Optimization of Control Factors for a Diesel Engine Fueled with Jatropha Seed Producer Gas on Dual Fuel Mode

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Abstract – *A combustible gas converted from carbonaceous material through gasification technology can be used to operate the internal combustion engine. Dual fueling of the diesel engine to run on the gasified biomass has been extensively investigated; however, optimization of control factors to offset operating cost and diesel and biomass consumption has remained largely unexplored. This study aims to optimize operating settings, i.e., diesel injection timing, gas flow rate, and engine load to maximize the overall desirability of specific diesel consumption, specific Jatropha seed consumption, and operating cost. The finding highlighted that the maximum desirability of 82.29% for the sampling design was obtained at the injection timing of 9° before top dead center (BTDC), the gas flow rate of roughly 9 kg/h, and the high engine load. The concept of this study can also be applied to other bioenergy types.*

Keywords – *diesel engine, jatropha, operating cost, producer gas, response surface methodology.*

1. INTRODUCTION

Jatropha is globally considered as the promising biodiesel energy crop in view of its high oil content, resistance to various kinds of agro-climatic conditions, biodiesel properties, and renewability [1],[2]. The cost of Jatropha-derived biodiesel, however, is relatively high as compared with the conventional fossil fuels and therefore hinders commercialization of the product [2]. The net energy ratio (NER) of Jatropha biodiesel production is about 1.5. This value is lower than the NERs of palm oil and coconut oil [3]. Consequently, the exploration of other energy utilization pathways for the Jatropha has gotten a growing interest.

A combustible gas converted via air gasification is widely known as producer gas with calorific value in a range of 4–6MJ/m^3 and density of 1.287 kg/m^3 at the ambient condition [4],[5]. The producer gas can be used to run the spark ignition (SI) engine to completely replace the gasoline and the compress ignition (CI) engine to partially reduce the fossil diesel. The Jatropha press cake, the Jatropha seed, and their mixture can be used as the potential feedstock for the gasifier-engine set [6]-[8]. An increase in gas flow rate is associated with a reduction in diesel consumption rate. However, unburned fuel, CO_2 emission, and smoke opacity were found to be higher [5],[9],[10]. Furthermore, the consumption of biomass feedstock is higher at a higher diesel replacement rate, which might provoke the operation cost higher than the cost of the neat diesel mode operation.

Most of the previous studies have focused on technical feasibility and improvement of the internal combustion (IC) engine to run on producer gas. Roy *et al.* [11] and Dhole *et al.* [12] mixed the hydrogen content with the producer gas to improve the combustion and emission characteristics. The HC, CO, and particulate emissions were lower for the dual fuel mode when the biodiesel was added to reduce the fossil diesel [7],[13],[14]. Advancing the injection timing [11],[12], increasing the compression ratio [15] and the injection pressure [16], and pilot injection splitting [17] can improve the combustion characteristics. Another recent study found that Toroidal re-entrant combustion chamber (TrCC) can improve the combustion pressure without any exhaust related problems in light of improved air entrainment and air-fuel mixture [18]. To the best of our knowledge, optimization of the operating settings to offset the operating cost, diesel consumption, and biomass consumption has remained largely unexplored in the literature.

Correspondingly, the thrust of this study is to optimize the operating settings of diesel injection timing (DIT), gas flow rate, and engine load in order to maximize the overall desirability of the specific diesel consumption, the specific Jatropha seed consumption, and operating cost. The response surface methodology (RSM) and the desirability function were applied. This study is highly expected to provide a key concept for effective, efficient utilization of biomass for the gasifier-engine system. Furthermore, the developed operating cost model can be used to study the cost-benefit analysis of Jatropha bio-energy production and utilization for future study.

2. METHODOLOGY

This section described the experimental design and equipment set-up adopted in this study.

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2.1 Experimental Design

The RSM consists of mathematical and statistical techniques applied for modeling and analysis of problems in which one or more response variables are affected by several explanatory variables, and the objective is to determine a region of the factor space with all satisfied requirements [19]. Face-centered central composite design (CCD) technique of the RSM was applied in our study because this technique facilitates in changing factor levels and requires only two or three center points enabling to provide a good variance of prediction [19]. The RSM design matrix of the study was generated using the Design Expert 6.0 statistical tool and implemented by inputting the lower and upper levels of the control variables, as listed in Table 1. The DIT was varied from 6 to 12° before top dead center (BTDC). The gas was limited from no gas to 20 kg/h, and the engine load was varied from 1 to 2 kWe. The statistical tool analyzed the models based on ANOVA (Analysis of Variance) and generated the mathematical models in terms of factors in actual values. The other statistical tool, JMP 11 software, was then used to make 3-Dimensional plots of the response variables and simultaneously optimize multiple responses of interest to maximize the overall desirability based on the desirability function.

Table 1. The independent variables and their levels with code and actual values.

Independent variables	Symbol	Codes and levels		
		-1	0	+1
DIT (degree BTDC)	DIT	6	9	12
Gas flow rate (kg/h)	Gas	0	10	20
Engine load (kWe)	Load	1	1.5	2

2.2 Desirability Function

The desirability function is a simultaneous optimization technique to find a set of operating conditions for multiple responses with the maximum overall desirability [19]. The desirability is dimensionless and ranges from zero (totally unacceptable) to one (extremely preferable).

As mentioned earlier, the response variables are the SDC (kg/kWh), the SJC (kg/kWh) and the operating cost (US$/kWh). The SDC is the ratio of diesel consumption rate (kg/h) to the electrical load (kWe), while SJC is the Jatropha seed consumption rate (kg/h) divided by the electrical load (kWe). The operation cost of one electrical kWh generation is the total cost of diesel and Jatropha seed divided by the electrical load (kWe). The fuel costs are based on the costs in India and considered as Indian Rupees (INR) because the Jatropha seed's price in India is slightly varied as compared with that in other countries. Jatropha seed’s price was INR 6 per kilogram [20], and this price was selected in the present study. The price of fossil diesel was assumed to be INR 55 per liter, and the price increases or decreases in terms of year and slightly varies with respect to oil company and city. The investment cost of machinery and maintenance cost were excluded owing to no data availability. The authors assumed INR 1 = USD 0.014.

The target of all the responses in our study is to minimize all the response variables. Optimization of the overall desirability is expressed below [19]:

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

$$d = \begin{cases} 1 & y < T \\ \left(\dfrac{U-y}{U-T}\right)^r & T \le y \le U \\ 0 & y > U \end{cases} \tag{2}$$

where d, D, and m are individual desirability, the overall desirability, and the number of response variables, respectively. The target T is the maximum value for the response y, and U is the upper limit of desirability. Choosing r > 1 makes more emphasis close to the target value.

2.3 Experimental Set-up

Figure 1 illustrates the schematic diagram of the experimental set-up. The set-up is composed of a throatless downdraft gasifier, a gas cleaning system, a diesel generator set, and a variable electrical load. The technical specifications of the gasifier are listed in Table 2. The Jatropha seed consumption rate was 5 kg/h and 5 kg of the seed produced 20 kg of producer gas using the designed gasifier.

Table 2. Basic technical specifications of the gasifier.

Item	Description
Type	Closed-top, throatless, downdraft
Gasifier’s weight (kg)	30
Critical dimension (mm)	D = 350 / h = 1800
Capacity (kW_{th})	130
Consumption rate (kg/h)	5
Biomass feedstock	Jatropha seed
Efficiency (%)	~77

A KM 186F engine test was used and its main characteristics are summarized in Table 3. The air intake system was modified to induct the gas synchronized with the air inlet into the engine. Five (5) 0.5 kWe electrical heaters in series were connected, and each heater was connected to an on-and-off switcher. The instrument is integrated to the set-up to measure the engine speed, producer gas mass flow rate, and diesel consumption. The engine speed was measured using a microprocessor tachometer with a reading accuracy of ±0.5 rpm. A glass burette and a digital stopwatch were used to continuously measure a quantity of diesel consumed over an interval of time. An orifice and U-tube manometer were used to calibrate the producer gas flow rate, and water was selected as the manometric fluid. The gas flow rate was calculated based on Bernoulli’s principle.

Table 3. Main characteristics of the test engine.

Item	Description
Model	KM 186F
Engine type	Single cylinder, 4-stroke, direct injection
Bore×stroke (mm)	86×70
Connecting rod length (mm)	117.5
Displacement (cm^3)	406
Engine speed (rpm)	3,000/3,600
Compression ratio	19:1
Rated output power (kW/rpm)	5.7/3,000
Full load (kWe)	2.5

For all the experimental settings, the engine speed remained constant at 3,000 rpm, and temperature of the cleaned gas was maintained around 30°C. The electrical load was varied by switching on-and-off switchers of the heaters, while injection timing variations were implemented by changing the shim thickness mounted under the diesel injector. A ball valve was used to control the producer gas loadings.

3. RESULTS AND DISCUSSION

3.1 Analysis of Response Surface Methodology

Table 4 lists the sixteen (16) experimental settings with the observed data. The analysis of experimental design is based on the analysis of variance (ANOVA). For more detailed information of the model analysis, Table 5 provides the key results of ANOVA and a summary of fit.

A term with a p-value less than 0.05 is statistically significant. The significant magnitude increases if the p-value is lower. All significant terms are the desirable outcomes, except lack of fit. All the models in this study were highly significant with p-values less than 0.0001, which was reliable to express a strong relationship between the response variables and the design variables. Lack of fit was non-significant for the specific diesel consumption and operation cost but significant for the specific Jatropha seed consumption. Non-significant lack of fit indicates that the model fits the data very well.

The R^2 is a proportion of variability in a response variable explained by the model. Adj. R^2 accounts for a number of significant factors in a model, and its value will decreases only if non-significant terms are added to a model. Pred. R^2 is a measure of how well a model predicts the output variable, and the model is a good predictor if its Pred. R^2 is close to one. The values of R^2, Adj. R^2, and Pred. R^2 close to one are preferable.

Only parameter estimates with p-values less than 0.05 were included in the developed models. The positive sign of coefficient presents a synergistic effect, while the negative sign of coefficient indicates an antagonistic effect.

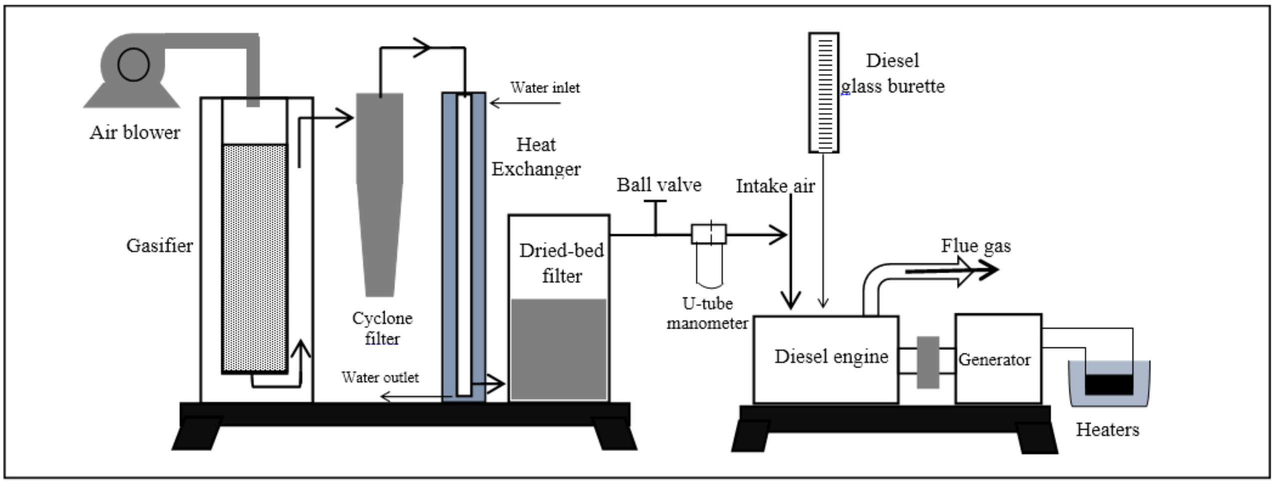


Fig. 1. Schematic diagram of the experimental set-up.

Table 4. Face-centered CCD based matrix of experimental design with the experimental data.

Run	Independent variables			Response variables		
	DIT (BTDC)	Gas (kg/h)	Load (kWe)	SDC (kg/kWh)	SJC (kg/kWh)	Cost (US$/kWh)
1	6	0	1	0.64	0	0.49
2	6	0	2	0.44	0	0.34
3	6	10	1.5	0.31	1.667	0.38
4	6	20	1	0.36	5	0.70
5	6	20	2	0.22	2.50	0.38
6	9	0	1.5	0.42	0	0.32
7	9	10	1	0.33	2.50	0.46
8	9	10	1.5	0.27	1.667	0.35
9	9	10	1.5	0.26	1.667	0.34
10	9	10	2	0.22	1.25	0.27
11	9	20	1.5	0.26	3.333	0.48
12	12	0	1	0.52	0	0.40
13	12	0	2	0.43	0	0.33
14	12	10	1.5	0.30	1.667	0.37
15	12	20	1	0.32	5	0.67
16	12	20	2	0.21	2.50	0.37

Table 5. Summary of ANOVA.

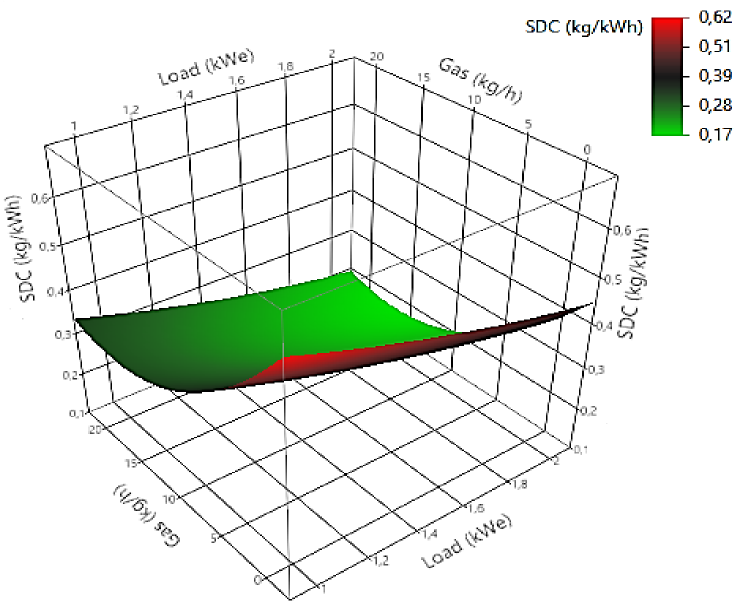
Terms	SDC (kg/kWh)		SJC (kg/kWh)		Cost (US$/kWh)	
	Coefficients	P-value	Coefficients	P-value	Coefficients	P-value
Model		<0.0001		<0.0001		<0.0001
Intercept	1.10727	<0.0001	1.70743	<0.0001	1.17643	<0.0001
DIT	-0.09542	0.0507	–	–	-0.08154	0.0174
Gas	-0.02671	<0.0001	0.37083	<0.0001	0.00997	<0.0001
Load	-0.13000	<0.0001	-2.49860	<0.0001	-0.50061	<0.0001
DIT^2	0.00495	0.0182	–	–	0.00351	0.0109
Gas^2	0.00079	0.0005	–	–	0.00059	0.0004
$Load^2$	–	–	0.83287	0.0004	0.10399	0.0255
DIT.Gas	–	–	–	–	–	–
$DIT.Load^2$	–	–	–	–	0.00898	0.0380
Gas.Load	–	–	-0.12500	<0.0001	-0.00973	<0.0001
Lack of fit		0.1909		0.002		0.2551
Summary of fit						
R^2	0.9657		0.9983		0.9927	
Adj. R^2	0.9485		0.9977		0.9843	
Pred. R^2	0.9014		0.9964		0.9438	

3.2 Specific Diesel Consumption (SDC)

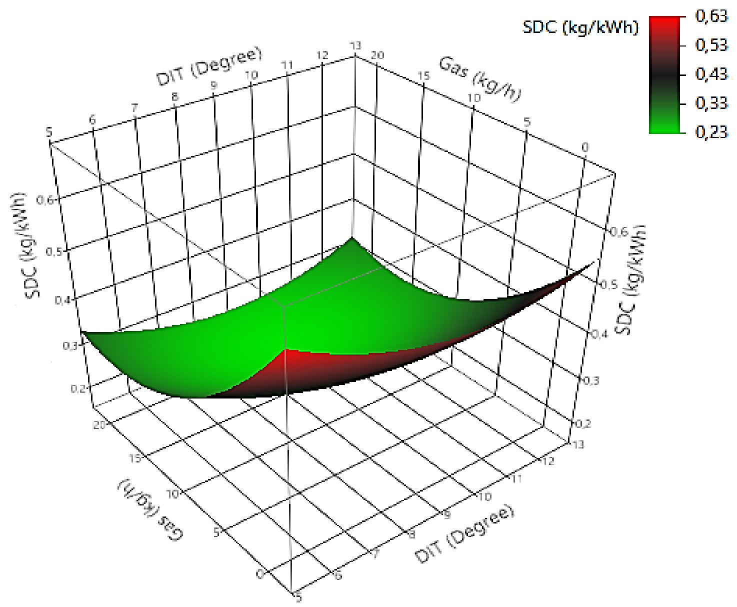
Based on the ANOVA analysis presented in Table 5, the linear terms of gas and load and the quadratic term of gas^2 had the extremely significant effects on the SDC response. The quadratic term DIT^2 was also significant but at a lower magnitude. A significant quadratic term shows a curvature in a response variable. The term DIT was significant at a 10% level. The other terms were not statistically significant. The mathematical model of the SDC as a function of the significant factors is expressed below:

$$SDC = 1.10727 - (0.09542 \times DIT) - (0.02671 \times Gas) - (0.13 \times Load) + (0.00495 \times DIT^2) + (0.00079 \times Gas^2) \quad (3)$$

Figure 2 illustrates the 3-dimensional plots of the response variable in terms of the control factors. Evident from Figure 2(a), the maximum SDC was found at no gas and low load where the engine is inherently inefficient. The SDC decreased with an increase in gas flow rate and engine load. This can be explained by increasing the heating value of higher gas flow coupled with improved combustion efficiency because the engine load approaches its rated power. As evident in Figure 2(b), the minimum SDC was found at the optimal 9° BTDC of diesel injection timing. It is due to that advancing injection timing results in better spray development and more rapid burning rate during the premixed combustion phase [21],[4], but the further advance of pre-injection timing provokes a decrease in in-cylinder temperature and pressure in spray [22]. Injection timing, therefore, has a significant effect on combustion pressure that is influenced by the premixed combustion phase and the intake charge thermodynamics properties. It was conceivable that wrong position of peak pressure could decrease the peak value, and more fossil diesel thus is probably required to address this issue.



(a)



(b)

Fig. 2. Specific diesel consumption: a) at 9 ° BTDC of diesel injection timing; b) at 1.5 kWe engine load.

3.3 Specific Jatropha Seed Consumption (SJC)

Regarding the ANOVA table, the effects of the linear terms of gas and load, the gas-load interaction term, and the quadratic term of load^2 had a considerable contribution to variability of the SJC response. The relationship between the significant terms and the response variable can be written as Equation 4:

$$SJC = 1.70743 + (0.37083 \times Gas) - (2.4986 \times Load) + (0.83287 \times Load^2) - (0.125 \times Gas.Load) \quad (4)$$

The surface plots of the SJC influenced by the significant terms are illustrated in Figure 3. The SJC is proportionally linked to gas flow rate, and the surface trend of the response falls down with increasing engine load, as can be seen in Figure 3(a). An increase in gas flow rate can replace more diesel fuel but consumes more biomass, for all the engine loads. The engine load had an extreme effect on the specific biomass consumption for the dual fuel operation mode when the gas flow rate was at the maximum level. This could be due to the highly significant term of the gas-load interaction on the response. Evident from Figure 3(b), the diesel injection timing did not affect the response. It was interpreted that the SJC is considerably associated with the gas flow rate irrespective of the injection timing.

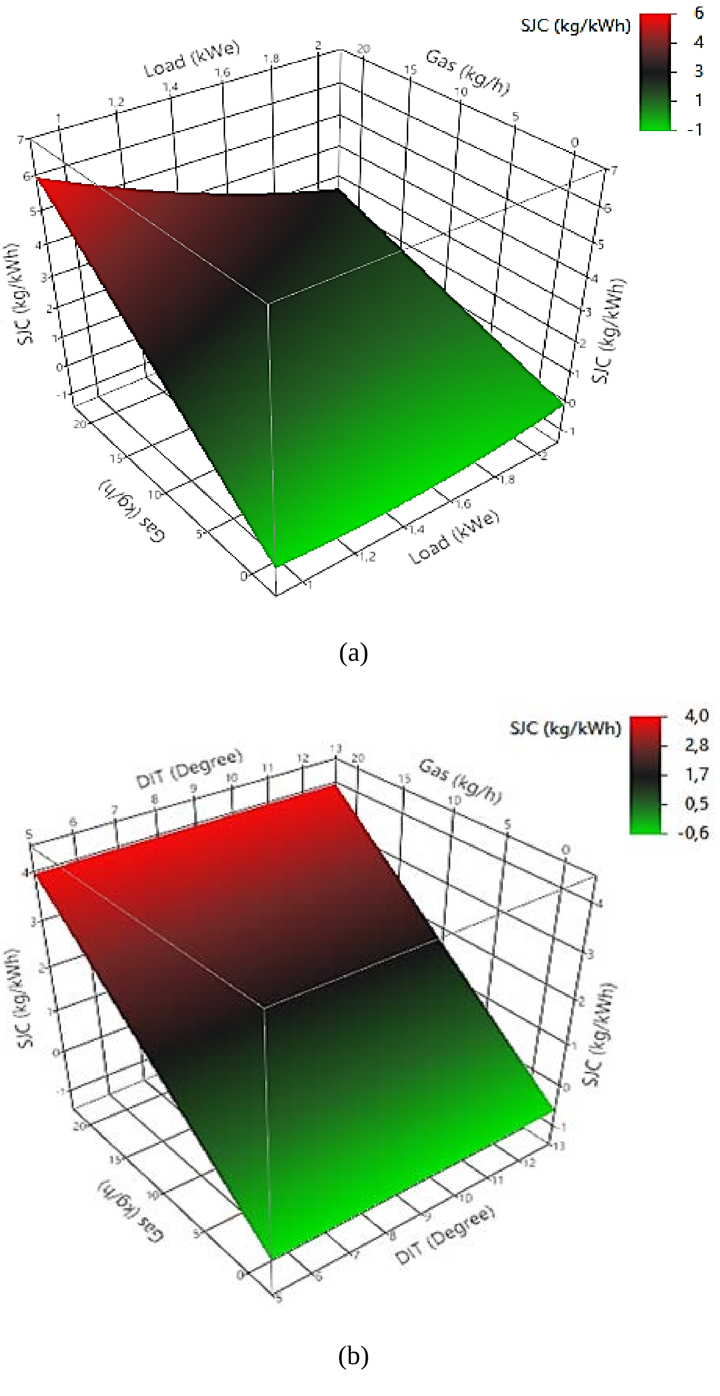


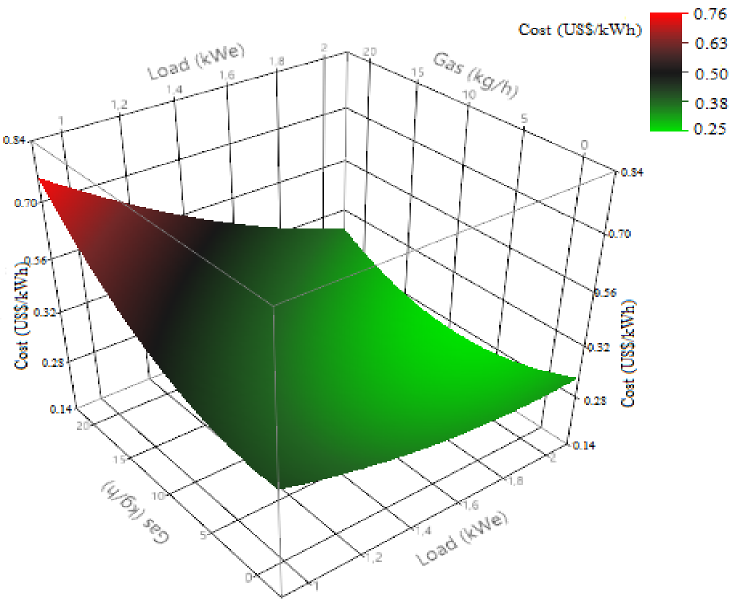
Fig. 3. Specific Jatropha seed consumption: a) at 9 ° BTDC of diesel injection timing; b) at 1.5 kWe engine load.

3.4 Operating Cost of 1 kWh Electrification

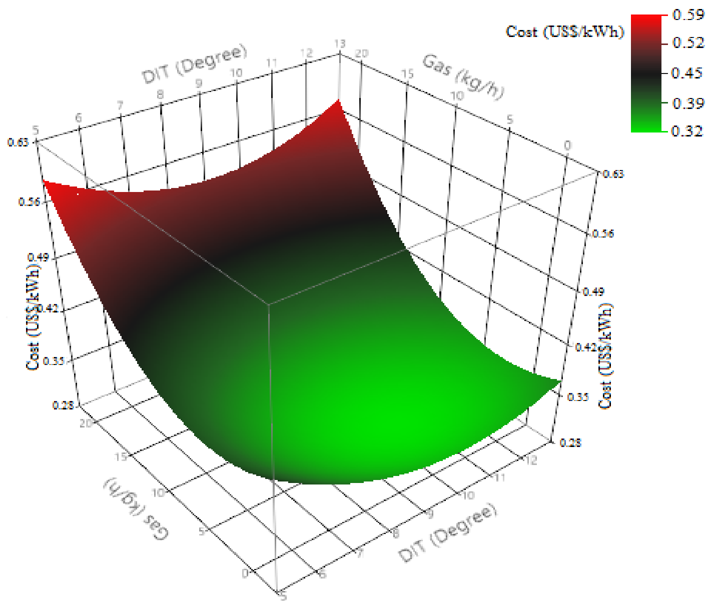
All the three control factors and their interaction and quadratic terms affected the operation cost significantly, except for the DIT-gas interaction term. Equation 5 describes the relationship between the significant terms and the response variable:

$$\text{Cost} = 1.17643 - (0.08154 \times \text{DIT}) + (0.00997 \times \text{Gas}) - (0.50061 \times \text{Load}) + (0.00351 \times \text{DIT}^2) + (0.00059 \times \text{Gas}^2) + (0.10399 \times \text{Load}^2) + (0.00898 \times \text{DIT.Load}) - (0.00973 \times \text{Gas.Load}) \quad (5)$$

As evident from Figure 4(a), an increased operating cost was found along with an increase in gas flow rate at low load operation. It is on account of less efficient combustion of producer gas on dual fuel mode at low load, and the price of diesel saving cannot compensate for the cost of Jatropha seed consumed. For the whole range of gas flow rate, the declined trend of the response surface is seen with an increase in engine load. It is mainly due to a percentage of an increase in engine load higher than a percentage of an increase in fuel consumption. At high load, the operating cost declined to the lowest point with the increase in gas flow rate as a result of the price of the consumed Jatropha seed lower than that of the reduced diesel. The cost went up with a further increase in gas flow as the price of the increased Jatropha seed cannot compensate for the saving price of the replaced diesel. The lowest point of operation cost was a result of the minimum total price of the biomass and the diesel used. From Figure 4(b), the low operation cost was found at 9° BTDC of diesel injection timing for the entire gas flow. It was probably on account of efficient combustion of the fuel-air mixture at the mentioned injection timing.



(a)



(b)

Fig. 4. Operating cost: a) at 9 ° BTDC of diesel injection timing; b) at 1.5 kWe engine load.

3.5 Desirability Function-Based Optimization

Figure 5 shows the prediction profiler of the predicted responses influenced by settings of all the control factors. The red vertical dotted lines are the operating settings, and changing the red lines can update the predicted responses and the overall desirability. Various overall desirability values can be obtained, but only the highest value of the overall desirability was chosen for the optimum operating settings. The maximum desirability was found to be 82.29% at 9° BTDC of diesel injection timing, about 10 kg/h gas flow rate, and 2 kWe engine load. At the optimum operating settings, SDC, SJC, and operation cost were equal to 0.22 kg/kWh, 1.23 kg/kWh, and 0.27 US$/kWh, respectively.

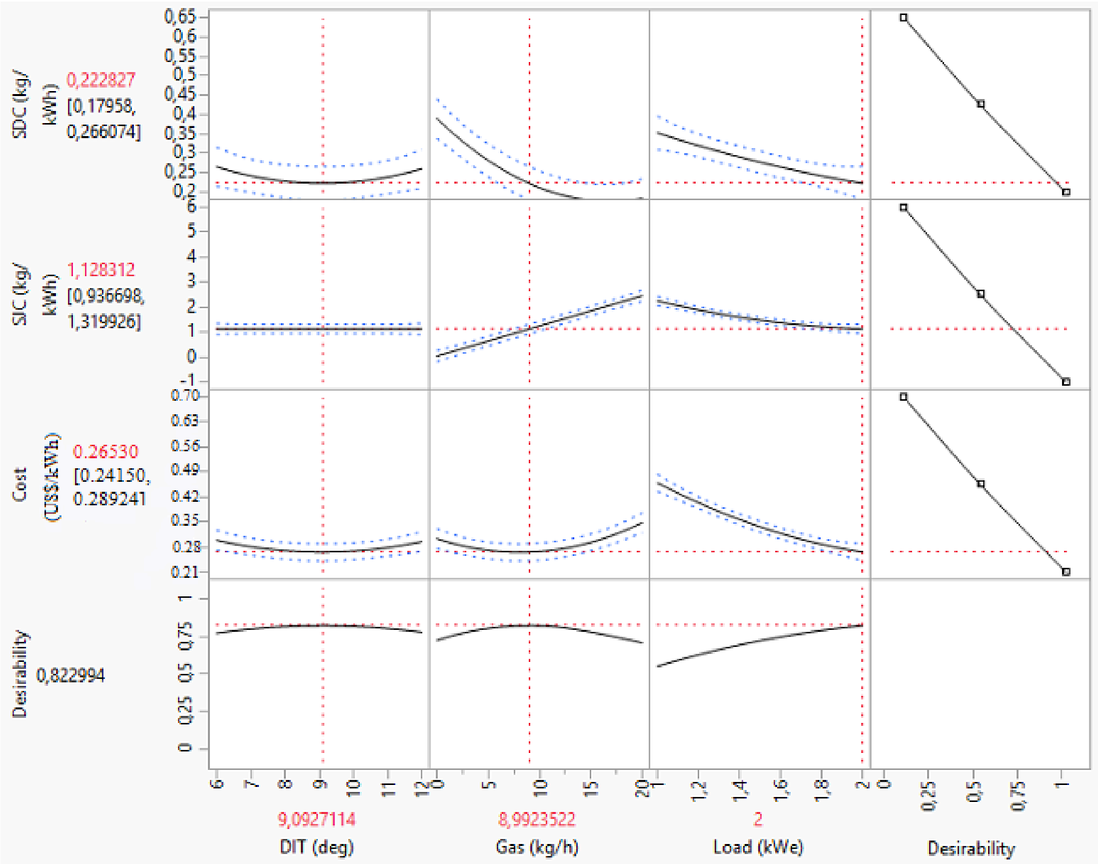


Fig. 5. Prediction profiler of desirability.

4. CONCLUSIONS

The impact of control factors and their interaction and quadratic terms on the response variables are analyzed based on the ANOVA. It highlighted that the gas flow rate and engine load had extremely significant effects on all the response variables.

The minimum SDC was found at 9° BTDC of diesel injection timing, high engine load, and high gas flow rate. An increase in gas flow replaces more fossil diesel but leads to an increase in Jatropha seed consumption. Consequently, the cost of one kWh electricity generation declined to a minimum point with an increase in gas flow and then the operation cost returned to increase when the gas flow rate was increased further.

The desirability function, therefore, was used for the optimization of the operating settings to maximize the overall desirability of the specific diesel and Jatropha consumption and operating cost. The maximum desirability of 82.29% was obtained at diesel injection timing of 9° BTDC, gas mass flow rate of roughly 10 kg/h, and high engine load. At the optimal operating settings, SDC, SJC and cost of one kWh electrification were computed to be 0.22 kg/kWh, 1.23 kg/kWh and 0.27 US$/kWh, respectively.

This study provides a novel concept for economic and efficient utilization of bio-energy to mitigate the fossil diesel consumption for decentralized electrification. The mathematical models developed in this study are highly expected to be informative for future studies related to the cost-benefit analysis of Jatropha bioenergy production and utilization.

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