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Statistical Analyses of Energy and Exergy of a diesel engine using diesel and biogas in dual fuel mode by Taguchi method

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Abstract

In this research, the first law and second law of thermodynamics were applied to analyze the quantity and quality of energy and exergy in a direct injection compression ignation engine using diesel and biogas in dual fuel mode of operation. The energy and exergy for the engine were calculated and analyzed by Taguchi method of optimization for both the modes of operation. The results of dual fuel mode offered similar energetic performance as diesel fuel. It was found that, similar trends were followed in the exergetic performance parameters and the energetic performance parameters. The analyses were based on energy and exergy distribution, exergy efficiency and different availabilities of dual fuel mode with the varying load and compared with the corresponding values of diesel mode.

Keywords:

First keyword;EnergySecond keyword;Exergy
Third keyword;Taguchi method
Fourth keyword;MINITAB software,
Fifth keyword; Diesel engine,
Sixth Keyword; Biogas

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1. Introduction

Energy-based performance analysis of the engine is based on first law of thermodynamics. We find some losses during the energy conversion in 1st law of analysis and some part of energy is being available. Exergy-based performance analysis of the engine is based on the second law of thermodynamics that overcomes the limit of energy-based analysis. Exergy destruction is the source of performance loss which is a measure of irreversibility.Therefore, an exergy analysis assessing the magnitude of exergy destruction identifies the location, the magnitude and the source of thermodynamic inefficiencies in an engine. This provides useful information to improve the overall efficiency and cost effectiveness of an engine. In this study, energy and exergy analyses of the engine were carried out by Taguchi method using MINITAB software.

2. Experimental Methodology

2.1Experimental Setup

The experimental setup consists of a single-cylinder, direct injection diesel engine, dynamometer, fuel supply and metering systems, water supply systems and measuring devices as shown in the Figure 1. The specifications of the engine are shown in Table 1.It is provided with necessary instruments for airflow, fuel flow, temperatures and load measurements. The engine and dynamometer is cooled by water cooling system. There is only one modification at intake manifold of biogas and air providing a 'T' joint. The set-up consists of air box, fuel tank, manometer, fuel measuring unit, air and fuel flow measurements and piezometer unit. Water meters are provided for flow measurement of cooling water.

Figure1. Experimental set up

Table 1. Specifications of the engine

Parameters	Specifications
Engine type	DICI
General details	Single Cylinder, water cooled
Stroke	4-stroke
Cylinder diameter	85mm
Stroke length	110mm
Orifice diameter	20mm
Compression ratio	17.5
Rated output	3.5kW at 1500rpm

2.2Experimental Procedures

The diesel engine was allowed to run for few minutes at 1500 rpm under no-load condition. The water flow was regulated for the engine, dynamometer and calorimeter. For the experiment, load of 1.75kg to 15kg were set for engine operation.

The following data were recorded at every load condition for analysis by different instruments.

1) Volume of diesel fuel consumption by the engine. This was made possible through of a fuel metering system consisting of burettes, flexible rubber fuel tubes and two shut-o taps. The components were mounted on a board measuring 1 m x 1m.
2) Volume of biogas consumption by the engine. The biogas flow to the engine is measured by a biogas flow meter.
3) Volume of cooling water circulated. Water flow meter is fitted in the pipe line for the measurement of flow of water to engine.
4) Volume of air consumption by the engine. The air flow to the engine is monitored by passing the intake air through an air box with orifice meter and a U- tube manometer.
5) Engine speed at different loads. Digital Tachometer was used to measure the engine speed.
6) Engine load. The engine load was measured by a rope brake dynamometer.
7) Temperatures. Thermocouples were fitted at relevant positions for the measurement of temperatures at the required positions.

For the biogas dual fuel operation, biogas flow was opened up slowly from the balloon and allowed the biogas to reach the inlet manifold of air flow. The air- biogas mixture was sucked into the cylinder to take part in the dual fuel combustion. The flow of biogas was regulated manually till the engine shows misfire and this was the maximum biogas flow for the dual fuel operation. The engine speed was increased due to the addition of extra chemical energy from biogas. The quantity of diesel was regulated to maintain a constant level of power and speed from both diesel and dual fuel modes at different load conditions.

2.3 Analysis Procedure

The results of the diesel fuel mode and dual-fuel mode were analyzed using the laws of thermodynamics. It provides proper informations for distribution of energy supplied by fuel in to power, cooling water and exhaust gas [6]. The energy that is utilized or destroyed is quantified through availability analysis. This analysis gives the exact amount of biogas and diesel composition which should be maintained to extract the maximum amount of energy from the fuel energy supplied. Therefore, the first law (Energy) along with the second law (Exergy) is applied to the engine for analysis. The study discusses both the energy and exergy balance of the diesel and dual fuel operations.

2.3.1 Energy analysis

According to the First Law of thermodynamics, the energy supplied in a system is conserved in its different processes and components[9].In a CI engine, the fuel energy supplied (Q_{in}) is transferred in its different processes, viz. Shaft power (P_s), Energy in cooling water (Q_{cw}), Energy in exhaust gas (Q_{eg}) and Uncounted energy losses (Q_{un}) in the form of friction, radiation, heat transfer to the surroundings etc. These different forms of energies are calculated according to the following analytical expressions [4].The amount of energy evaluated on the basis of the first law of thermodynamics is stated below:

1) The input energy (Q_{in}) is the amount of energy content in the fuel and it is given by Eq.1 and Eq.2.
For a diesel mode,
$Q_{in} = [m_d \times LHV_d]$ kW Eq. 1
Where, m_d - Mass flow rate of diesel in kg/sec, LHV_d - Low heating value of diesel (KJ/kg)
For a dual fuel mode,
$Q_{in} = [(m_d \times LHV_d) + (m_g \times LHV_g)]$ kW Eq.2
Where, m_g - Mass flow rate of biogas in kg/sec, LHV_g - Low heating value of biogas (KJ/kg)

2) The energy converted to shaft output is given in Eq.3
$P_s = 2\pi NT/60{,}000$ kW Eq.3
Where, N - Revolution per minute, T – Torque transmitted in N-m

3) The heat loss from the engine block to the cooling water is given by Eq.4
$Q_{cw} = [m_{cw} \times c_{pw} \times (T_2 - T_1)]$ kW Eq.4
m_{cw} - Mass flow rate of the cooling water passing through the engine jacket in Kg/sec, c_{pw} - Specific heat of water in KJ/kgK, T_1 - Cooling water inlet temperature in K, T_2 - Cooling water outlet temperature in K

4) Mass of exhaust gas is given by Eq.5 and Eq.6
$m_{eg} = m_a + m_d$ (for diesel fuel) Eq.5
$m_{eg} = m_a + m_d + m_g$ (for dual fuel) Eq.6
Where, m_a - Mass flow rate of air in kg/sec, m_g - Mass flow rate of biogas in kg/sec

5) The energy wasted in form of exhaust gas losses is evaluated by Eq.7
$Q_{eg} = [m_{eg} \times c_{peg} \times (T_3 - T_4)]$ kW Eq.7

Where, c_{peg} – Specific heat of exhaust gas in KJ/kgK, T_3 - Exhaust gas temperature from engine in K, T_4 - Ambient Temperature in K

For a more precise thermodynamic analysis, the specific heat of exhaust gas (c_{peg}) is calculated from the energy balance of the exhaust gas calorimeter.

6. Amount of the uncounted losses is evaluated by Eq.8
$Q_u = [Q_{in} - (P_s + Q_{cw} + Q_{eg})]$ kW Eq.8

2.3.2 Exergy analysis:

Exergy analysis helps to find the means of reducing the energy loss and to improve the performance of the engine in terms of efficiency and power output. The second law analysis indicates various forms of energy that have different levels of ability to do useful mechanical work, which is defined as availability.The availability can be described as the ability of the supplied energy to perform a useful amount of work[2]. In the C.I engine the chemical availability of fuel (A_{in}) supplied is converted into different types of exergy, viz., shaft availability (A_s), cooling water availability (A_{cw}), exhaust gas availability (A_{eg}) and destructed availability (A_d) in the form of friction, radiation, heat transfer to the surroundings, operating auxiliary equipments, etc. These forms of energies are calculated according to the following analytical expressions [5].

1. Chemical availability of fuel or input availability is given by Eq.9 and Eq.10.
For diesel mode,
$A_{in} = [1.0338 \times m_d \times LHV_d]$ kW Eq.9

For dual mode,

$A_{in} = [1.0338 \text{ x } m_d \text{ x } LHV_d] + [0.985 \text{ x } m_g \text{ x} LHV_g]$ kW Eq.10

2. Shaft availability is given by Eq.11

A_s = Brake power output in kW Eq.11

3. Availability transferred to cooling water is given by Eq.12

$A_{cw} = [Q_{cw} - \{(m_{cw}/3600) \text{ x } c_{pw} \text{ x } T_4 \text{ x } \ln (T_2/T_1)\}]$ kW Eq.12

4. Availability transferred to the exhaust gases is given by Eq.13

$A_{eg}= Q_{eg} + [(m_{eg}/3600) \text{ x } T_4 \text{ x } \{c_{peg} \text{ x } \ln (T_4/T_3) - R_{eg} \text{ x } \ln (P_o/P_{eg})\}]$ kW Eq.13

The exhaust gas constant (R_{eg}) is estimated from the energy balance of the exhaust gas calorimeter and the products of complete combustion of the diesel fuel.

5. Destroyed availability is given by Eq.14

$A_d= [A_{in} - (A_s+ A_{cw}+ A_{eg})]$ kW Eq.14

6. The exergy efficiency is given by Eq.15

$\eta_e= 1 - (A_d /A_{in})$ Eq.15

3. Results and Discussions

3.1Energy Analysis

The energy variations of diesel and dual fuel mode are represented in Figure 2 and Figure 3 respectively. Figure 2 shows the input fuel energy is more in diesel fuel mode. The uncounted energy decreased with the increase of load.Figure 3 shows the dual fuel mode required higher input energy than the diesel mode due to the poor combustion and low heating value of biogas. In the process, a higher shaft power was resulted at higher engine loads.

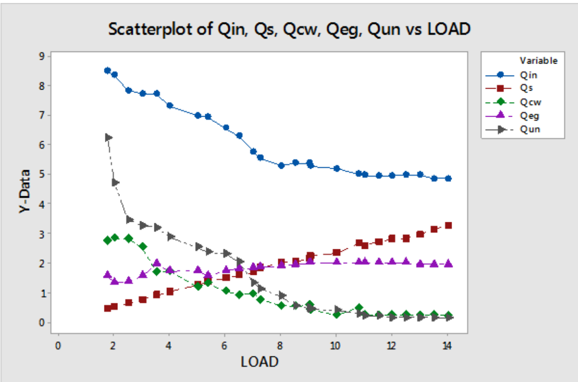

Figure 2Variation of Energy Distributions with the Load (diesel mode)

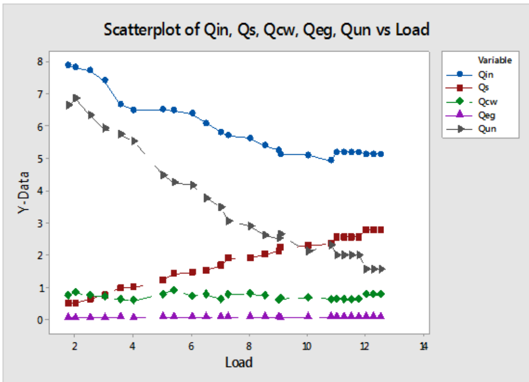

Figure 3Variation of energy distributions with the load (dual mode)

3.1.1 Input Energy Analysis

In diesel mode of operation, using an optimum set of parameters, which was achieved by response curve analysis, was used for prediction by Minitab software shown in Figure 4. The highest performance at set of engine load 1.75 kg, mass of fuel consumed 0.000126 kg/s and mass of air consumed 0.00952 kg/s, which are optimum parameter setting for highest input energy. Engine performance is mostly influenced by engine load and is least influenced by mass of air consumed. Minitab software for Taguchi method of optimization was suggested engine load 1.75 kg and S/N ratio was 17.51 for optimum set of parameter for input energy of

8.486 kW shown in Table 2. From the experimental data it was also found that at engine load 1.75 kg, mass of fuel consumed 0.000126 kg/s and mass of air consumed 0.00952 kg/s, input energy is 8.486 kW.
In dual mode of operation, the highest performance at set of engine load 1.75 kg, mass of fuel consumed 0.000220 kg/s and mass of air consumed 0.000843 kg/s, which are optimum parameter setting for highest input energy shown in Figure 5. Minitab software for Taguchi method of optimization was suggested engine load of 1.75 kg and S/N ratio was 16.87shown in Table 3 for optimum set of parameter for input energy of 7.869 kW. From the experimental data it was also found that at engine load 1.75 kg, mass of fuel consumed 0.000220 kg/s and mass of air consumed 0.000539 kg/s is 7.869 kW.

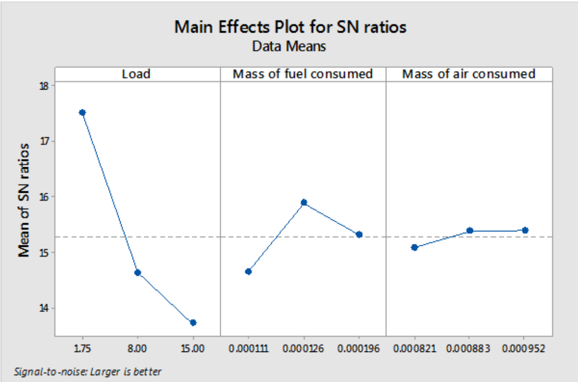

Figure 4 Main effect plot for SN ratio (diesel mode)

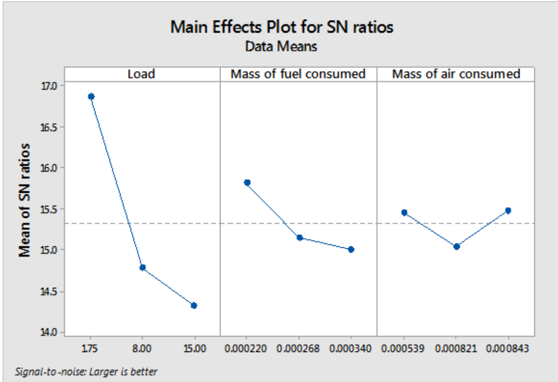

Figure 5. Main effect plot for SN ratio (dual mode)

Table 2. Response Table for Signal to Noise Ratios for Input Energy (diesel mode)
Larger is better

Level	Load	Mass of fuel consumed	Mass of air consumed
1	17.51	14.65	15.09
2	14.63	15.89	15.38
3	13.72	15.32	15.39
Delta	3.79	1.24	0.30
Rank	1	2	3

Table 3. Response Table for Signal to Noise Ratios for Input Energy (dual mode)
Larger is better

Level	Load	Mass of fuel consumed	Mass of air consumed
1	16.87	15.82	15.45
2	14.78	15.15	15.04
3	14.32	15.00	15.48
Delta	2.55	0.81	0.44
Rank	1	2	3

3.1.2 Unaccounted Energy Analysis

In diesel mode of operation, using an optimum set of parameters, which was achieved by response curve analysis, was used for prediction by Minitab software shown in Figure 6. The performance at set of engine load 1.75 kg, mass of fuel consumed 0.000126 kg/s and input energy 5.275 kW, which are optimum parameter setting for lowest unaccounted energy. Engine performance is mostly influenced by engine load and is least influenced by mass of fuel consumed. Minitab software for Taguchi method of optimization was suggested engine load 1.75 kg and S/N ratio was – 10.4256 shown in Table 4 for optimum set of parameter for unaccounted energy of 3.461 kW. From the experimental data it was also found that at engine load 1.75 kg, mass of fuel consumed 0.000126 kg/s, unaccounted energy is 6.265 kW.
In dual mode of operation, using an optimum set of parameters, which was achieved by response curve analysis, was used for prediction by Minitab software shown in Figure 7. The performance at set of engine load 1.75 kg, mass of fuel consumed 0.000220 kg/s and input energy 5.625 kW, which are optimum parameter setting for lowest unaccounted energy. Engine performance is mostly influenced by engine load and is least influenced by mass of fuel consumed. Minitab software for Taguchi method of optimization was suggested engine load 1.75 kg and S/N ratio was – 14.723 shown in Table 5 for optimum set of parameter for unaccounted energy of 6.318 kW. From the experimental data it was also found that at engine load 1.75 kg, mass of fuel consumed 0.000220 kg/s, unaccounted energy is 6.345 kW.

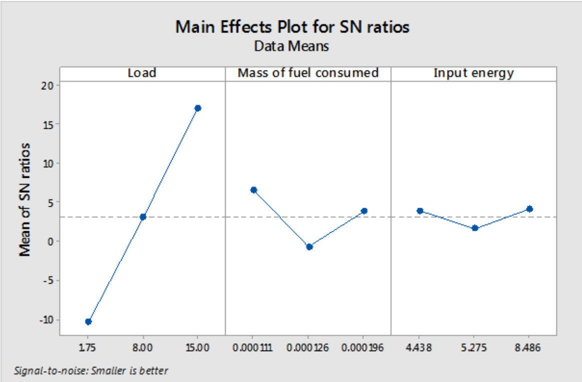

Figure 6. Main effect plot for SN ratio (diesel mode)

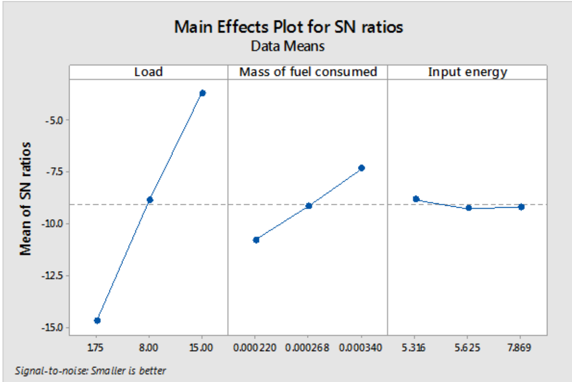

Figure 7. Main effect plot for SN ratio (dual mode)

Table 4. Response Table for Signal to Noise Ratios for Unaccounted Energy (diesel mode) Smaller is better

Level	Load	Mass of fuel consumed	Input energy
1	-10.4256	6.4965	3.8256
2	2.9618	-0.7675	1.6055
3	16.9697	3.7769	4.0749
Delta	27.3953	7.2640	2.4694
Rank	1	2	3

Table 5. Response Table for Signal to Noise Ratios for Unaccounted Energy (dual mode) Smaller is better

Level	Load	Mass of fuel consumed	Input energy
1	-14.732	-10.813	-8.846
2	-8.894	-9.166	-9.287
3	-3.712	-7.359	-9.205
Delta	11.019	3.453	0.440
Rank	1	2	3

3.2 Exergy Analysis

The exergy variations of diesel and dual fuel mode are represented in Figure 8 and Figure 9 respectively. Due to low heating value of biogas, the combustion temperature of dual fuel mode was reduced. This caused a reduction in both the fuel availability and work output of the dual fuel modes. . It affects the decrease of second law efficiency and an increase in the percentage of fuel availability destroyed in the form of irreversibility. At lower loads, the fuel availability was decreased. When load was increased, the rate of fuel energy increased to produce higher shaft output. In the process, higher shaft availability was resulted at higher engine loads.

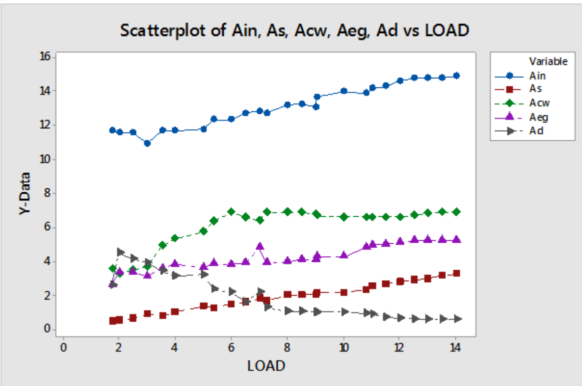

Figure 8.Availability Distributions with Fuel input as function of Load (diesel mode)

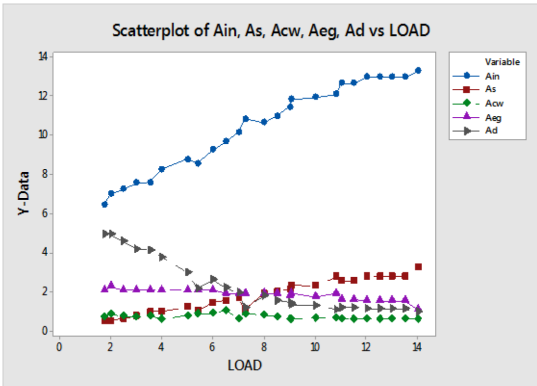

Figure 9.Availability Distributions with Fuel input as function of Load (dual mode)

3.2.1 Fuel Exergy Analysis

In diesel mode of operation, using an optimum set of parameters, which was achieved by response curve analysis, was used for prediction by Minitab software shown in Figure 10. The performance at set of engine load 15 kg and mass of fuel consumed 0.000111 kg/s, which are optimum parameter setting for highest fuel exergy. Engine performance is mostly influenced by engine load and is least influenced by mass of fuel consumed. Minitab software for Taguchi method of optimization was suggested engine load 15 kg and S/N ratio was 23.31 shown in Table 6 for optimum set of parameter for fuel exergy of 14.861 kW.

In dual mode of operation, using an optimum set of parameters, which was achieved by response curve analysis, was used for prediction by Minitab software shown in Figure 11. The performance at set of engine load 15 kg and mass of fuel consumed 0.000340 kg/s, which are optimum parameter setting for highest fuel exergy. Engine performance is mostly influenced by engine load and is least influenced by mass of fuel consumed. Minitab software for Taguchi method of optimization was suggested engine load 15 kg and S/N ratio was 22.27 shown in Table 7 for optimum set of parameter for fuel exergy of 13.251 kW.

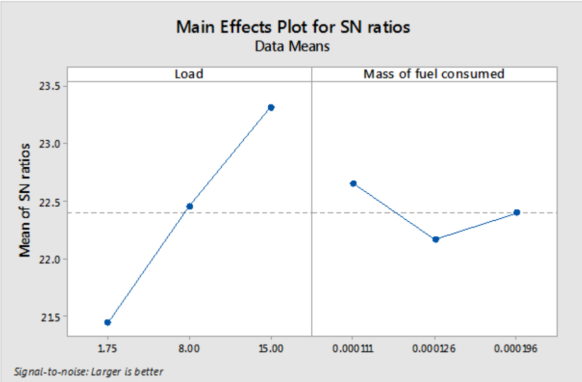

Figure 10. Main effect plot for SN ratio (diesel mode)

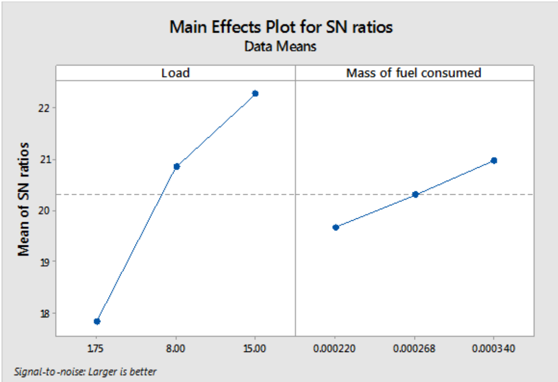

Figure 11. Main effect plot for SN ratio (dual mode)

Table 6. Response Table for Signal to Noise Ratios for Fuel Exergy (diesel mode)
Larger is better

Level	Load	Mass of fuel consumed
1	21.44	22.65
2	22.45	22.16
3	23.31	22.40
Delta	1.87	0.49
Rank	1	2

Table 7. Response Table for Signal to Noise Ratios for Fuel Exergy (dual mode)
Larger is better

Level	Load	Mass of fuel consumed
1	17.82	19.66
2	20.84	20.29
3	22.27	20.97
Delta	4.45	1.31
Rank	1	2

3.2.2 Destroyed availability Analysis

In diesel mode of operation, using an optimum set of parameters, which was achieved by response curve analysis, was used for prediction by Minitab software shown in Figure 12. The performance at set of engine load 1.75 kg, mass of fuel consumed 0.000126 kg/s and fuel exergy 13.162 kW, which are optimum parameter setting fordestroyed availability. Engine performance is mostly influenced by engine load and is least influenced by mass of fuel consumed. Minitab software for Taguchi method of optimization was suggested engine load 1.75 kg and S/N ratio was – 10.5325 shown in Table 8 for optimum set of parameter for destroyed availability of 4.1221 kW. But from the experiment it was found to be 4.597kW.

In dual mode of operation, using an optimum set of parameters, which was achieved by response curve analysis, was used for prediction by Minitab software shown in Figure 13. The performance at set of engine load 1.75 kg, mass of fuel consumed 0.000220 kg/s and fuel exergy of 10.625 kW, which are optimum parameter setting for destroyed availability. Engine performance is mostly influenced by engine load and is least influenced by fuel exergy. Minitab software for Taguchi method of optimization was suggested engine load 1.75 kg and S/N ratio was – 11.5405 shown in Table 9 for optimum set of parameter for destroyed availability of 4.565 kW. But from the experiment it was found to be 4.943kW.

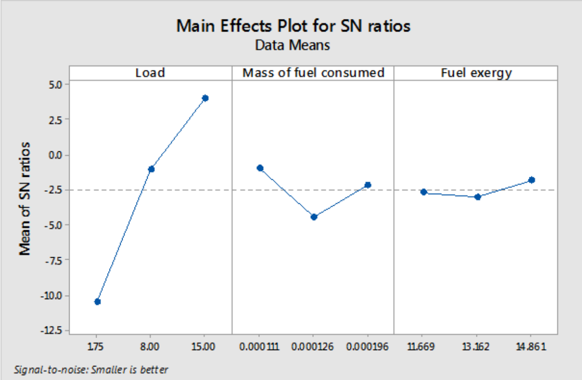

Figure 12. Main effect plot for SN ratio (diesel mode)

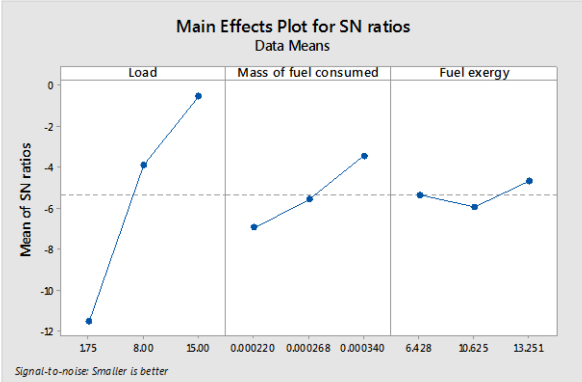

Figure 13. Main effect plot for SN ratio (dual mode)

Table 8. Response Table for Signal to Noise Ratios for Destroyed Availability (diesel mode) Smaller is better

Level	Load	Mass of fuel consumed	Fuel exergy
1	-10.5325	-0.9779	-2.7186
2	-1.0734	-4.4604	-3.0409
3	3.9811	-2.1865	-1.8653
Delta	14.5136	3.4825	1.1756
Rank	1	2	3

Table 9. Response Table for Signal to Noise Ratios for Destroyed Availability (dual mode) Smaller is better

Level	Load	Mass of fuel consumed	Fuel exergy
1	-11.5405	-6.9669	-5.3797
2	-3.9215	-5.6033	-5.9660
3	-0.5858	-3.4776	-4.7020
Delta	10.9547	3.4893	1.2640
Rank	1	2	3

3.2.3 Exergy Efficiency

In diesel mode of operation, using an optimum set of parameters, which was achieved by response curve analysis, was used for prediction by Minitab software shown in Figure 14. The performance at set of engine load 15 kg, chemical availability of fuel 14.861 kW and destroyed availability 0.576 kW, which are optimum parameter setting forexergy efficiency. Engine performance is mostly influenced by engine load and is least in destroyed availability. Minitab software for Taguchi method of optimization was suggested engine load 15 kg and S/N ratio was 39.95 shown in Table 10 for optimum set of parameter for exergy efficiency of 85.57%. But from the experiment it was found to be 99.54%

In dual mode of operation, using an optimum set of parameters, which was achieved by response curve analysis, was used for prediction by Minitab software shown in Figure 15. The performance at set of engine load 15 kg, chemical availability of fuel 13.251 kW and destroyed availability 0.976 kW , which are optimum parameter setting for exergy efficiency. Engine performance is mostly influenced by engine load and is least influenced by destroyed availability. Minitab software for Taguchi method of optimization was suggested engine load 15 kg and S/N ratio was 39.09 shown in Table 11 for optimum set of parameter for exergy efficiency of 91.43%. But from the experiment it was found to be 90.57%.

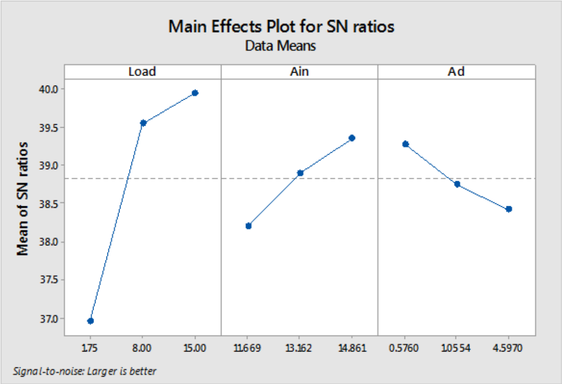

Figure 14. Main effect plot for SN ratio (diesel mode)

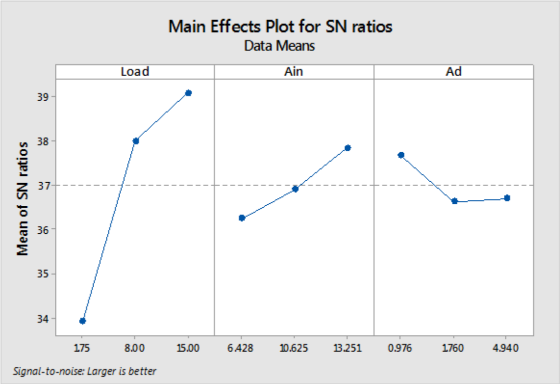

Figure 15. Main effect plot for SN ratio (dual mode)

Table 10. Response Table for Signal to Noise Ratios for Exergy Efficiency (diesel mode)
Larger is better

Level	Load	A_{in}	A_d
1	36.95	38.20	39.28
2	39.55	38.90	38.75
3	39.95	39.35	38.42
Delta	3.00	1.15	0.86
Rank	1	2	3

Table 11. Response Table for Signal to Noise Ratios for Exergy Efficiency (dual mode)
Larger is better

Level	Load	A_{in}	A_d
1	33.91	36.25	37.68
2	38.00	36.91	36.63
3	39.09	37.84	36.69
Delta	5.19	1.60	1.05
Rank	1	2	3

4. Conclusion

In this research, test engine was operated at steady-state with a small modification in the air inlet to run in dual fuel mode. Energy and exergy balances to the engine were performed for both the fuels using the data collected from the experiments. Then the energetic end exergetic performance parameters of the engine were computed and compared with each other. In this research, it was found that the diesel fuel is a greater quality fuel than biogas. Since the calorific value of diesel is greater than the biogas, more amount of biogas was required. The use of biogas develops similar exergetic performance values with diesel fuel. The most important factor of the engine inefficiency is the destruction of exergy by irreversible processes. This research shows that, a combined energy and exergy analysis provides much better results. It is also concluded that there is no much difference in performances at all test loads.

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