission characteristics

4.2.1 Carbon monoxide (CO)

Table 4: Response Table for Signal to Noise Ratio for minimizing CO%

Smaller is better

Level	**Injection Angle (deg)**	**EGR (%)**	**Load (N)**
1	38.05	37.02	37.32
2	40.31	37.99	37.99
3	33.98	37.32	37.02
Delta	6.33	0.97	0.97
Rank	1	2.5	2.5

The response tables are used to select the best level for each factor.

In the response table, first 3 rows contains the average signal-to-noise ratio for each factor level. Delta is the difference between the maximum and minimum average response (signal-to-noise ratio or standard deviation) for the factor. The Rank is the rank of each Delta, where Rank 1 is the largest Delta.

Injection Angle has Rank 1, that is, it is the most affecting parameter on CO%.

Table 5: Signal to Noise Ratio for CO%

Injection Angle (deg)	**EGR (%)**	**Load (N)**	**CO (%)**	**SNRA1**
15	0	12	0.014	37.0774
15	10	18	0.01	40
15	20	21	0.014	37.0774
20	0	18	0.01	40

20	10	21	0.01	40
20	20	12	0.009	40.9151
25	0	21	0.02	33.9794
25	10	12	0.02	33.9794
25	20	18	0.02	33.9794

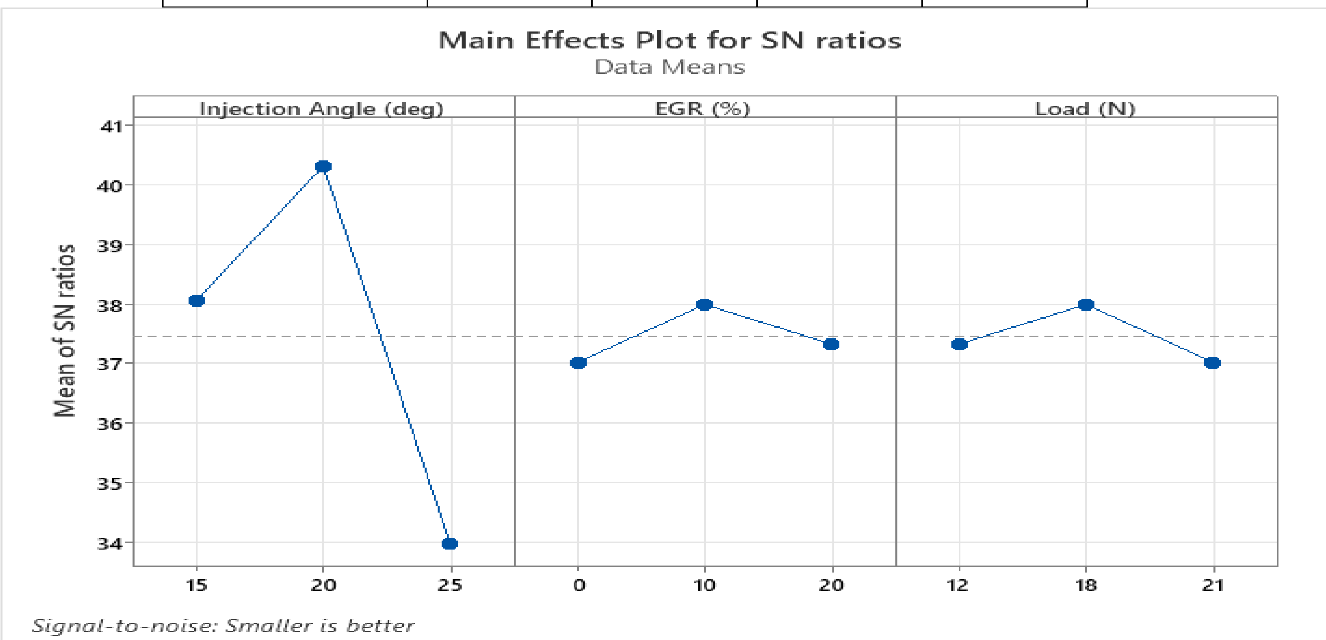

Figure 2. Optimal values of Injection angle, EGR and load for minimizing CO%

From the graph Main Effects Plot for SN ratios, the value of the parameter with high Mean of SN ratios is considered to be optimal.

The optimal parameters to minimize CO% are Injection Angle – 20deg, Load - 18N and EGR – 10%.

4.2.2 Carbon dioxide (CO_2)

Table 5: Response Table for Signal to Noise Ratios for minimizing CO_2%

Smaller is better

Level	Injection Angle (deg)	EGR (%)	Load (N)
1	-10.294	-10.570	-5.567
2	-9.930	-10.087	-11.268

3	-10.808	-10.375	-14.197
Delta	0.878	0.483	8.630
Rank	2	3	1

Load has Rank 1, that is, it is the most affecting parameter on CO_2%.

Table 6: Signal to Noise Ratio for CO_2%

Injection Angle (deg)	**EGR (%)**	**Load (N)**	**CO_2 (%)**	**SNRA3**
15	0	0	2	-6.0206
15	10	6	3.5	-10.8814
15	20	12	5	-13.9794
20	0	6	3.5	-10.8814
20	10	12	4.9	-13.8039
20	20	0	1.8	-5.1055
25	0	12	5.5	-14.8073
25	10	0	1.9	-5.5751
25	20	6	4	-12.0412

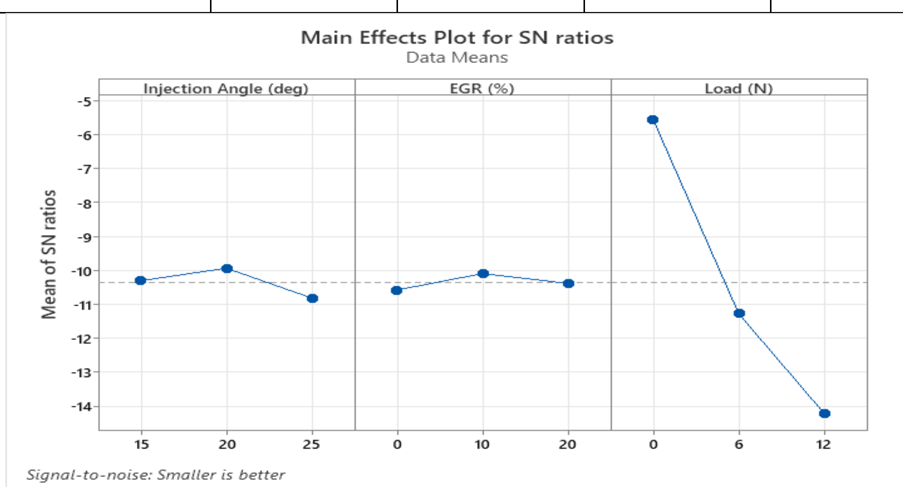

Figure 3. Optimal values of Injection angle, EGR and load for minimizing CO_2%

The optimal parameters to minimize CO_2% are Injection Angle – 20deg, Load - 0N and EGR – 10%.

4.2.3 Hydro Carbon (HC)

Table 7: Response Table for Signal to Noise Ratios for minimizing HC

Smaller is better

Level	Injection Angle (deg)	Load (N)	EGR (%)
1	-17.92	-23.16	-17.52
2	-18.08	-19.05	-20.97
3	-25.63	-19.43	-23.14
Delta	7.71	4.10	5.62
Rank	1	3	2

Injection Angle has Rank 1, that is, it is the most affecting parameter on HC (ppm).

Table 8: Signal to Noise Ratio for HC

Injection Angle (deg)	Load (N)	EGR (%)	HC (%)	SNRA2
15	0	0	8.5	-18.5884
15	6	10	7	-16.902
15	12	20	8.2	-18.2763
20	0	10	10	-20
20	6	20	10.3	-20.2567
20	12	0	5	-13.9794
25	0	20	35	-30.8814
25	6	0	10	-20
25	12	10	20	-26.0206

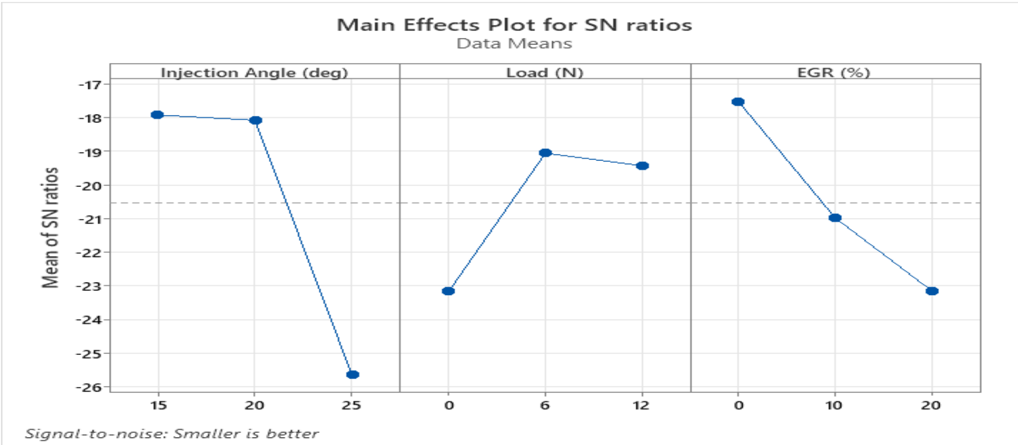

Figure 4. Optimal values of Injection angle, EGR and load for minimizing HC

The optimal parameters to minimize HC (ppm) are Injection Angle – 15deg, Load - 6N and EGR – 0%.

4.2.4 Nitrogen Oxide (NOx)

Table 9: Response Table for Signal to Noise Ratios for minimizing NOx

Smaller is better

Level	**Injection Angle (deg)**	**Load (N)**	**EGR (%)**
1	-54.10	-44.66	-58.03
2	-55.68	-58.46	-56.17
3	-56.61	-63.28	-52.20
Delta	2.51	18.62	5.83
Rank	3	1	2

Load has Rank 1, that is, it is the most affecting parameter on NOx (ppm).

Table 10: Signal to Noise Ratio for NOx

Injection Angle (deg)	**Load (N)**	**EGR (%)**	**NOx (ppm)**	**SNRA1**
15	0	0	250	-47.959
15	6	10	580	-55.269

15	12	20	900	-59.085
20	0	10	200	-46.021
20	6	20	750	-57.501
20	12	0	1500	-63.522
25	0	20	100	-40
25	6	0	1350	-62.607
25	12	10	2300	-67.235

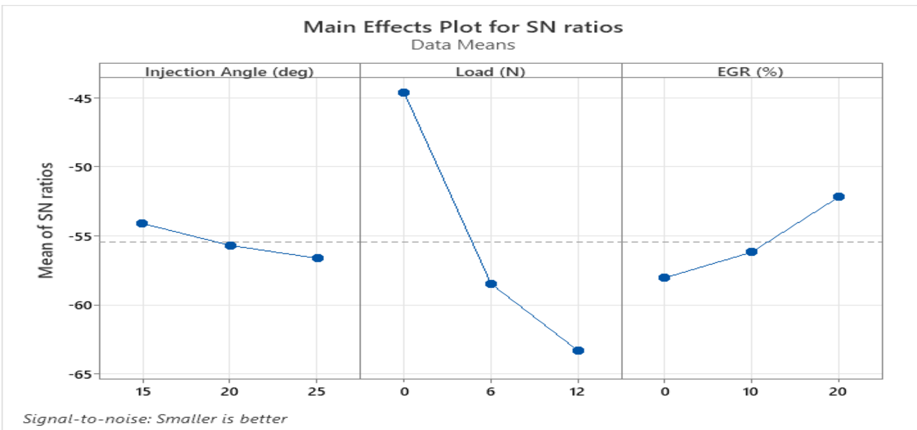

Figure 5. Optimal values of Injection angle, EGR and load for minimizing NOx

The optimal parameters to minimize NOx (ppm) are Injection Angle – 15deg, Load - 0N and EGR – 20%.

4.2.5 Brake Specific Fuel Consumption (BSFC)

Table 11: Response Table for Signal to Noise Ratios for minimizing BSFC

Smaller is better

Level	Injection Angle (deg)	Load (N)	EGR (%)
1	-47.66	-49.34	-48.71
2	-48.94	-48.80	-48.79
3	-50.17	-48.63	-49.27
Delta	2.50	0.72	0.56

Rank	1	2	3

Injection Angle has Rank 1, that is, it is the most affecting parameter on BSFC (g/Kw hr).

Table 12: Signal to Noise Ratio for BSFC

Injection Angle (deg)	Load (N)	EGR (%)	BSFC (g/kW hr)	SNRA1
15	18	0	250	-47.9588
15	21	10	240	-47.6042
15	24	20	235	-47.4214
20	18	10	280	-48.9432
20	21	20	290	-49.248
20	24	0	270	-48.6273
25	18	20	360	-51.1261
25	21	0	300	-49.5424
25	24	10	310	-49.8272

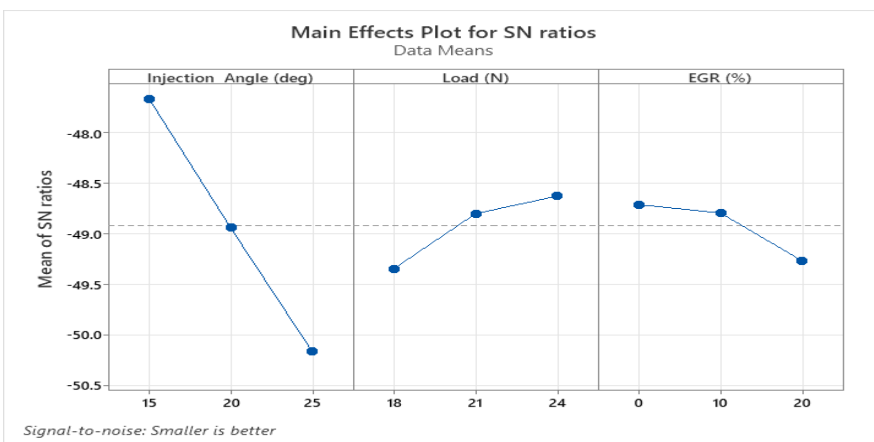

Figure 6. Optimal values of Injection angle, EGR and load for minimizing BSFC

The optimal parameters to minimize BSFC (g/Kw hr) are Injection Angle – 15deg, Load - 24N and EGR – 0%.

4.2.6 Brake Thermal Efficiency (BTE)

Table 13: Response Table for Signal to Noise Ratios for maximizing BTE

Larger is better

Level	Injection Angle (deg)	Load (N)	EGR (%)
1	28.81	27.94	28.80
2	29.13	28.84	28.62
3	28.05	29.22	28.57
Delta	1.08	1.28	0.23
Rank	2	1	3

Load has Rank 1, that is, it is the most affecting parameter on BTE (%).

Table 14: Signal to Noise Ratio for BTE

Injection Angle (deg)	Load (N)	EGR (%)	BTE (%)	SNRA1
15	18	0	25	27.9588
15	21	10	28	28.9432
15	24	20	30	29.5424
20	18	10	27	28.6273
20	21	20	28	28.9432
20	24	0	31	29.8272
25	18	20	23	27.2346
25	21	0	27	28.6273
25	24	10	26	28.2995

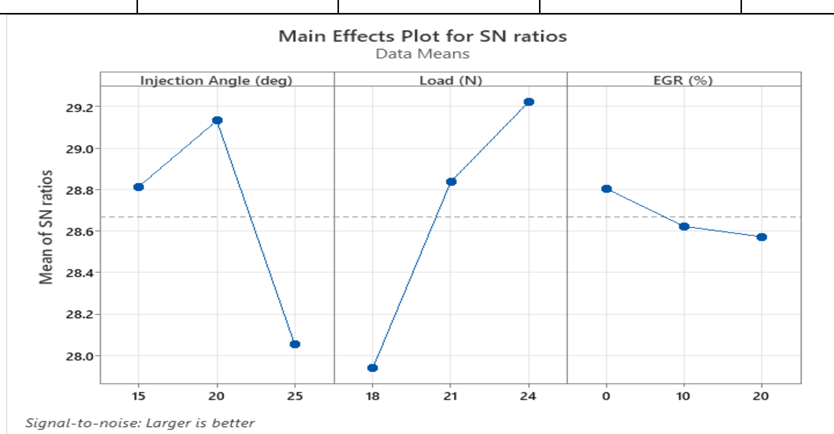

Figure 7. Optimal values of Injection angle, EGR and load for maximizing BTE

The optimal parameters to maximize BTE (%) are Injection Angle – 20deg, Load - 24N and EGR – 0%.

Conclusion

The experimentation is carried out for B 30 microalgae bio-diesel at various loads, injection angle before TDC and EGR with hydrogen flow rate of 7lpm. Taguchi method is used to optimize the parameters for obtained values. The results are as follows:

- The optimal parameters to minimize CO% are Injection Angle – 20deg, Load - 18N and EGR – 10%.
- The optimal parameters to minimize CO_2% are Injection Angle – 20deg, Load - 0N and EGR – 10%.
- The optimal parameters to minimize HC (ppm) are Injection Angle – 15deg, Load - 6N and EGR – 0%.
- The optimal parameters to minimize NOx (ppm) are Injection Angle – 15deg, Load - 0N and EGR – 20%.
- The optimal parameters to minimize BSFC (g/Kw hr) are Injection Angle – 15deg, Load - 24N and EGR – 0%.
- The optimal parameters to maximize BTE (%) are Injection Angle – 20deg, Load - 24N and EGR – 0%.

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