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Optimization of diesel injection timing, producer gas flow rate, and engine load for a diesel engine operated on dual fuel mode at a high engine speed

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Abstract

Jatropha seed cake is a byproduct of biodiesel production, and the seed cake can be used as a feedstock for a gasifier. The gasified seed cake can partially reduce fossil diesel consumption to run a diesel engine. However, an increase in gas flow rate is associated with a higher diesel substitution rate, but a higher specific CO_2 emission is observed. This study attempts to optimize diesel injection timing (DIT), gaseous fuel flow rate, and engine load to offset the specific diesel consumption and the specific CO_2 emissions at a high engine speed of 3,000 rpm. Response Surface Methodology (RSM) was applied to statistically develop mathematical models of the response variables as functions of the design variables. A desirability function was then applied to maximize overall desirability. It highlighted that an overall desirability of 0.829 was obtained at 11° before top dead center (BTDC) of the DIT, a 10 kg/h gas flow rate, and 70% of the full engine load. At the optimum operating settings, the specific diesel consumption (SDC) and the specific CO_2 emission were 0.0967 kg/kWh and 0.6123 kg/kWh, respectively. A value of electrical-thermal efficiency was found to be 14.10%. It is evident from these findings that a dual producer gas-diesel fuel engine should not be operated at the maximum diesel replacement rate.

Keywords: Response surface methodology, Jatropha seed cake, Producer gas, CO_2 emissions, Optimization, Diesel engine

1. Introduction

Skyrocketing petroleum fuel costs and shrinking fossil fuel reservoirs are the core reasons for encouraging bio-renewable energy development. The utilization of carbonaceous materials as a feedstock for a gasifier-diesel engine set can partially reduce the use of diesel fuel. This technology is being met with increasing interest for decentralized power plants in remote rural districts where it is more difficult to access petroleum fuels. Producer gas used in a diesel engine operated on a dual fuel mode can possibly substitute for diesel fuel, but the CO_2 emissions are inherently higher, as compared to the cleaner diesel mode [1]. It was found that the diesel replacement rate increased to 86% when the dual fuel engine was operated on the maximum diesel replacement rate mode at 60% of the full engine load [2].

Other recent studies have investigated the impact of gas flow rates on performance and emission characteristics of a diesel engine operated on a dual fuel mode [3-7]. The increase in the gas flow rate is consistent with a decrease in the diesel consumption rate [6-7], but CO_2 emissions were found to be higher [3], mainly due to an initial CO_2 content in the producer gas. An increase in engine load improves the mixed fuel-air combustion and thereby increasing the brake-thermal efficiency [6-7]. However, the CO_2 emissions increase with the engine load due to better combustion [3]. Diesel injection timing (DIT) was found to have a significant impact on the diesel consumption rate of a dual fuel engine. An improper DIT leads to an increased diesel consumption rate [5]. Our study seeks the optimum operating settings to balance the specific diesel consumption and the CO_2 emissions. To the best of our knowledge, there is no study that has been conducted to optimize the levels of the gas flow rate, engine load, and DIT to maximize the overall desirability of the diesel replacement rate and the CO_2 emissions at a high engine speed operation.

The study intends to optimize the operating settings of the design variables to offset the specific diesel consumption and the CO_2 emissions. Three influential factors were selected in our study. They included the gas flow rate, engine load, and DIT. Jatropha seed cake, a byproduct of Jatropha biodiesel production, was used as the feedstock for the gasifier. The engine was operated at a constant speed of 3,000 rpm throughout the experiments. Response Surface Methodology (RSM) and a Desirability Function were applied to statistically develop mathematical models as functions of the design variables and optimize the operating settings. The approach proposed in this study is expected to

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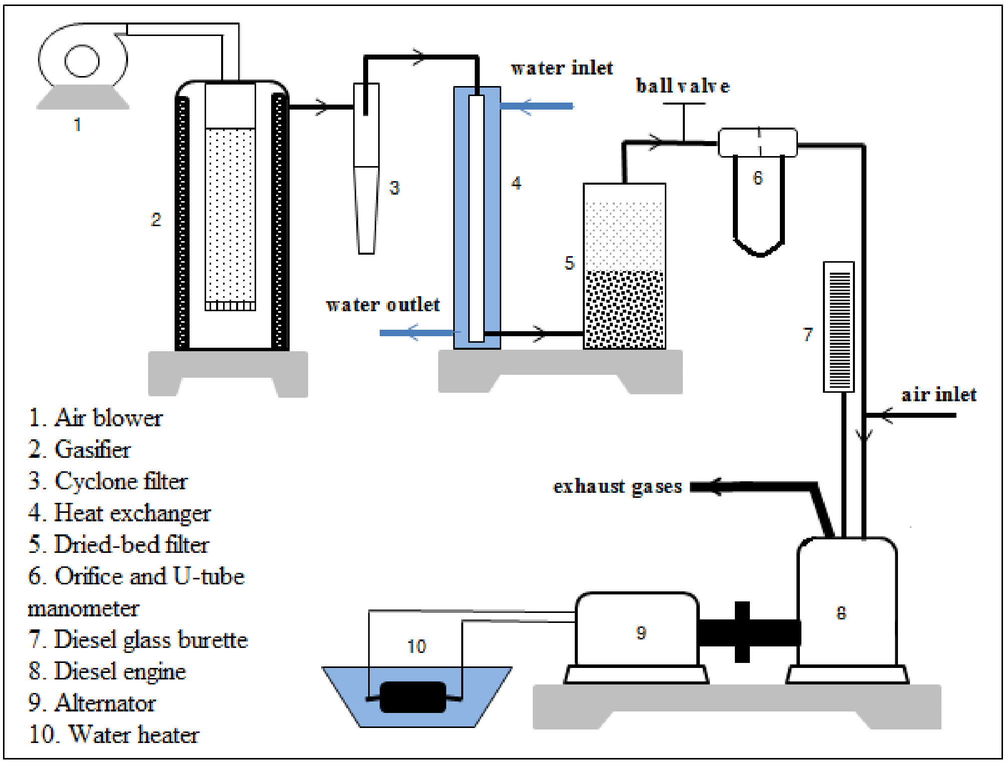

Figure 1 Schematic diagram of the experimental setup

Table 1 Technical specifications of the designed gasifier

Items	Descriptions
Type	Close top, throatless, downdraft
Gasifying agent	Air
Gasifier's weight (kg)	30
Critical dimensions (mm)	D = 350 / h = 1800
Capacity (kW_{th})	130
Fuel consumption rate (kg/h)	7 (approximately)
Biomass feedstock	Jatropha seed cake
Efficiency (%)	~74

be informative for practitioners and policy makers of bio-power plants in attempts to mitigate fossil fuel dependency and greenhouse gas (GHG) emissions, while satisfying overall requirements.

2. Experimental setup and methodology

This section consists of the experimental setup and procedures, properties of the test fuels, the experimental design, and the desirability function.

2.1 Description of the experimental setup and procedure

A schematic representation of the experimental setup is given in Figure 1. The setup consisted of a throatless downdraft gasifier, a gas cleaning unit, and a diesel generator set. The technical specifications of the gasifier are listed in Table 1. The cleaning unit consisted of a cyclone filter, a shell-tube heat exchanger, and a dried-bed filter (i.e., small-sized charcoal layered under a fabric material).

A KM 186F diesel engine test was adopted in the study, and its main characteristics are summarized in Table 2. The air intake system was modified to induct producer gas mixed with inlet air prior to entering the combustion cylinder.

Instruments were integrated into the experimental setup to measure engine speed, gas flow rate, and diesel consumption rate. A microprocessor tachometer with a reading accuracy of ±0.5 rpm was used to detect the engine speeds controlled through its throttle. A glass burette and a digital stopwatch were used to measure the diesel consumption rates. An orifice and a U-tube manometer were used to indicate the producer gas flow rates, based on Bernoulli's principle. The gas flow was assumed to be non-compressible because its streamline was inviscid and steady. A ball valve was used to control producer gas loading.

The data at each experimental setting was the average of three test replicates. The Jatropha seed cake consumption rate was 7 kg/h which was converted into 20 kg of producer gas using the designed gasifier. For all the experimental settings, the temperature of the cleaned gas was held close to 30 °C when the gas was fed into the engine, and the engine speed of 3,000 rpm remained constant.

Table 2 Main characteristics of the engine test

Items	Descriptions
Model	KM 186F
Engine type	Single cylinder, 4-stroke, air-cooled, direct injection, diesel engine
Bore×stroke (mm)	86×70
Connecting rod length (mm)	117.5
Displacement (cm^3)	406
Engine speed (rpm)	3,000
Compression ratio	19:1
Inlet valve	Open at 8.5° BTDC, close at 44.5° ABDC
Exhaust valve	Open at 55.5° BBDC, close at 8.5° ATDC
Rated output power (kW/rpm)	5.7/3,000
BTDC: Before top dead center	ABDC: After bottom dead center
BBDC: Before bottom dead center	ATDC: After top dead center

Table 3 Physical properties of producer gas and diesel

Producer Gas	H_2 (%)	CO (%)	CH_4 (%)	CO_2 (%)	N_2 (%)	O_2/Ar (%)	Density (kg/m^3)	C Content (kg/kg Gas)	Net Calorific Value (MJ/kg)
	7.9	8.8	2.1	18	60	3.8	1.19	0.1266	4.69
Diesel	Oxygen Content (% mass)		Sulfur Content (% mass)		Viscosity (cSt at 40 ℃)		Density (kg/m^3)	C Content (kg/GJ)	Net Calorific Value (MJ/kg)
	0[a]		0.595[a]		2.5[a]		837[a]	20.2[b]	42.72[a]

[a] [8] [b] [9]

Table 4 Control factors and their levels

Independent variables	**Symbol**	**Variable Codes and levels**		
		-1	0	+1
Diesel injection timing	DIT (° BTDC)	6	9	12
Gas flow rate	Gas (kg/h)	0	10	20
Engine load	Load (%)	35	52.5	70

° BTDC: degrees of crank angle before top dead center

2.2 Test fuels and CO_2 emissions

Properties of the producer gas and the diesel fuel are listed in Table 3. The producer gas sample was analyzed by CRL Calabarquez Corporation, located in Laguna, Metro Manila, Philippines. The results were the average of five samples taken randomly at different operating times of Jatropha seed cake gasification. Properties of the gas were analyzed using ASTM D1946 standard test methods for a volumetric percentage of each constituent and ASTM D3588 for the heating value and density. The carbon content of 1 kg producer gas was calculated using Eq. (1):

$$C\ Content_{PG} = \frac{1}{\rho_{PG}} \sum_k C\ Content_k \times V_k \times \rho_k \quad (1)$$

where $C\ Content$ is the carbon content, V denotes the volumetric percentage, and ρ is the gas density at a standard temperature and pressure. The *PG* defines the producer gas, while the index k is a constituent type of producer gas, i.e., CO, CH_4, and CO_2.

The specific CO_2 emission is calculated using Eq. (2) and (3) [9]:

$$Specific\ CO_2 = \frac{1}{Engine\ load} \sum_i (CO_2)_i \quad (2)$$

$$(CO_2)_i = Fuel_i \times C\ Content_i \times Oxidized\ Fraction \times 44/12 \quad (3)$$

where the index i represents a fuel type, $Fuel$ is the fuel consumption rate, $C\ Content$ is the carbon content (see Table 3), *Engine load* is measured in electrical power (kW). $Oxidized\ Fraction$ was assumed to be one [9].

2.3 RSM-based experimental design and desirability function

A Face-Centered Cube Design (FCCD) technique of the RSM was applied because this technique facilitates changing factor levels. Only two or three center points are satisfied to provide a good variance of prediction throughout the region of interest [10]. The response variables were the SDC, ETE, and specific CO_2 emission (CO_2). The design variables were the DIT, gas flow rate (Gas), and engine load (Load). The design variables and their levels are listed in Table 4. Based on the FCCD, three factors with two center points correspond to 16 experimental treatment combinations. The Design-Expert 6.0 statistical tool was used to do the statistical analysis of the observed data based by Analysis of Variance (ANOVA). The JMP 11 statistical tool was used to plot the surface graphs of the response variables and optimize the set of input parameters based on a Desirability Function. The FCCD-based RSM approach and the desirability function have been presented in detail in [10].

The desirability function is a technique applied to simultaneously optimize attribute levels of design variables for multiple response variables to achieve the maximum overall desirability [10]. The desirability is dimensionless and ranges from zero (totally unacceptable) to one

Table 5 Design matrix for the experimental data of the response variables

Run	Parameter settings			Experimental responses		
	DIT (º BTDC)	Gas (kg/h)	Load (%)	SDC (kg/kWh)	ETE (%)	CO_2 (kg/kWh)
1	6	0	35.0	0.572	17.079	0.493
2	6	0	70.0	0.392	24.887	0.169
3	6	10	52.5	0.220	6.542	0.92
4	6	20	35.0	0.188	3.574	2.542
5	6	20	70.0	0.138	3.64	1.25
6	9	0	52.5	0.396	24.64	0.228
7	9	10	35.0	0.181	6.719	1.346
8	9	10	52.5	0.161	6.816	0.886
9	9	10	52.5	0.162	6.808	0.887
10	9	10	70.0	0.148	6.874	0.659
11	9	20	52.5	0.193	3.567	1.698
12	12	0	35.0	0.545	17.932	0.47
13	12	0	70.0	0.333	29.343	0.144
14	12	10	52.5	0.169	6.776	0.891
15	12	20	35.0	0.156	3.616	2.515
16	12	20	70.0	0.088	3.710	1.228

Table 6 Analysis of variance, regression coefficients, and summary of fit of the models

Terms	SDC (kg/kWh)		ETE (%)		CO_2 (kg/kWh)	
	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value
Model		<0.0001		<0.0001		<0.0001
Intercept	0.77895	<0.0001	9.76888	<0.0001	1.76809	<0.0001
DIT	-0.0073	0.0598	–	–	–	–
Gas	-0.05035	<0.0001	-1.53162	<0.0001	0.13275	<0.0001
Load	-0.00506	0.0004	0.24776	0.0014	-0.05107	<0.0001
DIT^2	–	–	–	–	–	–
Gas^2	0.00127	<0.0001	0.06443	<0.0001	0.00084	0.002
$Load^2$	–	–	–	–	0.00040	0.0001
DIT. Gas	–	–	–	–	–	–
DIT. Load	–	–	–	–	–	–
Gas. Load	0.000196	0.0141	-0.01361	0.0008	-0.00138	<0.0001
Lack of fit		0.0160		0.0029		0.015
Summary of fit						
R^2	0.9679		0.9801		0.9985	
Adj.R^2	0.9519		0.9728		0.9978	
Pred. R^2	0.9281		0.9511		0.9957	

(extremely preferable). As the target of all the response variables in this study are minimized, the overall desirability can be calculated using Eq. (4) and (5):

$$D = (d_1 . d_2 \dots d_m)^{1/m} \quad (4)$$

$$d = \begin{cases} 1 & y < T \\ \left(\frac{U-y}{U-T}\right)^r & T \le y \le U \\ 0 & y > U \end{cases} \quad (5)$$

where d, D, and $\boldsymbol{m}$ are an individual desirability, the overall desirability, and the number of response variables, respectively. The target $\boldsymbol{T}$ is the maximum value for the response $\boldsymbol{y}$, and $\boldsymbol{U}$ is the upper limit of desirability. Choosing $\boldsymbol{r > 1}$ emphasizes data close to the target value.

3. Results and discussion

3.1 RSM analysis

The experimental data of each treatment combination are listed in Table 5. The units of SDC and specific CO_2 emission are kilograms mass (kg) divided by electrical power (kW). The estimation results of the analysis of variance (ANOVA) are presented in Table 6. The estimated coefficients were the actual values, not coded values. Only the terms with p-values less than 0.05 are tabulated. As can be seen from the table, all the three regression models are statistically significant. Consequently, these three models express a substantial relationship between the responses and the design variables. The lack-of-fit values of the three models are significant, and therefore the models did not statistically fit the data. However, the determination coefficient (R^2), the adjusted determination coefficient (Adj.R^2), and the predicted determination coefficient (Pred.R^2) for the SDC model were 0.9679, 0.9519, and 0.9281, respectively. These values were close to one (most preferably). The R^2 value expresses the total variability of the response explained by the regression model, the Adj. R^2 value accounts for the number of significant terms in the model, and the Pred. R^2 is a measure of how well the model predicts new observations. For the ETE model, the determination coefficient (R^2 =0.9801) indicated that 98.01% of the response variation was attributed to the design variables, and only 1.99% of the total variability could not be explained by the model. A high value of the Adj.R^2 (0.9728) indicates the high significance of the ETE model.

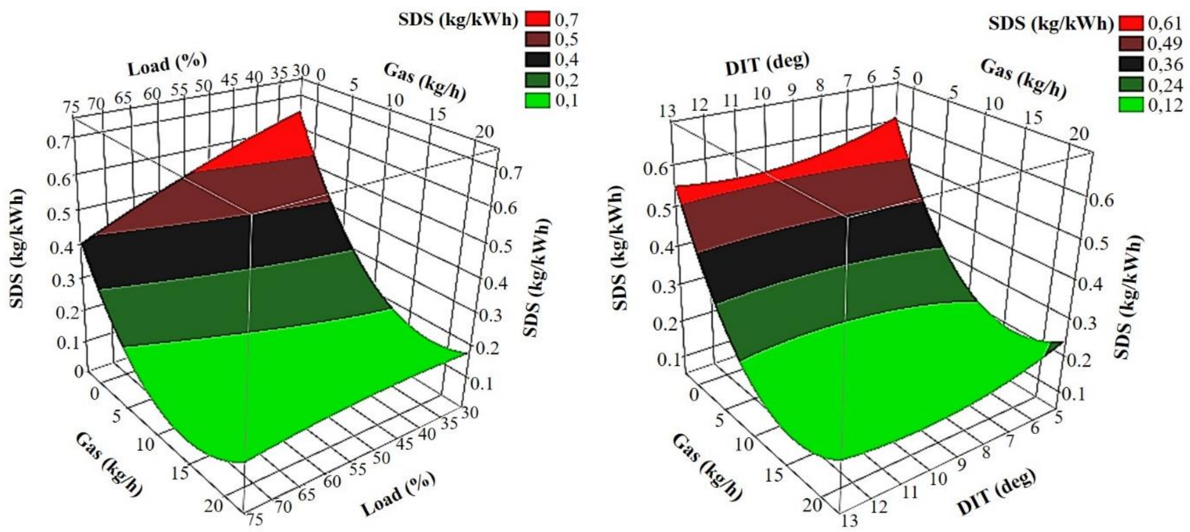

Figure 2 SDC (kg/kWh): (a) at 9° BTDC; (b) at 52.5% of the full engine load

A value of the Pred. R^2(0.9511) expressed that 95.11% of new predicted data could be explained by the ETE regression model. For the model of specific CO_2 emission, the high values of R^2 (0.9985), Adj. R^2 (0.9978), and Pred. R^2 (0.9957) accounted for an extreme sample variation of the response after considering the significant factors and their interactions. The developed mathematical models were used to plot the response variables shown in the subsections below. After that, the desirability function was applied to optimize the operating settings to offset the two response variables (i.e., the SDC and the specific CO_2 emission).

3.2 Specific Diesel Consumption (SDC)

The linear term of Gas and its square had an extremely significant effect on the SDC response. It was also observed that the linear term of Load and the interaction term of Gas-Load had a significant contribution to the SDC model. The DIT linear term was not found to be significant on the response at the 5% level but it was at the 10% level. The effects of the other terms on the response were not significant.

The interaction effect between the gas flow rate and the engine load on the SDC at 9° BTDC of the DIT is illustrated in Figure 2 (a). For all the load range, the SDC exponentially declined with increasing gas flow rate owing to the higher heating value contribution of the gaseous fuel. The SDC sharply decreased with an increased engine load at low gas flow rates. However, the SDC was slightly decreased with an increase in engine load at high gas flow rates. It was evident that the efficiency of the dual fuel engine is low under low engine loads. Figure 2 (b) depicts the interaction effect of the DIT and the gas mass flow on the SDC response at a medium engine load. The impact of DIT on SDC was slight at medium engine loads, compared to that of gas flow rate. However, advancing the injection timing produces a better fuel-air mixture and improves the pre-mixed combustion phase [11-12].

3.3 Electrical-Thermal Efficiency (ETE)

ETE is the ratio of the electrical energy to the thermal energy of the dual fuel, and ETE is calculated using Eq. (6):

$$ETE = \frac{Electric\ Power}{(\dot{m} \times LHV)_{diesel} + (\dot{m} \times LHV)_{producer\ gas}} \quad (6)$$

where $\dot{m}$ is the mass flow rate of fuel, and *LHV* is the lower heating value of fuel.

The effect of the single terms of gas flow rate and engine load on the ETE response variable was found to be significant. Also, it was found that the quadratic term of the gas flow had an extremely significant impact on the response. Among all the interaction terms, only the Gas-Load interaction term statistically affected the response variable. The other terms had no relationship with the response variable.

Figure 3 shows plots of the ETE influenced by the three design factors. As apparent from Figure 3 (a), the ETE rapidly declined when the gas flow rate increased, which necessarily indicates inefficient combustion in the dual fuel mode. This is inherently due to a lower adiabatic flame temperature of the producer gas, heating value, and mean effective pressure. The maximum adiabatic flame temperature of the gas was 1,730 K [13], much lower than the 2,325 K of the diesel [14]. At low gas levels in the dual fuel mode, the ETE considerably increased with respect to an increase in engine load due to a decline of the SDC and better combustion of fuel-air mixture at high load. This is because the optimum operating conditions of the engine are at the maximum engine load. The ETE at the highest gas flow was slightly decreased with an increase in engine load, which was attributed to better combustion. As seen in Figure 3 (b), the impact of the DIT on the ETE was slight compared with the impact of the gas flow rate on the ETE.

3.4 Specific CO_2 emissions (kg/kWh)

The linear terms of gas flow rate and engine load, as well as their square and interaction terms, had very significant effects on the specific CO_2 emission. The other terms were found to insignificantly affect the response variable.

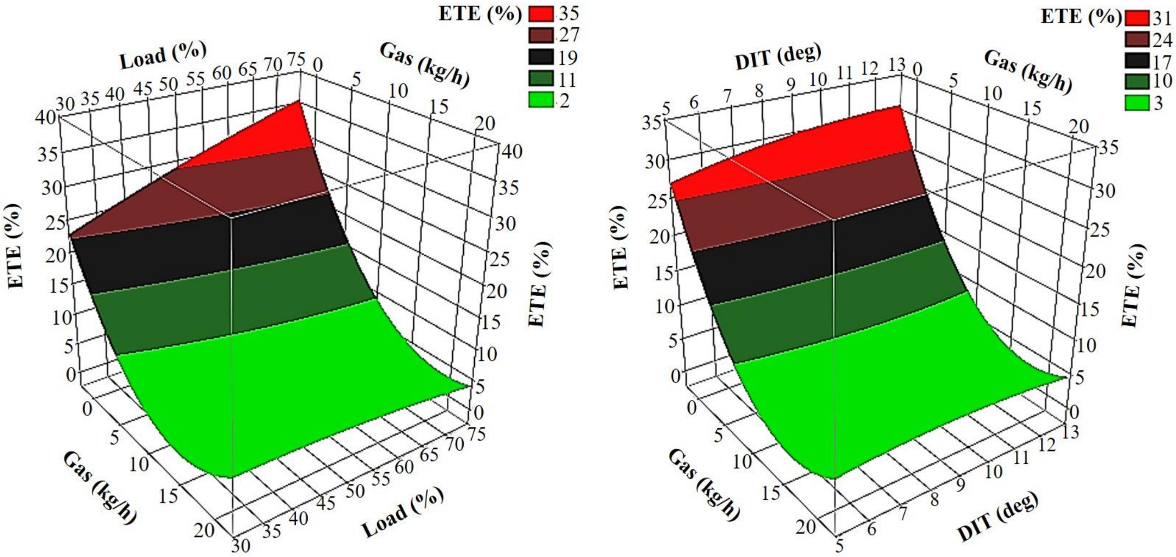

Figure 3 ETE (%): (a) at 9° BTDC; (b) at 52.5% of the full engine load

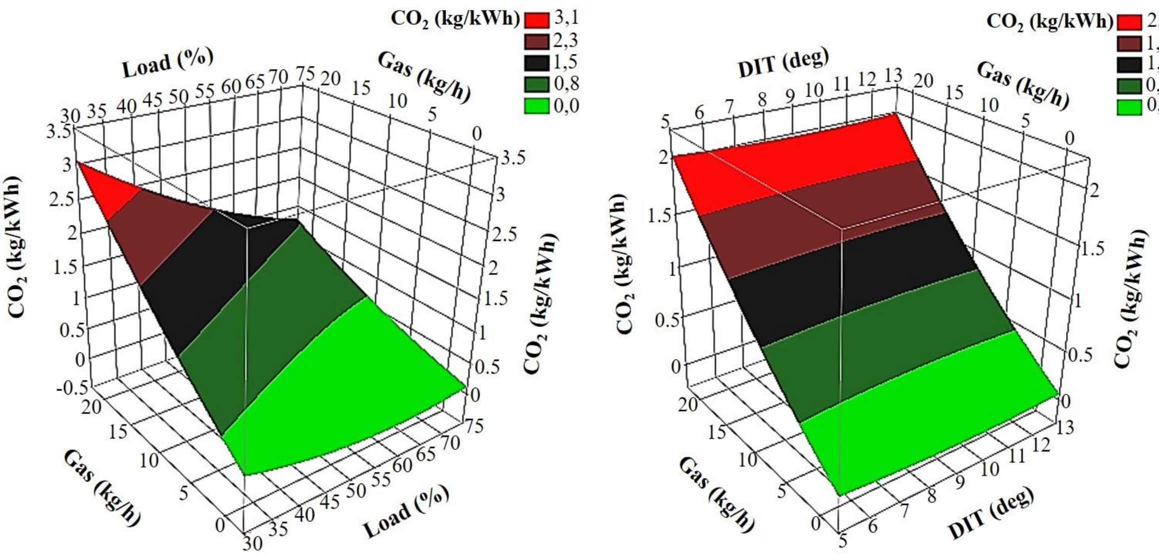

Figure 4 Specific CO_2 emission (kg/kWh): (a) at 9° BTDC; (b) at 52.5% of the full engine load

The level of producer gas possibly reduced diesel consumption. However, a great amount of CO_2 was emitted in the exhaust gases. The interactive effect of gas flow and engine load on the specific CO_2 emission at 9° BTDC is illustrated in Figure 4 (a). The gas flow rate had a significant effect on the response variable over the entire load range. Higher specific CO_2 emissions were seen with an increase in gas flow rate due to the presence CO_2 in the producer gas. The specific CO_2 emission was slightly reduced with an increase in engine load at low gas flow rates using the dual fuel mode. At high gas flows in the dual fuel mode, the specific CO_2 emission was considerably decreased with an increase in engine load. The percentage of the engine load increase was consistent with increasing CO_2 emissions. From Figure 4 (b), the impact of DIT was found insignificant on the response variable over the entire gas flow range.

3.5 Optimization

Figure 5 shows the prediction profilers of the response variables influenced by settings of all the design variables. The red vertical dotted lines are the operating settings, and changing the red lines updates the response variables (see rows 1 and 2) and the desirability value (see row 3). An increase in producer gas flow (see column 2) noticeably resulted in a reduction of SDC (see row 1 of column 2) but a sharp increase in specific CO_2 emission (see row 2 of column 2). Optimization of a set of operating conditions is required to offset the overall desirability between the two response variables. Only the maximum value of desirability was considered even though different best results with high desirability were obtained with response to variation in the operating factors.

The maximum desirability, 0.829, was attained at 11° BTDC, 10 kg/h of the producer gas flow, and 70% of the full engine load. At the optimum operating parameters, the specific diesel consumption and the specific CO_2 emissions were 0.0967 kg/kWh and 0.6123 kg/kWh, respectively. The electrical-thermal efficiency was 14.10%.

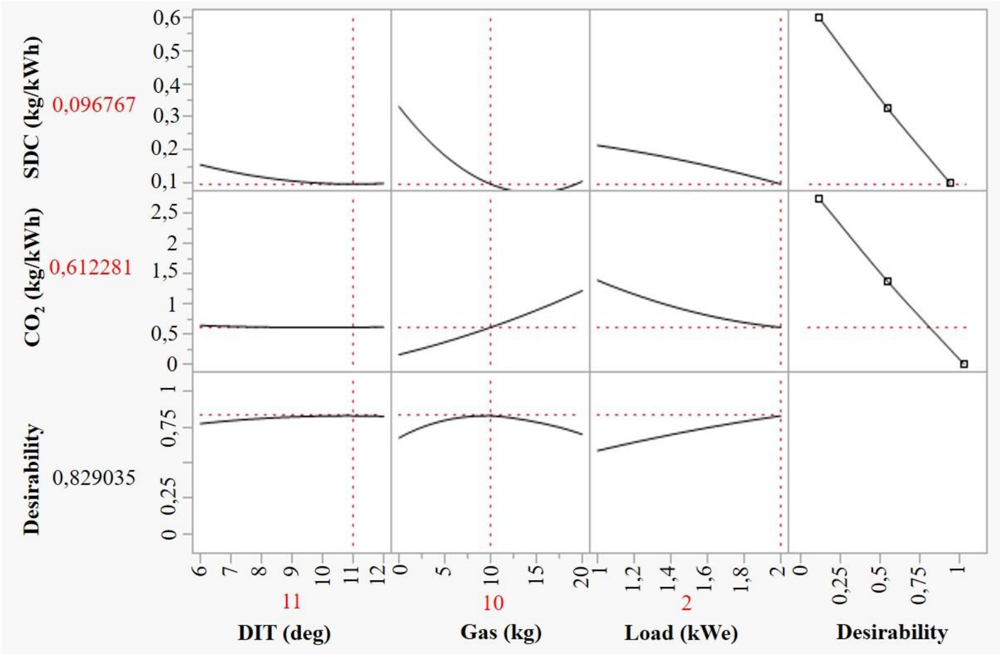

Figure 5 Desirability function-based prediction profilers

4. Conclusions and recommendations

This RSM-based investigation of the effect of design variables on all the response variables and optimization of a set of operating parameters leads to several conclusions. The gas flow rate and the engine load, their interaction terms, and the quadratic term of gas flow rate had the great impact on all the response variables (i.e., SDC, ETE, and specific CO_2 emission). It was also seen that the squared term of the engine load had a significant effect on the specific CO_2 emissions. The effect of the DIT term was observed to be marginally significant on the SDC. Increasing the engine load possibly decreased the specific diesel consumption as a result of more efficient combustion. With an increase in engine load, the ETE was noticeably improved at low gas flows in the dual fuel mode. The engine load had a great effect on the specific CO_2 emissions in the dual fuel mode at high gas flow rates and a marginal effect on the response at low gas flows.

The maximum desirability, 0.8290, was provided by the prediction profilers at an injection timing of 11° BTDC, a gas flow rate of 10 kg/h, and 70% of the full engine load. At the optimum settings, the specific diesel consumption and the specific CO_2 emission were 0.0967 kg/kWh and 0.6123 kg/kWh, respectively. The ETE at the maximum desirability was 14.10%. The dual fuel mode of the diesel engine should not be operated at the maximum diesel replacement rate.

The computational approach to optimize the operational settings in this study is very informative for practitioners and policy makers. Bio-power plants can offset the fossil fuel substitution rate and their specific CO_2 emissions. This approach can also be applied to other bioenergy types toward reduction of GHG emissions and fossil fuel dependency.

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