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Statistical Analysis of Industry Scale Up Draft Coal Gasifier Using Response Surface Methodology for Sustainable Development

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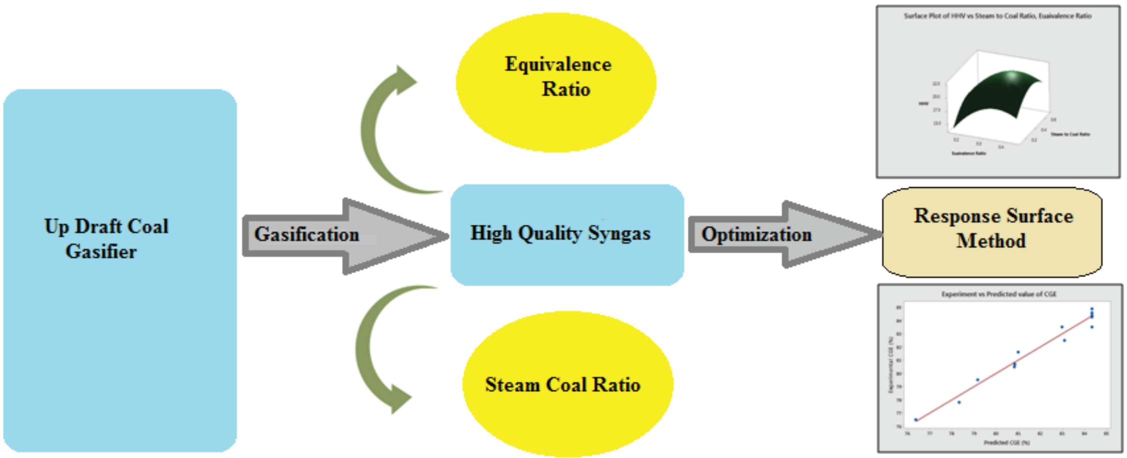
ABSTRACT

Radhe Renewable Energy Pvt. Ltd. in Rajkot has developed an updraft hot filtration coal gasifier technology with a coal consumption capacity of approximately 35 metric tons per day for various industrial applications. This gasifier is designed to supply clean fuel gas for a porcelain insulator manufacturing plant at Bikaner Ceramics in Rajasthan. The present study involves a series of experimental runs aimed at examining the influence of two operating variables—equivalence ratio (ER) and steam coal ratio (SCR) — as well as how their interactions affect the gasifier's performance metrics, like higher heating value, cold gas efficiency, and carbon conversion efficiency, using Indonesian coal. In order to maximize the coal gasification process, the steam coal ratio (SCR) fluctuates between 0.2 and 0.6, and the equivalence ratio (ER) inside ranges between 0.2 and 0.4. The response surface optimizer tool in Minitab Software has been employed to determine the optimal values for the equivalence ratio and steam coal ratio that maximize syngas quality. It was found that an equivalence ratio of 0.3699 and a steam coal ratio of 0.499 yield syngas with an increased higher heating value (HHV) of up to 22.32 MJ/kg, an improved carbon gasification efficiency (CGE) of up to 84.90%, and an enhanced carbon conversion efficiency (CCE) of up to 97.90%.

GRAPHICAL ABSTRACT



Index-words: *Gasifier, Equivalence ratio, Steam coal ratio, Efficiency.*

I. INTRODUCTION

Coal is a profuse energy source, but it is unreliable due to its significant carbon dioxide emissions. Reducing CO_2 emissions is the goal of the energy sectors to stop the harmful effects of global warming [1]. Coal gasification has proven to be a process that reduces CO_2 emissions and is considered a clean coal technology [2]. The coal gasification process is a better solution because of the lower cost for the removal of CO_2 in comparison with conventional energy systems deep-rooted in direct coal combustion. Coal gasification technology is an incorporated mode that produces power, hydrogen, chemicals and their products, fertilizer, etc. [3]. These end products will help to move towards self-capability under Atmanirbhar Bharat Abhiyaan. Along with the above objective, The Ministry of Coal proposed a coal-use program using coal gasification technology, and as such, this National Coal Gasification Mission (NSG Mission) has been prepared to attain 100 MT of coal gasification by the end of the year 2030 [4].

A gasifier is the prime component where all the changes of coal into syngas occur. Before World War II, gasification technologies were invented in Germany. The type of gasifier influences the quality of gas produced [5,6,7]. Classification of gasifiers based on syngas extraction systems like updraft (syngas flows upside) and downdraft (syngas flows downside) was given by Higman and Burgt.Ronald W. Breault described twelve major gasifiers along with the hydrodynamics and kinetics of gasifiers [8]. Ruyi Shao et al. presented circulating fluidized bed technology at KEDA by gasification with low-rank coal to produce syngas at low Btu , and cold gas efficiency attaining up to 73% at a steam coal ratio of 0.38 and an equivalence ratio of 0.3 [9]. Ran Li et al. found that for the highest hydrogen production, the optimal oxygen-to-coal ratio and steam-to-coal ratio were 0.52 and 0.05, respectively [10]. Hao Xie et al. examined the effects of the oxygen/coal ratio, and water/coal ratio on the temperature and cold gas efficiency of the gasifier in Integrated Gasification Combined Cycle (IGCC) systems. It is found that the optimal range for the oxygen/coal ratio was between 0.74 and 0.78, and for the water/coal ratio was between 0.36 and 0.50 [11]. Gasification temperature was observed as the most influential factor among all factors, followed by the equivalence and steam coal ratio found by G Suresh Kumar et al. [12]. The lower value of equivalence ratio and pressure promotes H_2 formation. Even a higher steam coal ratio also promotes H_2 formation. CO decreases with a higher equivalence ratio and steam-to-coal ratio, while it is increased by lowering the gasifier temperature [13]. Low equivalence ratios and high temperatures favor the formation of CO. The maximum amount of CO is produced in the temperature range of 600°C to 900°C. Detailed reaction kinetics was investigated by Ahmed M. Salem and Manosh C. Paul at different values of ER [14].

In various industries where heating is a primary requirement, updraft coal gasifiers are utilized. Different industries employ different types of gasification technology based on their specific needs. Consequently, the design features—such as size, fuel type, fuel capacity, and type of firing—vary across applications. As a result, various fuels have been used in different units.

Radhe Renewable Energy Development Pvt. Ltd. is well-known for manufacturing updraft coal gasifiers, which have been widely used in ceramic industries. This study marks a significant milestone in the field of energy generation and environmental issues by evaluating the performance of an updraft coal gasifier with hot filtration technology on an industrial scale for the first time.

Hot filtration is an advanced technology developed by Radhe Renewable Energy Pvt. Ltd., Rajkot, to remove tar from produced syngas. Till now, a regression model with two factors equivalence ratio and steam coal ratio using the RSM method has not been analyzed by any authors for an updraft coal gasifier with hot filtration technology in MINITAB Software. In the present study, experiments have been carried out on different values of ER and SCR. The equivalence ratio represents the amount of air supplied for gasification compared to the theoretical air required for complete combustion of fuel. The steam coal ratio shows how much quantity of steam has been added into the gasifier per kg of coal for the gasification [15]. For a constant coal feed rate, the air and steam mixture was added from the bottom according to the different ER and SCR [16]. After obtaining the best possible value of the equivalence ratio, the amount of steam was increased gradually, and the effect of steam was analyzed. All these experiments (DOE) were carried out by using the design of experiment methods. Response surface methodology (RSM) was the best tool for obtaining the optimum solution to maximize the gasifier performance parameters [17].

II. METHODOLOGY

A. Geometric Configurations of Gasifier

The coal gasifier used in the present research is an updraft coal gasifier manufactured by Radhe Renewable Energy Pvt. Ltd., Rajkot. This updraft coal gasifier, with a coal consumption capacity of approximately 35 MT/day, is designed to produce clean fuel gas for porcelain insulator manufacturing plants. The gas produced is used to meet the heating requirements of the plant. The gasifier has a

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cylindrical shape and features two ports on the top. It stands 5500 mm tall with a diameter of 3790 mm. Dry coal (fuel) is fed into the gasifier through a top-centered hole via a coal hopper with a diameter of 855 mm. The syngas outlet port, located next to the coal inlet port, has a diameter of 800 mm. Air and steam, used as oxidizers, are introduced through the bottom of the cylinder. Fig. 1 illustrates the schematic diagram of the updraft coal gasifier plant. A key drawback of updraft coal gasifiers is tar generation [18]. However, in this plant, a hot coal filter media are employed after a cyclone-type separator to remove tar from the produced syngas. The hot and clean gas flame temperature at the burner is approximately 1400 °C, which is high enough to convert the remaining tar into a gaseous form and thereby increase the heating value of the produced syngas [19].

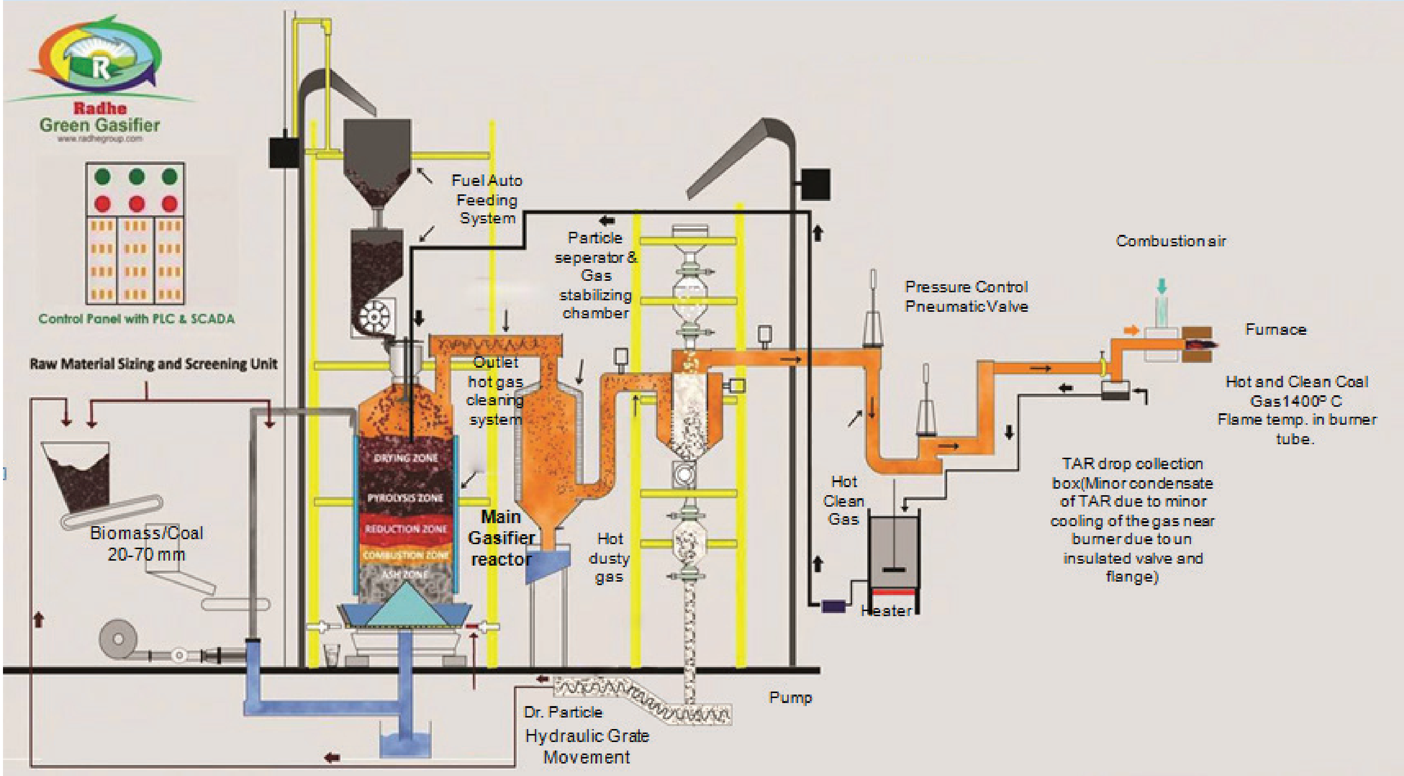


Fig. 1. Schematic diagram of Updraft Coal Gasifier@ Radhe Pvt.Ltd. Rajkot [20]

B. *Test Material*

Coal was passed through a pulverizer and screening unit to achieve a particle size between 20 and 50 mm. The coal had a density of 940 kg/m^3 and a heating value of 24.81 MJ/kg. It is crucial to ensure the coal quality is uniform throughout the lot. Charcoal was uniformly spread up to a height of approximately 1 foot above the ash bed. Then, 100 kg of coal was ignited outside the unit. This ignited coal was evenly distributed over the charcoal bed through the main hole, which was then sealed.

Once the coal bed temperature reached 500 °C, prepared coal was fed into the top inlet port of the gasifier. As the temperature of bed increased rapidly, the combustion process transitioned to gasification by increasing the coal feed rate while decreasing the flow rate of air. The steam was then injected into the gasifier. The pressure and bed temperature inside the gasifier were continuously monitored until a steady-state condition was achieved. The coal feeding rate from the top hopper of the gasifier was approximately 90 kg every 6 minutes. A sample of coal was collected for ultimate and proximate analysis, as shown in Table I.

TABLE I
COAL ANALYSIS.

Proximate Analysis on wet basis. %		Ultimate Analysis on wet basis. %	
Fixed Carbon	41.66	C	68.01
Volatile Matters	32.42	H	4.55
Moisture	20.32	O	26.4
Ash	4.65	N	1.04

C. *Process Flow Description*

The values of the operating variables, namely the equivalence ratio (ER) and the steam coal ratio (SCR), were selected for each test run based on the experimental design matrix suggested by the Response Surface Methodology (RSM). The temperature of the gasifier reactor was maintained at approximately 800 °C. During the test period, six thousand tons of coal were used. Signals from all measurement units were automatically transmitted to the PLC SCADA system, which monitored the reactor temperature, gasification pressure, and the flow rates of air and steam during operation.

The gasification plant was fully equipped with pressure measurement devices, thermocouples for temperature measurement, flowmeters, and other necessary instruments. After cleaning and cooling the syngas to room temperature, the fuel gas composition was analyzed by a gas chromatograph under steady-state conditions.

D. *Design of Experiments*

Two effective operating variables—namely, the equivalence ratio and the steam-to-coal ratio—were selected for the experimental study. The values of these variables ranged from 0.2 to 0.3 and 0.2 to 0.6, respectively. These ranges were determined through pilot experiments. The experimental results were used to compute syngas quality indices.

The design of experiment (DOE) method has been used to determine the best combinations of variables to analyze a system with a minimum number of experimental runs. This method also evaluates the interaction effects between the selected variables. Response surface methodology, a statistical tool complemented by design of experiment methods, was chosen for modeling and analyzing the process, where output variables (responses) are significantly influenced by some independent variables. It is developed by Box and Wilson, supports quality improvement across various fields [21,22,23].

In many cases, first- and second-order polynomial equations are used to assess the relationship between variables. The Central Composite Design (CCD) method was selected for this study because of the significant interactions between variables. The CCD method includes three types of experimental runs: cube runs (4), axial runs (4), and center runs (5) [23,24].

III. *RESULTS AND DISCUSSION*

A. *Syngas Quality Indices*

A total of 13 runs were performed, and the results of all 13 experiments are presented in Table II. The Higher Heating Value (*HHV*) of syngas is defined as:

$$HHV_{syngas} = \sum x_i HHV_i \tag{1}$$

Where x_i the portion of each combustible is gas in syngas such as CH_4, CO, C_2H_4, C_2H_2, and HHV_i is its corresponding heat of combustion.

The cold gas efficiency (CGE) is defined as the ratio of the heat value of syngas to the heat value of coal and is calculated as:

Cold Gas Efficiency (%)

$$= \left(\frac{m_{out}(yH_2HHV_{H_2} + yCOHHV_{CO} + yCH_4HHV_{CH_4}}{m_{incoal}HHV_{coal}} \right) \times 100 \tag{2}$$

Where, y is the mass fraction of that specific species. HHV of hydrogen is 120 MJ/kg, HHV of carbon monoxide is 10.1 MJ/kg and HHV of methane is 50 MJ/kg. m_{out} is the mass flowrate of syngas, and m_{incoal} is the mass flowrate of coal.

The carbon conversion efficiency (CCE) evaluates the fraction of carbon content converted from coal into syngas. It is calculated as:

Carbon Conversion Efficiency (%)

$$= \left(1 - \frac{m_{out}\left(yCO_2 \frac{12}{44} + yCO\frac{12}{28} + yCH_4 \frac{12}{16} \right)}{m_{incoal}\, y_C} \right) \times 100 \qquad (3)$$

Where, y is the mass fraction of species. m_{out} is the mass flowrate of syngas, and m_{incoal} is the mass flowrate of coal.

The gasifier was tested at different ER and SCR values, as shown in Table II. Based on the output syngas composition (% of CO, CO_2, H_2, CH_4, and H_2O) and its flowrate, values of HHV, CGE, and CCE were computed and observed from 17.52 to 22.32 MJ/kg, 77.8 to 84.9%, and, 93.51 to 97.89 %, respectively. Other researchers also reported the same range of data provided by this study [25,26].

Coal particles have been fed into the gasifier, where pyrolysis and gasification reactions start with an increase in the coal bed temperature in the reactor [27,28]. Besides the pyrolysis, CO is generated by heterogeneous H_2O and CO_2 gasification. A considerable amount of CH_4 is produced primarily during pyrolysis at the heating stage [29,30]. Hydrogasification was found significant merely at high pressure and temperatures [31,32]. The water/gas shift reaction controls the H_2/CO ratio in syngas. At high steam partial pressures, the gasification reaction promotes CO consumption while enhancing H_2 production. The steam/O_2 ratio has the most significant effect on the H_2/CO ratio. This ratio can increase with rising the coal federate [33,34,35].

TABLE II
LIST OF DESIGNED EXPERIMENTS AS PER RSM METHOD.

Run no.	Equivalence Ratio	Steam to Coal Ratio	HHV Of Syngas (MJ/kg)	Cold gas efficiency (%)	Carbon Conversion Efficiency (%)
1	0.3	0.4	22.16	84.41	96.13
2	0.4	0.2	20.38	80.5	96.5
3	0.3	0.4	22.32	84.25	96.2
4	0.441421	0.4	21.2	80.7	97.89
5	0.3	0.682843	20.34	82.5	96.5
6	0.3	0.4	22.04	84.9	96.5
7	0.3	0.4	22.12	83.5	96.11
8	0.3	0.117157	18.65	81.6	93.12
9	0.4	0.6	21.23	83.5	97.9
10	0.158579	0.4	17.52	76.5	94.01
11	0.3	0.4	22.24	84.6	96.24
12	0.2	0.6	18.8	79.5	94.8
13	0.2	0.2	17.68	77.8	93.51

B. ANNOVA Analysis

ANOVA (Analysis of Variance) is a powerful statistical tool for understanding the gasification process and the performance of the gasifier by quantifying the effects of variables and their interactions. ANOVA evaluates all factors individually, their squares, and their interactions in a single analysis. This comprehensive approach allows for assessing how each term contributes to the variability in the response and whether these factors interact in significant ways. Table III presents the ANOVA results for the coal gasification tests, which are intended to develop prediction models generated by Minitab software.

TABLE III
ANALYSIS OF VARIENCE.

Source	HHV Of Syngas (MJ/kg)		Cold Gas Efficiency (%)		Carbon Conversion Efficiency (%)	
	SS	P-value	SS	P-value	SS	P-value
Model	38.209	0.000	86.1578	0.000	26.570	0.000
Linear	15.726	0.000	24.4295	0.000	23.729	0.000
ER	13.349	0.000	19.9702	0.000	16.753	0.000
SCR	2.3762	0.000	4.4593	0.011	6.9752	0.000
Square	22.465	0.000	61.3057	0.000	2.8387	0.006
ER*ER	13.329	0.000	57.1406	0.000	0.0328	0.623
SCR *SCR	12.061	0.000	9.0566	0.002	2.8372	0.002
2-Way Interaction	0.0182	0.266	0.4225	0.325	0.0030	0.880
ER *SCR	0.0182	0.266	0.4225	0.325	0.0030	0.880
Error	0.0875		2.6400		0.8666	
Lack-of-Fit	0.0408	0.427	1.5405	0.276	0.7685	0.023
Pure Error	0.0467		1.0995		0.0981	
Total	38.297		88.7977		27.437	
R-Square	0.9977		0.9703		0.9684	
R-Square (adj)	0.9961		0.9490		0.9459	
R-Square (pred)	0.9905		0.8573		0.7952	

The R-squared test, significance of terms test, and lack-of-fit test are used to assess the reliability of a statistical model. If the P-value for a term is less than 0.05 (the chosen significance level, α), there is sufficient evidence to reject the null hypothesis, indicating that the term is statistically different from zero and that there is a meaningful relationship between all the dependent and independent variables. Table III presents the results of the significance tests for each term and their interactions for three responses. The P-value indicates the probability that each term has a significant effect on the model. A P-value less than 0.05 means that the term significantly affects the response, while a P-value greater than 0.1 suggests that the term is insignificant. By omitting insignificant terms from the regression model, the model can be simplified without compromising its accuracy, as measured by the R-squared value.

The R-squared value measures the percentage of variance in the dependent variable that can be predicted from the independent variables in the regression model. It serves as an indicator of the model fit. A high R-squared value, close to 1, signifies that the independent variables in the model are highly effective in explaining the variation in the response, indicating a good fit between the model predicted data and the observed data. Table III presents the R-squared value for the response model, which indicates a good fit of the regression model.

The lack-of-fit test assesses the consistency between experimentally measured values and those predicted by the model, identifying any discrepancies linked to random or systematic errors.

Table IV presents the response surface regression models developed by Minitab software for all three responses.

TABLE IV
RESPONSE SURFACE REGRESSION MODEL FOR RESPONSES.

Response	Correlation
Higher Heating value	HHV = -0.920 + 97.32 ER + 30.07 SCR - 138.42 ER * ER - 32.92 SCR * SCR - 3.38 ER * SCR
Cold Gas Efficiency	CGE = 49.69 + 181.3 ER + 21.68 SCR - 286.6 ER * ER - 28.52 SCR * SCR + 16.2 ER * SCR
Carbon Conversion Efficiency	CCE = 87.02 + 18.04 ER + 17.03 SCR - 6.9 ER * ER - 15.97 SCR * SCR + 1.38 ER * SCR

C. Effects of Equivalence Ratio and Steam to Coal Ratio on Syngas Quality

Three types of plots are used to visualize the effects of the ER and SCR on the higher heating value of syngas (HHV), cold gas efficiency (CGE), and carbon conversion efficiency (CCE), and to compare the predicted responses from the Response surface methodology (RSM) model with the experimental results.

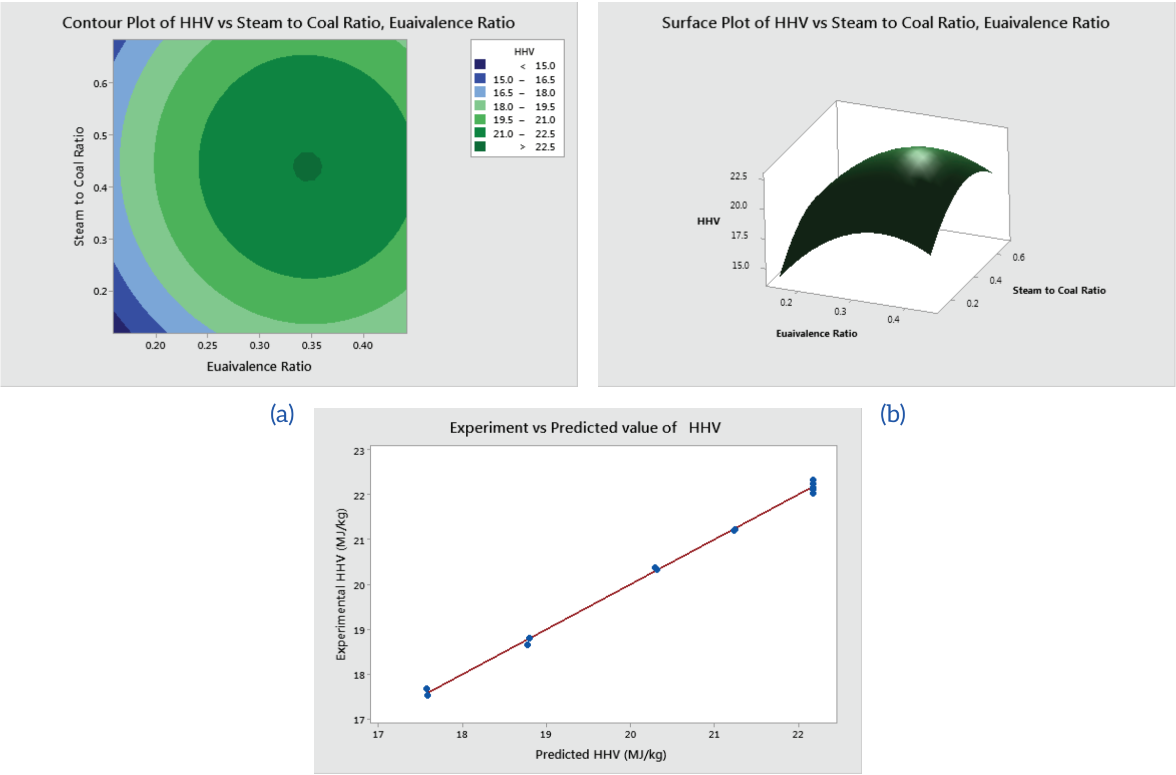
Contour plots illustrate the spatial relationships between predictor variables and the response variable. The shape, density, and intersections of contour lines indicate how changes in the independent variables affect the response variable and reveal interaction effects. Surface plots show the relationship between dependent and independent variables, while scatter plots display the distance between experimental data points and predicted data points.

The equivalence ratio and steam coal ratio significantly influence the composition of syngas and its higher heating value in coal gasification. The pilot experiment results suggest that the optimal ranges for the ER and SCR are 0.2 to 0.3 and 0.2 to 0.6, respectively. The higher heating value and cold gas efficiency of syngas are significantly influenced by the concentrations of combustible gases, particularly carbon monoxide (CO) and hydrogen (H_2). When ER is high, more air is supplied than is theoretically needed for complete combustion. This results in a more thorough combustion process, where carbon monoxide (CO) is oxidized to carbon dioxide (CO_2). While this enhances the conversion of CO to CO_2, it also leads to a reduction in CO concentration. In contrast, lower ER leads to lower the temperatures which in turns into lower the endothermic reactions in gasifier.

The steam coal ratio (SCR) is the ratio of the amount of steam introduced to the gasifier relative to the amount of coal used. Increasing the SCR promotes the water-gas shift reaction ($CO + H_2O \leftarrow CO_2 + H_2$). That reaction converts CO and water into CO_2 and H_2. As the SCR increases, this reaction is driven more towards the production of H_2, thus increasing its concentration in the syngas. Hydrogen is a high-energy gas, so an increase in H_2 typically raises the HHV.

However, beyond a certain point, increasing SCR further can have diminishing returns. Excessive steam leads to an imbalance in the water-gas shift reaction. As the reaction progresses, CO and H_2 are generated, but the excess steam can cause the reaction to become less efficient, leading to a lower H_2 production rate and increased CO levels due to the reversible nature of the reaction. At high SCR values, the reaction dynamics shift, and the formation of CO might increase due to the endothermic nature of the water-gas shift reaction becoming less favorable, especially as the gasification temperature increases rapidly.

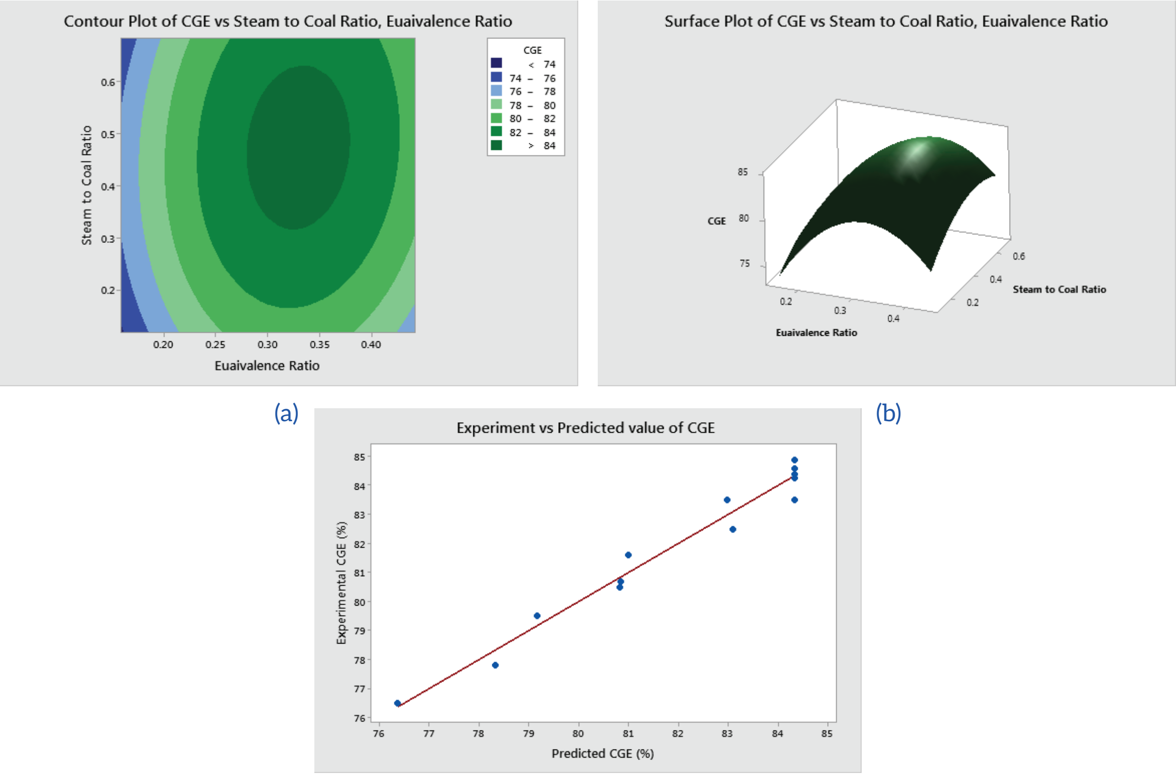
For optimum syngas quality involves balancing the ER and SCR to maximize the concentration of CO and H_2, which directly influences the HHV and CGE of the syngas. In the contour plot, darker regions indicate higher quality. Figures 2, 3, and 4 present the highest values of HHV, CGE and CCE nearly 22 MJ/kg, 84%, and 97%, respectively, at optimized value of ER and SCR.



(a) (b)

(c)

Fig. 2. Effect of equivalence ratio and steam to coal ratio on HHV (a) Contour plot (b) Surface plot (c) Predicted versus experimental graph



(a) (b)

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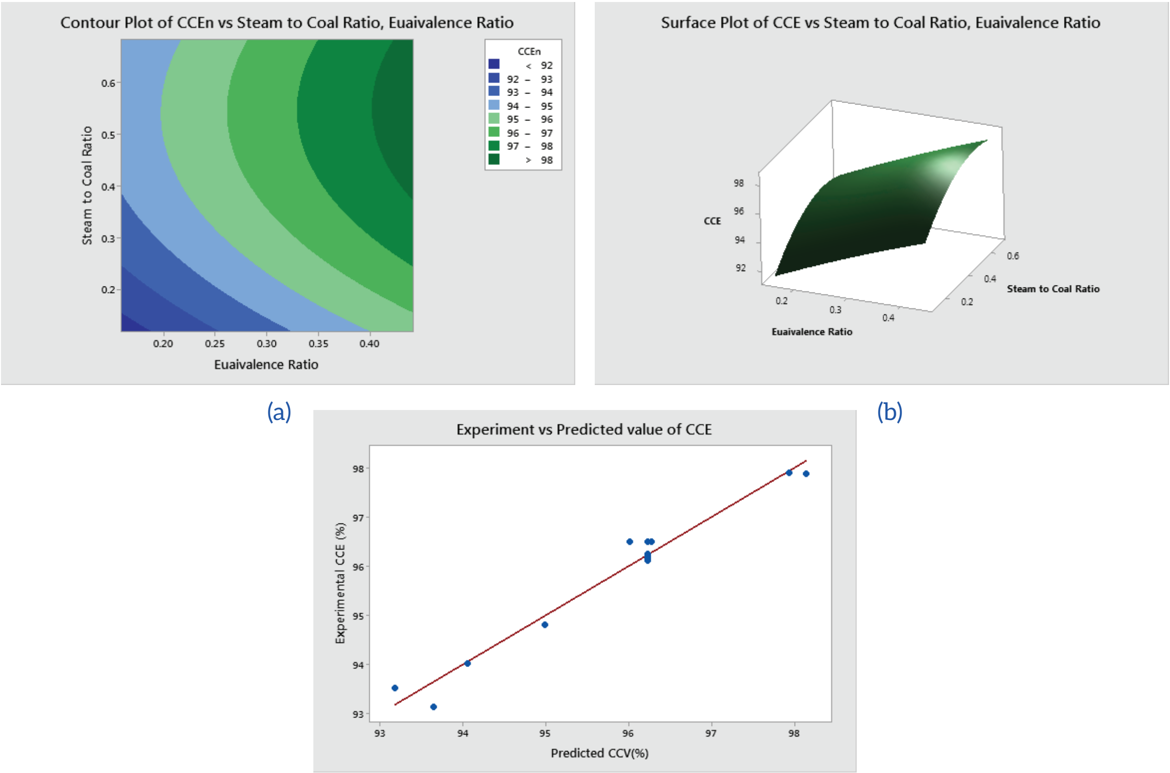
Fig. 3. Effect of equivalence ratio and steam to coal ratio on CGE (a) Contour plot (b) Surface plot (c) Predicted versus experimental graph



(a) (b)

(c)

Fig. 4. Effect of equivalence ratio and steam to coal ratio on CCE (a) Contour plot (b) Surface plot (c) Predicted versus experimental graph

D. *Process Optimization and Confirmation of Experiment*

Response surface methodology offers more accuracy for process variable optimization. The optimization of the equivalence ratio (ER) and steam coal ratio (SCR) for maximum higher heating value (HHV), cold gas efficiency (CGE), and carbon conversion efficiency (CCE) was carried out by applying the response optimizer tool in Minitab. The desirability function in optimization explains how close a particular set of variables or responses is to the preferred to meet targets. It does consider multiple criteria into a single value that ranges between 0 and 1.

To verify the optimal combination of the parameters and their levels, a confirmation experiment was carried out with the same set of parameters. A comparison between the experimental test results and predicted results was made and determined the error, which is less than 5%. Therefore, it can be concluded that the proposed mathematical model can accurately predict the output response.

TABLE V
OPTIMUM EQUIVALENCE AND STEAM TO COAL RATION, MODEL PREDICTION AND CONFIRMATION VALUES OF HIGHER HEATING VALUE, COLD GAS EFFICIENCY AND CARBON CONVERSION EFFICIENCY.

Solution	Equivalence Ratio	Steam Coal Ratio		Higher Heating Value (MJ/kg)	Cold Gas Efficiency (%)	Carbon Conversion Efficiency (%)
1	0.3699	0.499	Predicted	22.317	84.236	97.532
			Actual	22.759	85.124	97.92
			Error	±1.94%	±1.04%	±0.3%

IV. CONCLUSION

This parametric study of an updraft coal gasifier explains the dynamics of gasification processes, providing practical guidance for optimizing operational parameters and enhancing overall efficiency. Furthermore, response surface method serves as a best statistical tool to analyze the effect of the equivalence ratio and steam coal ratio on the syngas quality. The following measures were found to be the effects of each operating variable and their interactions with each syngas quality index:

- The equivalence ratio and steam coal ratio significantly influence the concentrations of CO, CO_2, and H_2 in the produced syngas.
- An increase in air supply leads to more conversion of CO_2, which results in a lower HHV of syngas.
- At a certain value of SCR, hydrogen production decreases while CO generation increases due to the exothermic reactions.
- The highest value of HHV nearly 22 MJ/kg is observed with ER value about 0.35 and SCR value 0.45.
- Produced syngas with a high value of HHV could lead to higher cold gas efficiency.
- The maximum value of CGE about 84%, which occurs at ER value of nearly 0.32 and SCR of 0.46.
- For an updraft coal gasifier with constant coal feed rate, CCE can increase up to 97% at high value of SCR.
- An optimum value of equivalence ratio and steam to coal ratio are found to be 0.3699 and 0.499, respectively.

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