Optimization of engine emissions and performance of a dual-fuel engine using producer gas

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Abstract: The researchers around the globe are trying to overcome energy crisis by developing suitable alternative energy source. In this work, performance of a diesel engine running in dual-fuel mode using producer gas was optimized by Grey-Taguchi technique. The variations in engine load, producer gas flow rate (PGFR) and biodiesel blend percentage were investigated to observe their influence on brake thermal efficiency, un-burnt hydrocarbons and smoke opacity. The obtained result shows that, optimal factor setting with 80% engine load, 10% blend of biodiesel and PGFR at 21.49 kg h^{-1} gave the best result for the selected responses. Analysis of variance determines the relative contribution of engine load, biodiesel blend percentage, and PGFR were found to be 75.1, 5.12, and 7.83% respectively. This indicates that, variation in engine load has the highest contribution on the desired output responses as compared to biodiesel blend percentage and PGFR.

Keywords: Biodiesel, Producer gas, Emissions, Alterative fuel

1. Introduction

Diesel engines are vastly used as prime mover in various workplaces like in transportation, agricultural sector, construction sector etc. to meet the power requirements. The accelerated depletion of fossil fuels knocking at the door as a global problem pursuing attention of the researchers to experiment on the use of alternative gaseous fuels (Jena & Acharya, 2020). They have worked with liquefied petroleum gas (LPG), natural gas, biogas, syngas, and hydrogen in diesel engines under dual-fuel mode. Alternate gaseous fuels can be utilized in a dual-fuel mode diesel engine with minor modifications. In most cases researchers had worked with different combination of engine input parameters like compression ratio (CR), fuel injection pressure (FIP), injection timing (IT), and revealed their findings. Some research findings on the above are mentioned below. Patnaik and Acharya (2014) experimented with variation in blends of Karanja oil methyl ester (KOME) at different CR. They noticed an increasing trend of BTE with reduction in emissions at higher CR. Lal and Mohapatra (2017) investigated on a dual-fuel engine to improve its performance by varying the CR at different loads. They achieved a higher diesel saving with increase in CR and un-burnt hydrocarbon (HC), oxides of nitrogen (NO_x) emissions were reduced for the dual-fuel run with producer gas. Gawale and Naga Srinivasulu (2020) studied the influence of blends of ethanol-diesel and ethanol-biodiesel on dual-fuel mode engine at different engine loads. They achieved a lower smoke and NO_x emissions with improved fuel efficiency. Researchers have put sincere efforts to find out the suitable alternate fuels for diesel engine with minimum impact on the performance and emission parameters by varying the different combination of input parameters. These whole experimental procedures are very lengthy and comparatively costly to operate. Hence, the design of experiments (DOE) must be performed to minimize the number of experiments generating possible maximum overall output responses. Different statistical techniques can be used to optimize the process parameters; one of such technique is the Grey-Taguchi technique. Initially the required number of experimental combinations are predicted through orthogonal arrays of Taguchi technique and the analysis was performed based on signal to noise ratios (SNR). Then Analysis of variance (ANOVA) was performed to obtain the relative contribution of control factors on the output response. Grey relational analysis (GRA) will help to define the key elements of the system under consideration. Wu, Wu and Hung (2014) used Taguchi method to optimize the combustion characteristics of a diesel engine running with diesel/biodiesel blends along with LPG as inducted fuel. They observed the optimal factor setting to be

B10 (10% volume ratio biodiesel mixed with diesel) blend, 40% LPG energy share and 20% exhaust gas recirculation ratio. Ansari, Sharma and Singh (2018) performed Taguchi analysis to optimize the performance and emission characteristics of a diesel engine operated with polonga biodiesel. They have noticed the optimal setting of input parameter for best output response in engine performance is to be B30 (30% volume ratio biodiesel mixed with diesel) blend, IT of 15° before top dead center (bTDC) and 200 bar FIP. Roy, Das and Banerjee (2014) studied the multi-objective optimization of performance and emissions of a compressed natural gas (CNG) operated dual-fuel engine using Grey-Taguchi technique. They observed the best output response at the optimized setting of input parameters to be FIP of 540 bars and 15% CNG energy share. Jena, Mahapatra and Acharya (2020) optimized the emission and performance of a diesel engine running with different blends of Karanja biodiesel under the changes in CR.

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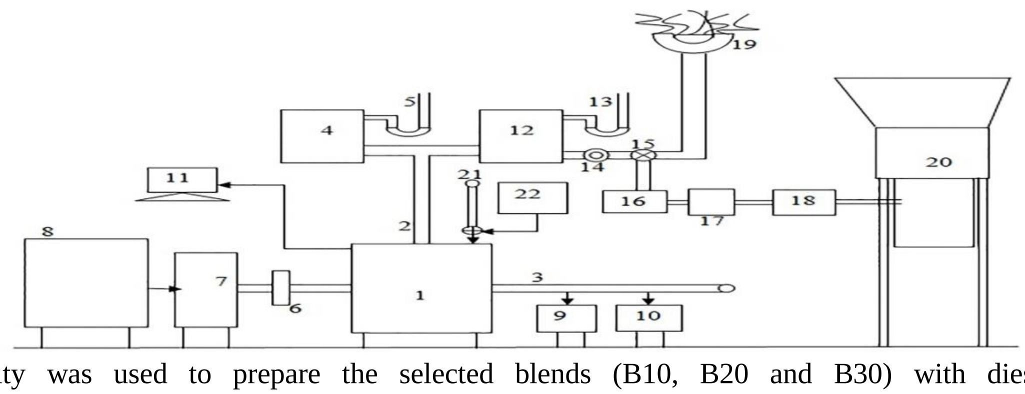
They found the optimal input parameters to be B20 (20% volume ratio biodiesel mixed with diesel) biodiesel ratio with diesel, 17.5 CR at full engine load operation gave best results. The above literature confirms that Taguchi method along with Grey relational analysis predicted the operating combinations effectively to optimize the desired results. The brief review indicates that, till now no work has been done to determine the optimal factors of a dual-fuel diesel engine operating with producer gas using Grey-Taguchi method.

In the present analysis, we have performed the multi-objective optimization of emission and performance characteristics of a dual-fuel mode compression ignition (CI) engine operated with producer gas as inducted fuel and blends of KOME as the pilot fuel. We have used L_{16} orthogonal array of Taguchi method to get the optimized engine load, blend percentage of KOME and PGFR to achieve highest BTE, lowest HC and smoke opacity emissions.

2. Experimental Method

2.1. Experimental Setup

A twin cylinder, 4-stroke CI engine of 14 hp rated power at constant engine speed of 1500 rpm with compression ratio 16.5:1, injection timing 23˚ bTDC and injection pressure 220 bar was used for experimentation. An AC alternator of three phase, 415 volt with loading circuit was used for loading purpose of the engine. A downdraft biomass gasifier was used to deliver producer gas for dual-fuel operation, where small piece (0.025 m length and 0.03 m diameter) of Eucalyptus wood with moisture content 10.2% under dry basis is used as feedstock. The calorific value of the generated producer gas was 5.38 MJ kg^{-1}. A suitably designed gas surge tank is fabricated with the attachment of orifice meter and a water manometer to quantify the producer gas flow rate (PGFR) during the experiment. A data acquisition device (DAD) is used to record and analyse the experimental data. Engine combustion analyser ECA 1.0.1 was used for online combustion and performance analysis. The engine emission parameters were gathered by online AVL-444 model (India), multi-gas analyzer and smoke opacity was measured with AVL-437 model smoke meter. The layout diagram of the dual-fuel engine test rig is showed in Figure 1. KOME produced in the Alternative fuel laboratory, SOA deemed to be



University was used to prepare the selected blends (B10, B20 and B30) with diesel for experimentation. The fuel properties of diesel and blends of KOME were measured and showed in Table 1.

1. Engine, 2. Inlet manifold, 3. Exhaust manifold, 4. Air box, 5. Manometer,6. Coupling,7.Alternator, 8. Electrical resistance loading unit, 9. Multi-gas analyzer, 10. Smoke meter, 11. DAD, 12. Gas surge tank, 13. Manometer, 14. Orifice meter, 15. Flow control valve, 16. Fine filter, 17. Passive filter, 18. Cooling unit, 19. Burner, 20. Gasifier unit, 21. Burette, 22. Fuel tank

Figure 1. Layout diagram of the dual-fuel engine test rig.

Table 1. Fuel properties of diesel and KOME

Property	Diesel	B10	B20	B30	KOME
Viscosity (cSt, 40^0 C)	1.9	2.18	2.41	2.62	4.5
Specific gravity	0.832	0.837	0.843	0.838	0.885
Calorific value (MJ kg^{-1})	42.21	41.50	41.03	40.52	36.12
Cetane number	45-55	-	-	-	56.61

2.2. Experimental Method

To predict the optimum flow rate of producer gas for optimized performance and emission characteristics of the dual-fuel engine running with different blends of KOME under the variation in engine load was observed in the current experiment. The selected input parameters were considered for 4 different levels as represented in Table 2. Based on these parameters BTE, smoke and HC emissions are optimized. Since there are many noise factors are present, so many experiments should be conducted to find out all the possible outcomes. Hence, a properly planned DOE can obtain better output considering a smaller number of trails. Therefore, Taguchi technique was used to recognize the noise factors that influence the desired output responses.

Table 2. Input parameters and their level

Parameters	Level 1	Level 2	Level 3	Level 4
Engine Load (%)	40	60	80	100
Biodiesel Blend (%)	0	10	20	30
PGFR (kg h^{-1})	10.74	15.2	18.61	21.49

2.3. Taguchi Method

Dr. Genichi Taguchi invented a statistical method to increase the production rate of manufactured goods by reducing variations in the process development stages through a suitable DOE. He used a special set of orthogonal arrays that carries the complete information about the selected input parameters that have influence on output responses. This technique provides an estimation of performance known as SNR to signify the trend of deviation of the observed outputs. The output responses that are desired to be decreased, can be estimated with smaller the better SNR criteria using (1), while the output responses need to be increased can be estimated with larger the better SNR criteria using (2) (Jena, Mahapatra and Acharya, 2020).

$$SNR_S = -10 \log \frac{1}{n} \left\{ \sum_{i=1}^{n} y_i^2 \right\} \quad (1)$$

$$SNR_L = -10 \log \frac{1}{n} \left\{ \sum_{i=1}^{n} \left(\frac{1}{y_i^2} \right) \right\} \quad (2)$$

Here, y_i (k) is the actual reference sequence. In the present work, larger the better SNR is considered for BTE, while smaller the better SNR is used for smoke opacity and HC emission.

2.4. Grey Relational Analysis

To perform multi-objective optimization, GRA method was found to be an effective tool for such analysis. This technique can define the key elements of the system under consideration. Here the main elements are identified by the input and output sequence (Jena, Mahapatra and Acharya, 2020). In the current paper first, the experimental results which are obtain from Taguchi's L_{16} orthogonal arrays were first normalized between 0 and 1. This helps to obtain the grey relational coefficients (GRC). In the next step grey relational grade (GRG) were computed from the obtained GRC to evaluate the multiple output responses. As a result, the multiple-objective problems transform to a single objective problem. The GRG with highest value identified as the optimized process parameters.

Equation (3) is used to optimize the response parameters obtained with "higher the better" criteria, while (4) is used to optimize the response parameters obtained with "lower the better" criteria (Jena, Mahapatra and Acharya, 2020).

$$x_i\,(k) = \frac{y_i\,(k) - min\,y_i\,(k)}{\max y_i\,(k) - min\,y_i\,(k)} \quad (3)$$

$$x_i(k) = \frac{max\,y_i\,(k) - y_i\,(k)}{\max y_i\,(k) - min\,y_i\,(k)} \quad (4)$$

Here, $x_i(k)$ is the normalized value of the response, i=1,2,….m , $min\,y_i\,(k)$ is the smallest value of $y_i\,(k)$ and $\max y_i\,(k)$ is the largest value of $y_i\,(k)$. Grey Relational Coefficient $\xi_i(k)$ depicts the relationship between the anticipated output responses and actual investigated experimental result. It can be estimated by using (5) and (6) (Jena, Mahapatra and Acharya, 2020).

$$\xi_i(k) = \frac{\Delta_{min} + \Psi\Delta_{max}}{\Delta_{oi}(k) + \Psi\Delta_{max}} \quad (5)$$

Where,

$$\Delta_{oi} = \|x_o(k) - x_i(k)\| \quad (6)$$

Δ_{oi} is said as the deviation sequences, $x_o(k)$ is the ideal sequence, $\Delta_{max}\ and\ \Delta_{min}$ are the maximum and minimum value of the deviation sequences Δ_{oi}, $\Delta_{oi}(k)$ is the actual reference in the deviation sequence, and Ψ is designated as the distinguishing coefficient and its value always remains in between $0 \leq \Psi \leq 1$. The objective of choosing the distinguishing coefficient was to weaken the effect of larger values of Δ_{max}. In the present analysis the value of Ψ was chosen to be 0.5. Then the GRG was to be calculated by averaging the GRCs. A higher value of grey relational coefficient was a stronger co-relation between the given sequence $x_i(k)$ and the ideal sequence $x_o(k)$. The best sequence $x_o(k)$. was assumed to be the ideal response.

Grey relational grade y_0 is obtained for all the responses by assigning suitable weighting factors. A weighting factor 'β' is set for a specific response depending upon their relative importance where the addition of weighting factor must be equal to unity. In the current study the weighting factors for BTE was taken as 0.5, 0.25 for smoke opacity and 0.25 for HC. GRG is a weighted average of the GRC and is computed using (7) and (8) (Jena, Mahapatra and Acharya, 2020).

$$y_o = \sum_{k=1}^{n} \xi_i(k)\beta y_i \dots, \quad (7)$$

Where,

$$\sum \beta = 1 \quad (8)$$

3. Results and Discussion

The objective of the present work was to define the optimal combination of selected input variables (engine load, KOME blend percentage and PGFR) of a dual-fuel CI engine, to get the desired output responses for achieving highest diesel saving. The proposed multi-objective optimization can be performed by combining Grey relational analysis with Taguchi method.

3.1. Results of Taguchi Method

To apply Taguchi technique, L_{16} orthogonal array was selected based on the number of input parameters and their respective levels as shown in Table 3.

Table 3. Taguchi L_{16} orthogonal array with experimental results

Exp. No.	**Engine Load (%)**	**Blend (%)**	**PGFR (kg h^{-1})**	**BTE (%)**	**Smoke Opacity (%)**	**HC (ppm)**
1	40	0	10.74	16.45	36	66
2	40	10	15.2	15.5	31	36
3	40	20	18.61	13.9	40	46
4	40	30	21.49	15.12	24	68
5	60	0	15.2	22.4	32	52
6	60	10	10.74	20.9	42	19
7	60	20	21.49	22.1	11	24
8	60	30	18.61	18.88	22	33
9	80	0	18.61	24.95	32	32
10	80	10	21.49	24.75	24	16
11	80	20	10.74	22.43	43	25
12	80	30	15.2	22.1	35	28
13	100	0	21.49	22.66	96	28
14	100	10	18.61	20.1	85	30
15	100	20	15.2	20.39	55	18
16	100	30	10.74	21.7	81	29

As the SNR values are considered in four levels for each factor, the plots are generated for mean SNR with respect to level of factors. The change in performance and emission characteristics with variation in selected input parameters level is graphically narrated by the SNR curves. Figure 2 depicts that, the optimized input parameters for BTE were noticed to be 80% engine load, blend 0% volume of biodiesel mixed with diesel (B0) and 18.61 kg h^{-1} PGFR.

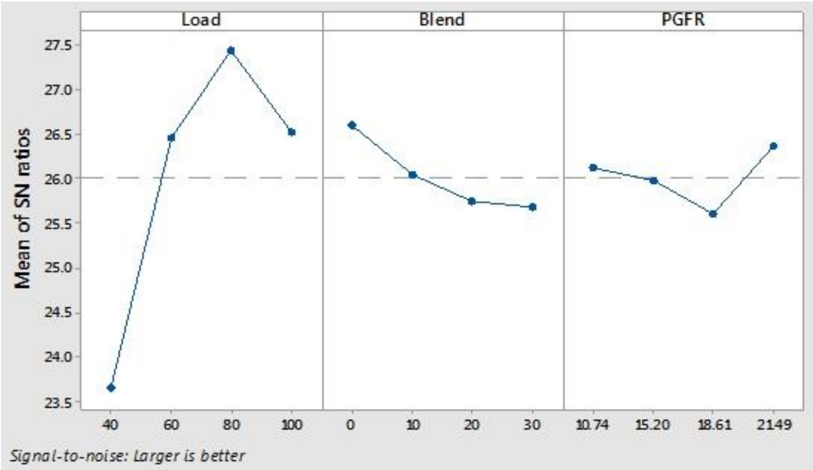


Figure 2. SNR plot of brake thermal efficiency.

It can be linked with increase in in-cylinder temperature and pressure with increase in engine load, that results in improved combustion kinetics leads to increase the BTE. At full load operation the presence of comparatively richer fuel-air mixture affects the flame propagation leading to incomplete combustion results a decrease in BTE. Figure 3 and Figure 4 represents the optimized combination of input parameters for smoke opacity (100% engine load, B0 blend and 10.74 kg h^{-1} PGFR) HC emission (40% engine load, B0 blend and 18.61 kg h^{-1} PGFR). The increase in viscosity and specific gravity of the pilot fuel with increase in KOME percentage in the blend, affects the atomization and vaporization of the fuel. As a result, HC and smoke opacity increased with increase in percentage of KOME blend.

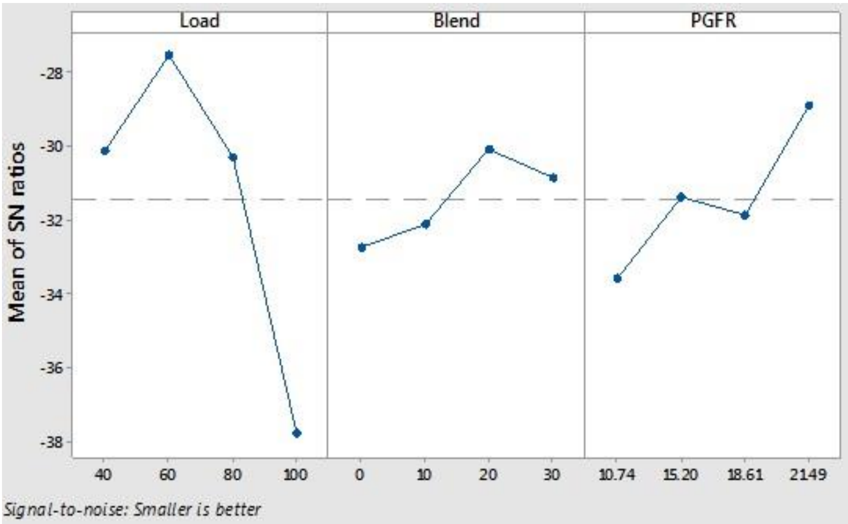


Figure 3. SNR plot of smoke opacity.

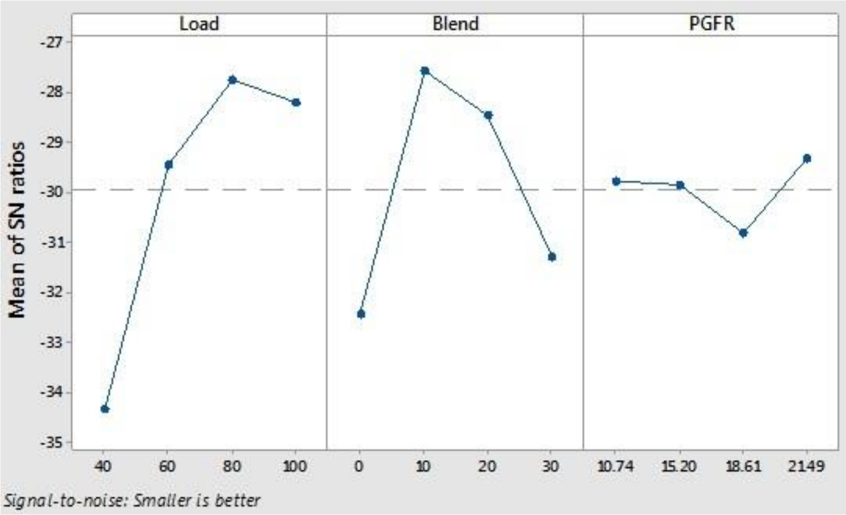


Figure 4. SNR plot for HC.

3.2. Results of Grey Relational Analysis

The grey relational coefficients were derived using (3) and (4) and at last the GRG is obtained as showed in Table 4. After the GRG was established for the responses, a rank was allocated corresponding to each grade. The grade with rank '1' was designated to be closest to the optimal factor setting. The SNR for the GRG is depicted in Figure 5, which indicates that the optimized setting of input parameters was found to be engine load 80%, blends of KOME is B10 and PGFR is 21.49 kg h^{-1}.

Table 4. Grey relational coefficient and GRG

Weights	**0.5**	**0.25**	**0.25**		
Exp No	**BTE**	**HC**	**Smoke opacity**	**Grade**	**Rank**
1	0.393	0.342	0.629	0.455	15
2	0.368	0.565	0.68	0.538	16
3	0.333	0.464	0.594	0.464	14
4	0.359	0.333	0.765	0.486	13
5	0.684	0.419	0.669	0.591	9
6	0.577	0.896	0.578	0.684	4
7	0.659	0.764	1	0.808	2
8	0.476	0.604	0.794	0.625	8
9	1	0.619	0.669	0.763	3
10	0.965	1	0.765	0.910	1
11	0.686	0.742	0.57	0.667	5
12	0.659	0.684	0.639	0.661	6
13	0.706	0.684	0.333	0.575	10
14	0.532	0.65	0.364	0.516	12
15	0.547	0.928	0.491	0.656	7
16	0.629	0.667	0.377	0.558	11

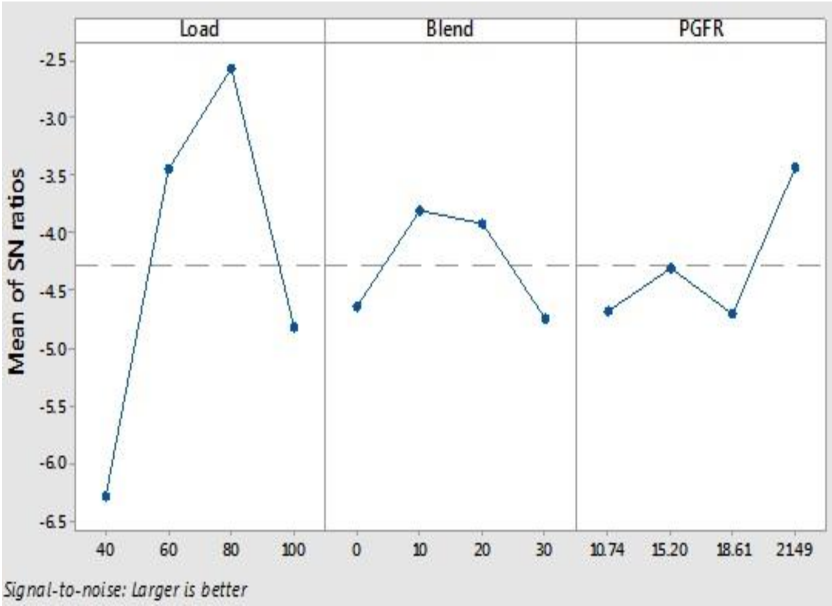


Figure 5. SNR plot for GRG.

3.2. Analysis of Variance

The relative contribution of selected input parameters on the output response were obtained from ANOVA. Minitab software was used to execute the steps and the corresponding results are given in Table 5. From the ANOVA results it was reported that engine load was the most influential parameter with a contribution of 75.1% on the output response and blends of biodiesel was the least important parameter with a contribution of 5.12% on the output response, whereas PGFR having a contribution of 7.83% on the output response.

Table 4. ANOVA results for GRG

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	P Value
Engine Load	3	1.168	75.1%	1.168	0.389	0.005
Blend	3	0.079	5.12%	0.079	0.026	0.513
PGFR	3	0.121	7.83%	0.121	0.040	0.355
Error	6	0.185	11.96%	0.185	0.030	
Total	15	1.555	100.00%			

4. Conclusions

In the present work, we have attempted to evaluate statistically the effects of selected input parameters on performance and emission characteristics of a dual-fuel CI engine using Grey-Taguchi technique. The following findings are strained from the above analysis:

- The setting of input factors for optimized output responses are recorded to be 80% engine load, B10 blend of KOME and 21.49 kg h-1 flow rate of producer gas.
- ANOVA indicates engine load has the highest relative contribution on desired outputs with a contribution percentage of 75.1%.

- Blends of KOME and PGFR have lower relative contribution on desired output, recorded to be 5.12 and 7.83% respectively.

The above analysis indicates that, partial substitution of diesel consumption can be achieved with the use of KOME blend as pilot fuel and producer gas as inducted fuel in dual-fuel CI engines. The obtained input parameter setting will give best performance from the dual-fuel engine.

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