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Statistical Approach to Predict the Gas Efficiencies of Biomass Gasification Using Different Biomasses

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Abstract : The objective of this work was to assess the combined effects of the blending ratio in a fluidized gasification process, where the focus was to quantify the relationships between the response variables and vital operating factors. With a view to the shortcomings of the classical "one factor-at-a-time" method in identification of the effect of experimental factors and their interactions, a statistical design of the experiment based on response surface methodology (RSM) was used. The response variables used in this work were gasification efficiency, tar yield and carbon conversion with different bed materials such as silica and limestone. Experiments were conducted over a temperature range of 700-900°C, using equivalent to 0.35. All of the response variables were successfully fitted to either a two-factor interaction or quadratic model. Using RSM, the effects of individual operating factors and their interactions were categorically determined, which were not otherwise possible by the classical design of experiment methodology. Using the resultant response variable correlations, gas efficiency was optimized as a function of the different blending ratios and bed materials respectively. The full potentiality of wheat husk, Corn Stalk and coconut shell for fluidized gasification was successfully investigated via RSM. The results of this work, however, are only applicable to fluidized bed gasification updraft systems.

Keyword : Corn Stalk; Wheat Husk, Coconut Shell Fluidized bed gasifier; Response surface methodology and Gas Efficiency.

1. INTRODUCTION

An agricultural residue that could be utilized for the recovery of energy is Corn Stalk because of its reasonably high energy content (12–18 MJ/kg). Today in many countries, most of the surplus Corn Stalk are disposed by direct burning in open heaps, which results in loss of energy as well as emission of various pollutants to the atmosphere [1–4]. Gasification as a process of converting carbonaceous materials into gaseous products using a gasifying medium such as air, oxygen, and steam has been considered as an alternative to combustion of low density biomass materials [5]. Further, the gasification process is typically 80–85% thermodynamically efficient in converting the organic content of the feed into a fuel gas mixture containing carbon dioxide, carbon monoxide, hydrogen, methane, excess steam and also nitrogen (if air is used as a gasifying agent), in addition to some minor organic compounds, tars, other minor components such as ammonia, and sulfur compounds. Besides, the gasification process generates a clean fuel gas which can be utilized in a combined cycle power generation system with enhanced efficiency. An integrated gasification combined cycle system offers a generating efficiency in the order of 40%, which is higher than that for a conventional direct combustion pulverized coal fired plant (~34%) [6].

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Recently, gasification technology that converts solid fuels into synthetic gas for integrated gasification combined cycle, coal-to liquid products, and chemical products has been rapidly developed in many countries [7-9]. The technology has been especially developed for woody biomass and agricultural residues [10−13]. Among solid fuels, coal leads to serious environmental pollution and carbon dioxide emission, whereas biomass is carbon-neutral, environmentally friendly, and renewable. However, biomass has a low calorific value and density, and shortages of this fuel occur seasonally [14], potentially necessitating an increase in gasifier size as well as high transportation and storage costs. Co-gasification technology of coal and biomass offers advantages, such as reduction of air pollutants (*e.g.*, NOx and SOx) and volatile organic compounds [15], improved gasification reactivity (alkali and alkaline earth metal in biomass ash behave as catalysts in coal gasification [16], and increase in gas yield. Thus, it is becoming increasingly important, because it allows for the use of coal in a more environmentally friendly way and contributes to the implementation of biomass gasification on a commercial scale [17]. However, with a view to enhance the reduction of air pollutants and volatile matter, co-gasification of agro-based biomass is appreciated. Hence it tends to discover a substitute for the coal for the co gasification. Agro based biomass is the only source of carbon-based renewable fuels and the sustainable exploitation of this resource is essential to secure the energy security. Wheat husk and coconut shell are high in sulfur content and vanadium and nickel contents (EPA-regulated elements), whereas Corn Stalk are high in moisture and ash content and low in sulfur content. Blending the above three is regarded as a promising option to improve the slag flow difficulties of high ash content husk because of the relatively low ash content of coconut shell, which reduces the risk of slag plugging the reactor tapping system. Mixing biomass also helps to reduce the sulfur loading in flue gas, which in turn results in lowering downstream processing requirements [18] Blending also helps to alleviate the high Ni and V difficulties of oil sand coke gasification, such as destroying the refractory binder, slagging and fouling on economizer heat-transfer surfaces, problems with burners and the syngas cooler, and formation of low-melting-point sodium vanadate, which deposits in the syngas cooler [19]. Furthermore, there is a chance that blending coke with coal can enhanced the conversion through catalytic activity of alkali metals in coal ashes, although the results reported in the literature are not consistent in this respect. Last but not the least; blending is one of the promising options that can further help to reduce the environmental impacts and footprints of the oil and gas industry.

From the literature review, it is understood that there are a large number of fluidized bed biomass gasifiers developed worldwide for co-gasification; unfortunately most of these projects are struggling to reach commercialization. Very few investigations have been done related to the prediction of the gas efficiency, gas yield and tar yield , incorporating the process parameters like temperature, equivalent ratio and steam to biomass ratio alone. Hence, the present work was aimed to develop a fluidized bed biomass gasifier using air as the gasifying agent and to investigate the effect of biomass ratio on the gasifier performance. A pilot scale fluidized bed gasifier had been developed for this purpose. The effect of biomass ratio on the fuel gas yield, tar yield and carbon conversion efficiency had been studied. An empirical relationship was developed to predict the product gas yield, carbon conversion efficiency and tar yield with the assumptions that the principal reactions were at thermodynamic equilibrium condition. The experimental data and the predicted vales have been analyzed, compared and discussed in the present work.

2. EXPERIMENTAL WORK

2.1. Feedstock and inert bed materials

The feed stock selected to study the fluidized bed gasification were coconut shell, Corn Stalk and wheat husk with different biomass ratio. These biomaterials were collected from rural industries of Cuddalore district, India. The proximate and ultimate analyses of coconut shell, Corn Stalk and wheat husk used as feed stock are presented in Table 1. The inert bed materials used were silica and lime stone and its particle size distribution were selected as 0.400 mm using sieve analysis. The properties of these materials and the procedures followed in finding out physical and chemical properties are mentioned in detail. Absolute specific gravity of the selected materials was measured using specific gravity bottle method. To minimize the complexities, resulting from the non-uniform particle size distribution in the bed, the average particle diameter was used to represent the particle size. Sieve analysis is commonly used to predict the particle size distribution of the feed stock having size of 70-500 µm. The test materials were dried and then sieved in a set of standard sieves and particle size distribution was observed [20]. Using oven method (110°C till reaching standard borne dry weight), moisture content of feed stock was measured (ASTM, E – 871). Proximate composition such as volatile matter (ASTM, E – 872) and ash (ASTM, E – 830) and fixed carbon (by weight difference) was found out by ASTM procedures. The elemental composition of the feed stock was found out using Elemental Analyzer (Carlo Erba EA 1108) coupled with auto sampler AS-200 and data processor DP 200-PRC. The minimum fluidization velocity was measured using pressure drop method. U tube manometers are used to measure the pressure drop below and above the distributor plate and at different heights of fluidized bed reactor. The air velocity corresponding to the peak pressure drop gives the experimental value of minimum fluidization velocity [20].

Table 1

Ultimate and proximate analysis of corn stalks

Ultimate Analysis				*Proximate Analysis*			
Components	*Percent*			*Component*	*Percent*		
	Coconut Shell	*Corn stalks*	*Wheat Husk*		*Coconut Shell*	*Corn stalks*	*Wheat Husk*
Carbon	53.73	47.54	40.1	Volatile matter	72.93	69.5	84.1
Hydrogen	6.15	6.02	6.4	Fixed carbon	19.48	2.97	5.68
Sulphur	0.02	0.13	0.36	Moisture	6.98	12.2	9.92
Nitrogen	0.86	0.77	1.35	Ash	0.61	5.8	1.63
Oxygen	38.45	43.87	51.79	Calorific Value	20.88	15.57	17.94

2.2. Experimental Setup

A pilot scale fluidized bed Corn Stalk gasifier (capacity: 20 kg/h) had been developed and installed in the laboratory to carry out the experimental investigation. The schematic diagram of the setup is shown in Fig. 1. Table 2 shows the design and operating features of Fluidized Bed Gasifier. The cylindrical gasifier with 108 mm inside diameter up to a height of 1400 mm made of carbon steel material having inside refractory lining of thickness 0.1 m. The gasifier is fitted with a multiple hole distributor plate of 105 mm diameter was used for air distribution The ash discharge systems were provided for periodical disposal through the lock hopper arrangements. Silica sands and lime stone as bed materials were initially put into the gasifier through the screw feeder and air was introduced at the bottom of gasifier to maintain the bed in fluidized state. The air flow, after the discharge of blower, was controlled by a regulating valve and the flow was then estimated by an orifice meter placed in the supply pipe on the basis of pressure drops recorded across it. The orifice had been calibrated prior to the experiment with two reference instruments; namely a digital micromanometer (make: Furnace Control, England) and a thermal anemometer (make: Dantec, Denmark). The pressure drops across the orifice were recorded in the manometer and the corresponding flow rates were measured by the anemometer; the calibration curve was thus generated by plotting the flow rates along abscissa and the corresponding pressure drops along the ordinate.

During experiment, the pressure drops were noted to get the corresponding air flow rates from the curve at different equivalence ratios. External electric heating was used for preheating the bed materials as well as the refractory lining during start up. The electric heating was switched onto and the gasifier was allowed to run until the bed temperature was 450°C. The raw Corn Stalk was then fed through the under-bed feeding system having a screw feeder. The feed rate was controlled by the screw feeder fitted to a variable speed drive and it push the solid fuel immediately into the gasifier preventing pyrolysis outside the chamber. Supply of air was then regulated to maintain the desired equivalence ratio.

Table 2

Design and operating features of Fluidized Bed Gasifier

Parameters	*Range*
Type of gasifier	Fluidized Bed Gasifier
Geometrical parameters	Diameter (Inner) : 108 mm Total height : 1400 mm
Heating Type	External electric heating
Cooling medium	Water
Feedstock capacity	5-20 kg / *h* (depending on the type of fuel)
Feeding equipment	Screw feeder
Gasifying agents	Air&Steam
Operating temperature	650-950 ºC
Heating rate	1-60°C/min
Main process variables	Bed Temperature, Pressure, Feed rate, Equivalence ratio and Particle size.
Fuel gas treatments	Cyclone, Water scrubber, Dry filter

The cyclone at the outlet of gasifier was used to separate the solid particles from the fuel gas mixture. The bag filter placed after the cyclone further cleaned up the gas by capturing dust and other smaller particles. The water cooler and an ice trap system were used in series to cool the fuel gas to separate the tar through condensation. A second orifice meter (50 mm diameter) was positioned in the fuel gas pipe (108 mm diameter) to estimate the gas yields. The calibration of the orifice was done prior to the experimental work by following the similar procedure as it was done in case of orifice meter in airline to generate a separate calibration curve. While the gasifier was running, the pressure drops across the orifice were noted in manometer to get the corresponding gas flow rates from the curve. The flow rates thus obtained corresponding to gas temperatures was then corrected by the temperature factor to get the actual flows at NTP. Equivalence ratio is very important in gasification process as it determines the fraction of the fuel that is burnt and thereby it controls the bed temperature. It also affects the fluidization of the bed. The lower limit of equivalence ratio is decided by the minimum quantity of air required to burn a portion of the fuel to release enough heat to support the endothermic reactions, to meet the sensible heat losses in gas, char and ash, and to maintain the required bed temperature of the reactor. As Corn Stalk has high ash content, it requires larger fraction of the fuel to be burnt – this ultimately demands a higher equivalence ratio [21]. In Hartiniati et al. [22], it is reported that the equivalence ratio was maintained between 0.30 and 0.48 during experimentation in a pilot scale fluidized bed gasifier fueled by mixture. Later on, Mansaray et al. [23] also investigated the Corn Stalk and wheat husk gasifier performance in a fluidized bed system by varying the equivalence ratio at 0.25, 0.30 and 0.35. In view of these observations, the gasifier was operated with equivalence ratios of 0.20-0.50 in the present investigation to get the experimental results.

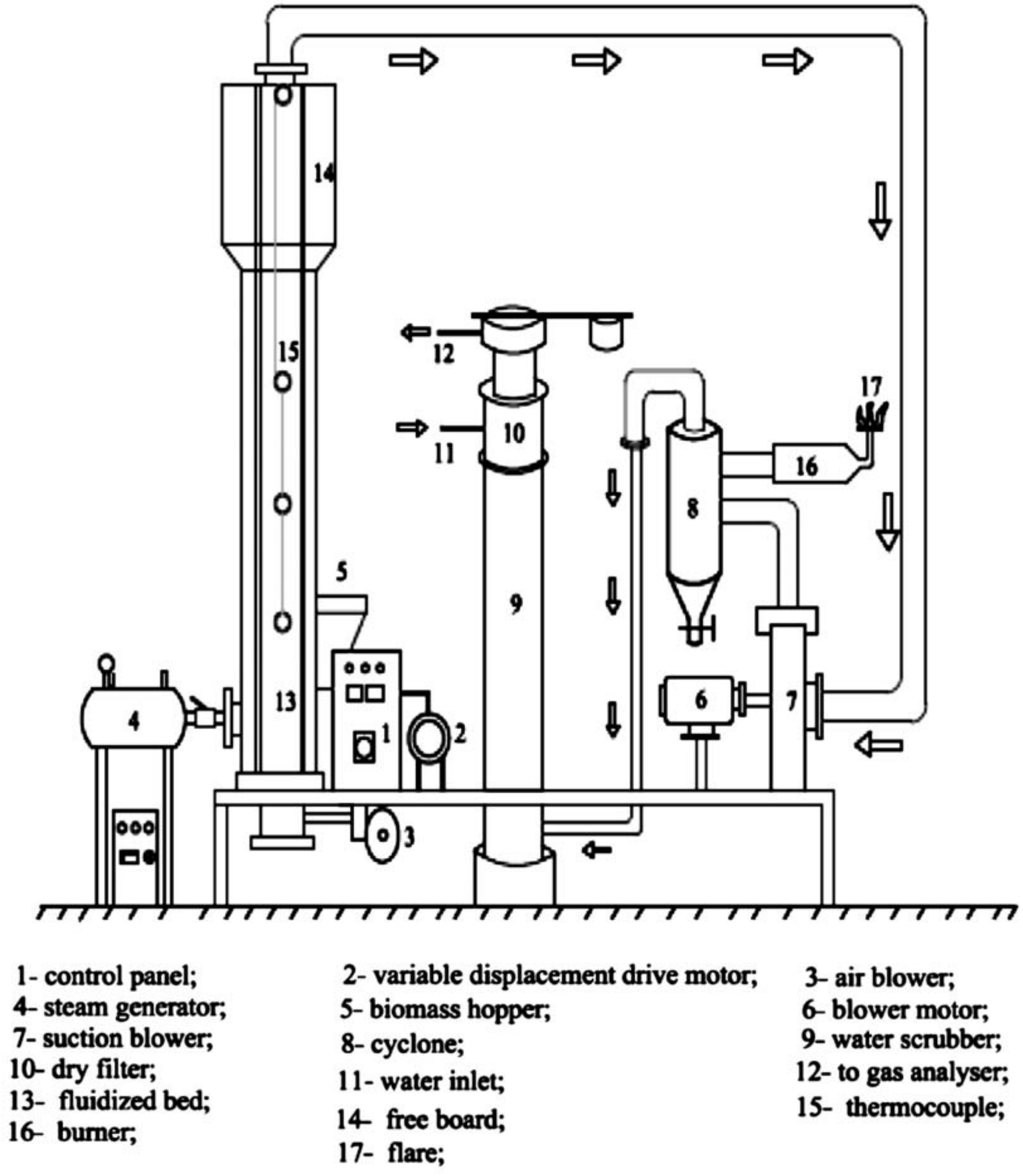


Figure 1: Experimental Setup

2.3. Experimental Design Matrix

From the studies [24-33], the biomass blending ratio as a predominant factor that have a greater influence on the quality of the producer gas and the carbon conversion efficiency have been identified. The biomasses such as coconut shell, Corn Stalk and wheat husk are used in the present investigation. Owing to a wide range of factors, the use of five factors and central composite rotatable design matrix was chosen to minimize number of experiments. The number of tests required for the CCRD includes the standard 2k factorial with its origin at the center, 2k points fixed axially at a distance, say α, from the center to generate the quadratic terms, and replicate the tests at the center; where k is the number of variables. The axial points are chosen such that they allow rotatability, which ensures that the variance of the model prediction is constant at all points equidistant from the design center. By adding axial points which extend, the design will provide protection against the curvature from twisting. Hence, the design was extended up to ± α (axial point). The value of α is chosen to maintain rotatability. To maintain rotatability, the value of α depends on the number of experimental runs in the factorial portion of the central composite design, which is given by Equation (3.1)

$$\alpha = [\text{number of factorial points}]1/4 \qquad (3.1)$$

If the factorial is a full factorial, α is evaluated from the Equation (3.2)

$$\alpha = [23]1/4 = \pm 1.682 \qquad (3.2)$$

It can be noted that when $\alpha > 1$, each factor is run at five levels ($-\alpha$, –1, 0, +1, + α) instead of the three levels of –1, 0, and +1. The reason for running the central composite designs with $\alpha > 1$ is to have a rotatable design. However, the factorial portion can also be a fractional factorial design of resolution. The center values for the variables were carried out at least six times for the estimation of error, and single runs for each of the other combinations. Replicates of the test at the center are very important as they provide an independent and more uniform estimate of the prediction variance over the entire design. Table 3 presents the ranges of factors considered. For the convenience of recording and processing the experimental data, the upper and lower levels of the factors are coded as +1.682 and -1.682 respectively. The coded values of any intermediate value can be calculated by using the Equation (3.3)

$$Xi = 1.682\ [2X - (X\text{max} - X\text{min})] / (X\text{max} - X\text{min}) \qquad (3.3)$$

where,

X*i* is the required coded value of a variable X, and X is any value of the variable from Xmin to Xmax

Xmin is the lower level of the variable.

Xmax is the upper level of the variable.

Xmax is the upper level of the variable.

Design matrix consisting of 20 sets of coded conditions (comprising full replication 8 factorial points, 6 corner points and six center points) was chosen in this investigation. Table 3 represents the ranges of factors considered, and Table 4 shows the 20 sets of coded and actual values with experimental results.

Table 3
Important factors and their levels

Factors	*Units*	*Notation*	*Factors levels*				
	%		–1.682	–1	0	+1	+1.682
Coconut Shell		C	0	6	15	24	30
Corn stalks		R	0	12	30	48	60
Wheat Husk		F	0	5	12.5	20	25

2.5. Experimental Testing

During experimentation, special care was taken to maintain the desired bed temperatures as the selected feedstock were coconut shell, Corn Stalk and wheat husk. One of the important features of biomass gasification is that the bed temperature can be kept as low as 700–900°C, thereby preventing sintering and agglomeration of this ash which would otherwise cause serious operational problems during the conversion process [34]. The upper temperature is fixed by slagging phenomena which primarily depends upon the ash composition and the reaction atmosphere (like oxidation or reduction). Above this temperature, silica and potassium oxide in ash fuses on the surface of Corn Stalk char particles forming a glass-like barrier that prevents the further reaction of the remaining carbon [21]. Some studies [35, 36] also indicate that oxidation of biomasses at a temperature higher than 900°C results in a physical structural transformation of silica from its original amorphous state to a crystalline state thereby encapsulating residual carbons. Once the structural changes of silica occurs, the combined carbon becomes unavailable for further oxidation reactions even at higher temperatures. In view of this, the gasifier was operated in the range of 700–950°C when the experiments were carried out with equivalence ratio 0.2 and 0.5.

The gasification temperature was raised up to 700°C only in case of equivalence ratio of 0.25. The gasifier temperatures were recorded using Ni–Cr–Ni thermocouples with a digital display system. The gas sampling system was composed of probes fitted with septum. The sampling point was located at the outlet pipe of gasifier. The gas sampling probe made of glass was 50 mm in diameter and 500 mm in length. A syringe of volume capacity of 10 ml was used to collect the gas sample. The sample was analyzed in the Gas Chromatograph (Make – Chemito, model – GC1000) to get the raw experimental data and those were compared with the predicted values of the developed model. The energy content of the gas is assessed through the variable CCE (carbon conversion efficiency). This variable represents the ratio between the energy content of the permanent gas (HHV_{gas}) and the energy content of the initial biomass feedstock ($HHV_{biomass}$) without taking into account the heat input in the reactor:

$$\text{CCE} = 100\,(\text{Carbon content in the producer gas x Producer gas yield}) / (\text{Carbon content in feed material x Total feed}) \quad (1)$$

At the end of the experiment the residual tar were weighed and stored in a sealed recipient for further characterization. The tar yield is expressed as the ratio of the residual tar to the initial mass of biomass

$$Y_{Tar}\% = [(M_{Tar}) / (M_{biomass})] \text{ x } 100 \quad (2)$$

3. DEVELOPING THE EXPERIMENTAL DESIGN MATRIX

In the present investigation, to correlate the process parameters and the quality of the producer gas, a second order quadratic model was developed. In this study, the RSM provides a quantitative form of relationship between the desired response (Quality of the Producer gas) and the independent input variables (Biomass ratio), Coconut shell (C), Corn Stalk (R), and Wheat husk (W), and can be expressed as a function, as in Equation (3)

$$\text{Quality of the Producer gas (Q)} = f\,(\text{C, R, X}).....\quad (3)$$

The empirical relationship must include the main and interaction effects of all factors and hence the selected polynomial is expressed as follows:

$$Y = bo + \sum bi\ xi + \sum bii\ xi^2 + \sum bij\ xi\ xj \quad (4)$$

For three factors, the selected polynomial could be expressed as

$$\text{Quality of the Producer gas (Q)} = \{b_0 + b_1\,(C) + b_2\,(R) + b_3\,(W) + b_{11}\,(C^2) + b_{22}\,(R^2) + b_{33}\,(W^2) + b_{12}\,(CR) + b_{13}(CW) + b_{23}\,(RW)\} \quad (5)$$

where b_0 is the average of responses () and b_1, b_2, b_3… b_{11}, b_{12}, b_{13}… b_{22}, b_{23}, b_{33}, are the coefficients that depend on their respective main and interaction factors, which are calculated using the expression given below,

$$B_i = (\sum(Xi,Yi)\,)/n \quad (6)$$

Where '*i*' varies from 1 to *n*, in which X*i* the corresponding coded value of a factor and Y*i* is is the corresponding response output value (Biomass Blend) obtained from the experiment and '*n*' is the total number of combination considered. All the coefficients were obtained applying central composite rotatable design matrix including the Design Expert statistical software package. After determining the significant coefficients (at 95% confidence level), the final relationship was developed including only these coefficients. The final empirical relationship obtained by the above procedure to estimate producer gas generation, tar yield and carbon conversion efficiency of biomass blend under fluidized bed gasification is given below;

Gas Efficiency (Silica)

$$\text{Producer Gas (GE S)} = +\,82.338 - 2.768\,{*}(C) - 0.570\,{*}(X) - 0.569\,(W) - 5.185 \text{ x } 10^{-3}\,{*}(CX) + 0.0126\,(CW) + 0.013\,{*}(XW) + 0.079{*}(C^2) + 3.150\text{x } 10^{-3}\,(X^2) + 0.054{*}(W^2)$$

Gas Efficiency (Limestone)

$$\begin{aligned}\text{Producer Gas (GE L)} = {} & +72.555 - 2.546{*}(C) - 0.528{*}(S) - 0.397\,(X) - 4.305\text{ x }10^{-3}{*}(CX)\\ & + 9.277\text{x }10^{-3}{*}\,(CW) + 9.446\text{x }10^{-3}{*}\,(XW)\\ & + 0.072{*}\,(C^{2}) + 3.208\text{x }^{10-3}\,(X^{2}) + 0.053{*}(W^{2})\end{aligned}$$

Carbon Conversion Efficiency (Silica)

$$\begin{aligned}\text{Producer Gas (CCE S)} = {} & +86.323 - 2.759{*}(C) - 0.557{*}(X) - 0.539(W) - 5.185\text{x }10^{-3}{*}(CX)\\ & + 0.0126{*}\,(CW) + 0.013{*}\,(XW) + 0.078{*}\,(C^{2})\\ & + 2.887\text{x }^{10-3}\,(X^{2}) + 0.052{*}(W^{2})\end{aligned}$$

Carbon Conversion Efficiency (Limestone)

$$\begin{aligned}\text{Producer Gas (CCE L)} = {} & +90.192 - 2.759{*}(C) - 0.557{*}(X) - 0.539(W) - 5.185\text{x }10^{-3}{*}(CX)\\ & + 0.0126{*}(CW) + 0.013{*}(XW) + 0.078{*}(C^{2})\\ & + 2.882\text{x }10^{3}\,(X^{2}) + 0.052{*}(W^{2})\end{aligned}$$

Tar yield (Silica)

$$\begin{aligned}\text{Producer Gas (TY S)} = {} & +11.017 - 0.499{*}(C) - 0.138{*}(X) - 0.163\,(W)\\ & + 5.342\text{ x }10^{-4}{*}(CX) - 1.236\text{x}10^{-3}\,(CW) + 8.975\text{x }10^{-4}{*}\,(XW)\\ & + 0.014{*}\,(C^{2}) + 1.384\text{x }10^{-3}\,(X^{2}) + 0.015{*}\,(W^{2})\end{aligned}$$

Tar yield (Limestone)

$$\begin{aligned}\text{Producer Gas (TY L)} = {} & +14.537 - 0.499{*}(C) - 0.138{*}(X) - 0.163\,(W)\\ & - 5.342\text{ x }10^{-4}{*}(CX) - 1.236\text{x}10^{-3}\,(CW) + 8.975\text{x }10^{-4}{*}\,(XW)\\ & + 0.014{*}\,(C^{2}) + 1.384\text{x }10^{-3}\,(X^{2}) + 0.015{*}\,(W^{2})\end{aligned}$$

The Analysis of Variance (ANOVA) technique was used to find the significant main and interaction factors. The results of second order response surface model fitting as Analysis of Variance (ANOVA) are given in the Table 5. The determination coefficient (r^2) indicated the goodness of fit for the model. The Model F-value of ($CCE_L = 5.76$, $CCE_S = 5.76$, $GE_L = 5.88$, $GE_S = 6.24$, $TY_L = 4.66$, $TY_S = 4.66$, implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

Tar yield (Limestone)

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case W, C^2, W^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 2.62 implies the Lack of Fit is not significant relative to the pure error. There is a 15.66% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit. A negative "Pred R-Squared" implies that the overall mean may be a better predictor of you response than the current model "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The present ratio of 6.072 indicates an adequate signal.

Tar yield (Silica)

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case W, C^2, are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 2.62 implies the Lack of Fit is not significant relative to the pure error. There is a 15.66% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit. A negative "Pred R-Squared" implies that the overall mean may be a better predictor of your response than the current model. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The present ratio of 6.072 indicates an adequate signal

Carbon Conversion Efficiency (Limestone)

Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case X, W, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 3.12 implies the Lack of Fit is not significant relative to the pure error. There is a 11.89% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit. The "Pred R-Squared" of 0.0121 is not as close to the "Adj R-Squared" of 0.6926 as one might normally expect; *i.e*. the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The present ratio of 7.484 indicates an adequate signal.

Carbon Conversion Efficiency (Silica)

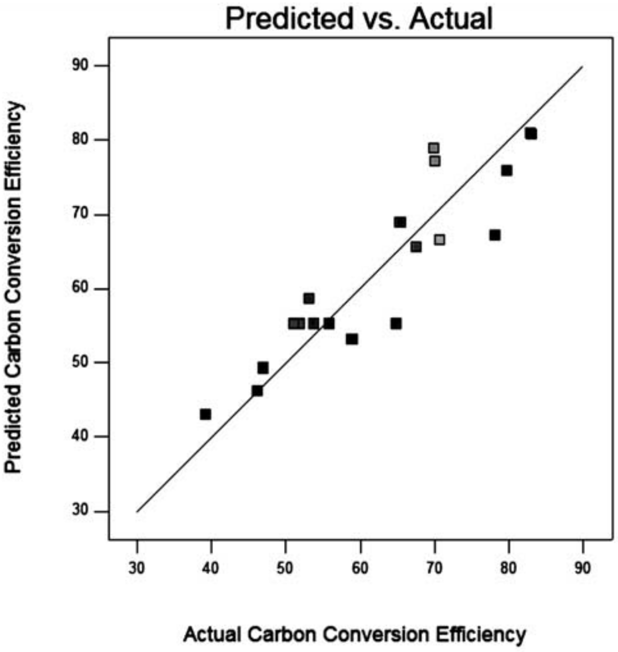
Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case X, W, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 3.12 implies the Lack of Fit is not significant relative to the pure error. There is a 11.89% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit. The "Pred R-Squared" of 0.0121 is not as close to the "Adj R-Squared" of 0.6926 as one might normally expect; *i.e*. the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The present ratio of 7.484 indicates an adequate signal.

Gas Efficiency (Limestone)

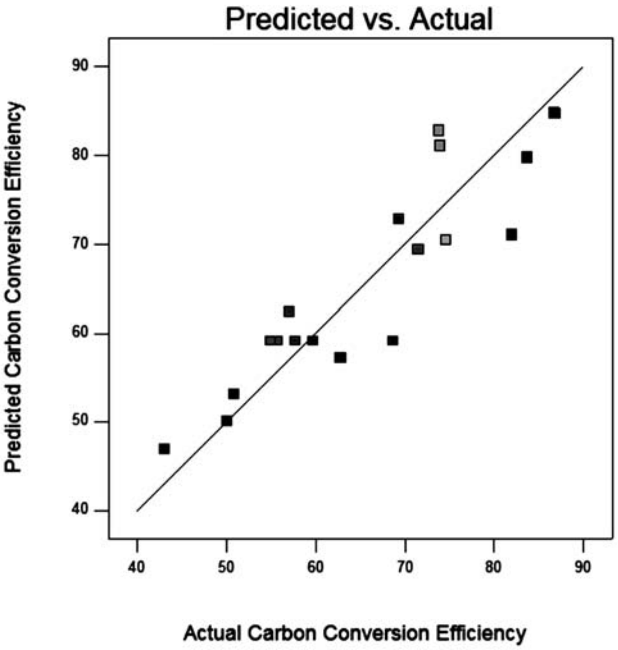
Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case X, W, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The "Lack of Fit F-value" of 4.22 implies there is a 7.00% chance that a "Lack of Fit F- value" this large could occur due to noise. Lack of fit is bad -- we want the model to fit. This relatively low probability (<10%) is troubling. The "Pred R-Squared" of 0.0275 is not as close to the "Adj R-Squared" of 0.7128 as one might normally expect; *i.e*. the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs."Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The present ratio of 7.858 indicates an adequate signal.

Gas Efficiency (Silica)

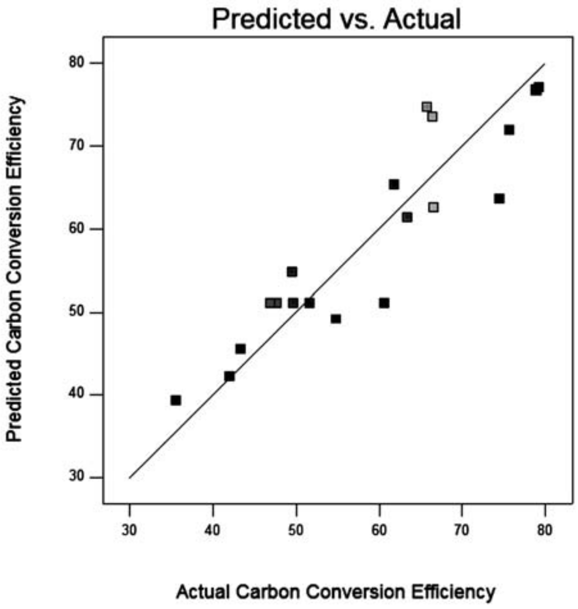
Values of “Prob > F” less than 0.0500 indicate model terms are significant. In this case X, W, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The “Lack of Fit F-value” of 3.05 implies the Lack of Fit is not significant relative to the pure error. There is a 12.34% chance that a “Lack of Fit F-value” this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit. The “Pred R-Squared” of 0.0334 is not as close to the “Adj R-Squared” of 0.6980 as one might normally expect; i.e. the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs. “Adeq Precision” measures the signal to noise ratio. A ratio greater than 4 is desirable. The present ratio of 7.524 indicates an adequate signal.



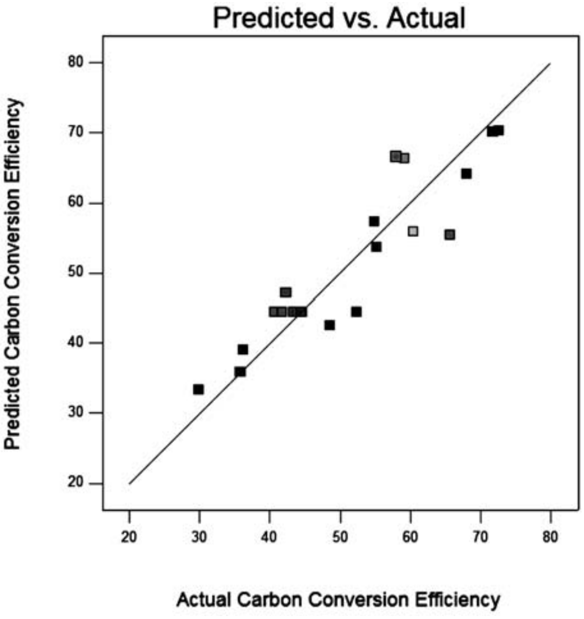
Carbon conversion efficiency(L)



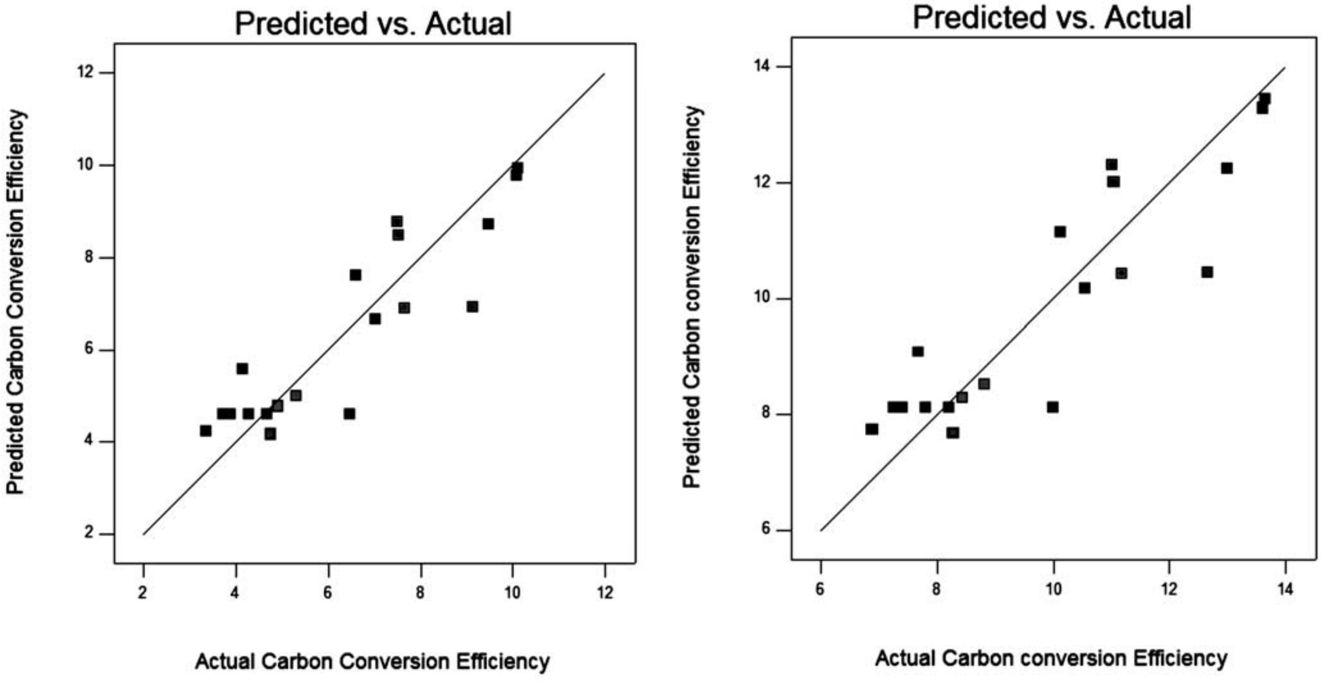
Carbon Conversion efficiency(S)



Gas Efficiency(L)



Gas efficiency(S)



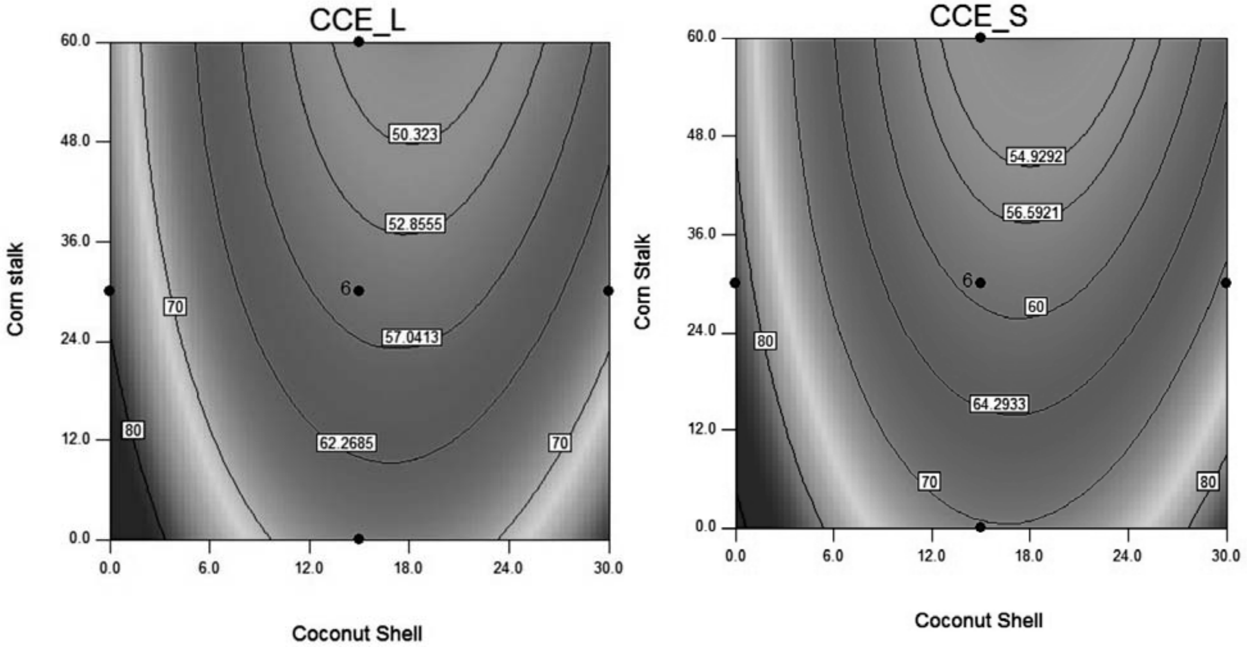
Tar yield(L) Tar yield(S)

Figure 2: Predicted Vs Experimental

All of this indicated an excellent suitability of the regression model. Each of the observed values compared with the experimental values shown in the Fig.2. A scatter plot of the two variables indicates that a straight line provides a suitable fit to the data. The differences between actual and predicted responses are termed as residuals, the residuals provide a measure of the closeness of agreement of the actual and the predicted responses; hence, they provide a measure of the adequacy of the fitted model. The difference in the actual and the predicted responses, with red dotted lines, is the residuals. The linear fit approximates the observed data points so well; the sum of squares residuals are all very small as shown in the Table 5. Small residuals are one important indicator of the adequacy of a regression fit.

3. RESULTS AND DISCUSSION

3.1. Effects of the interaction variables on the gas efficiency



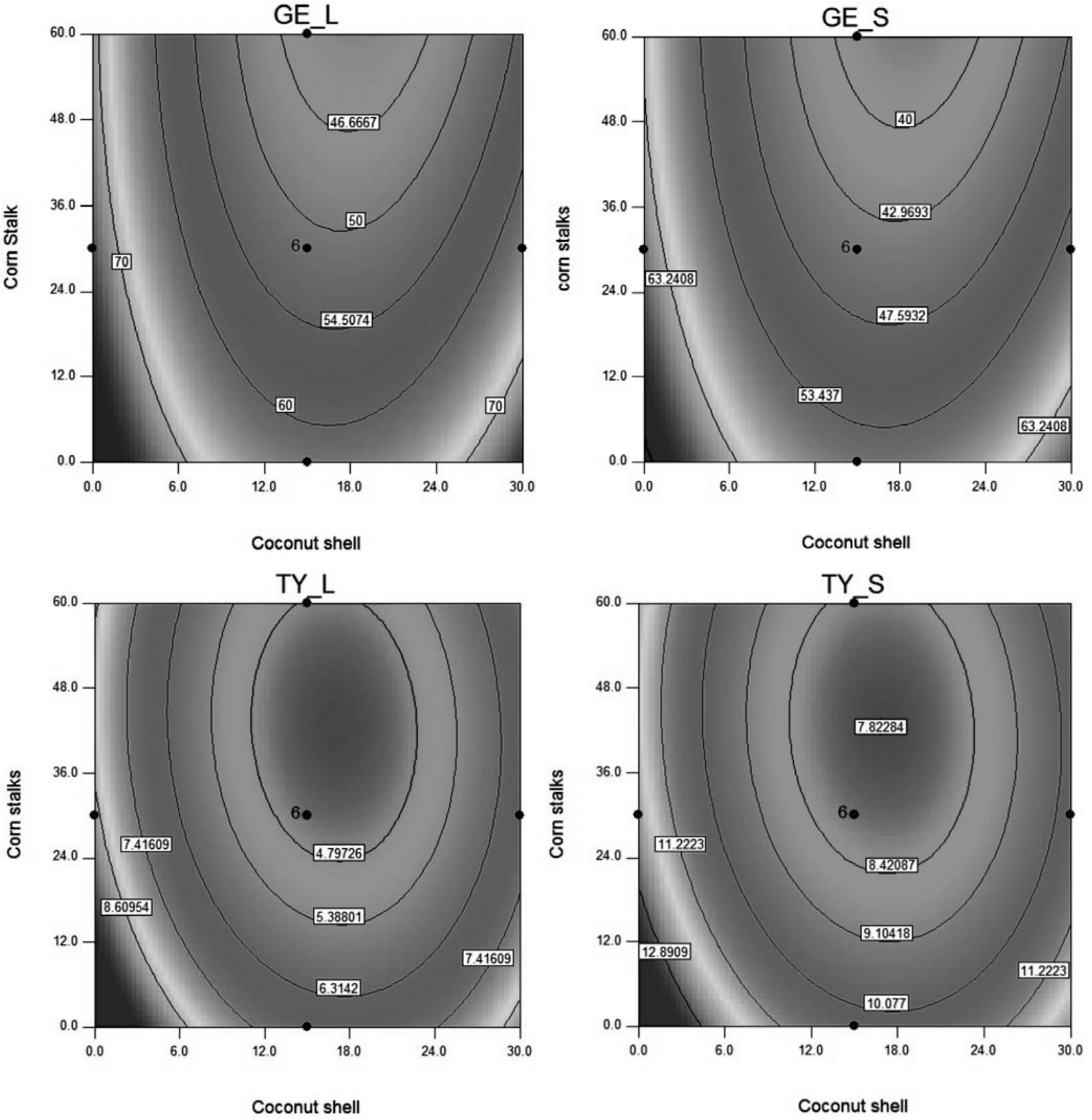
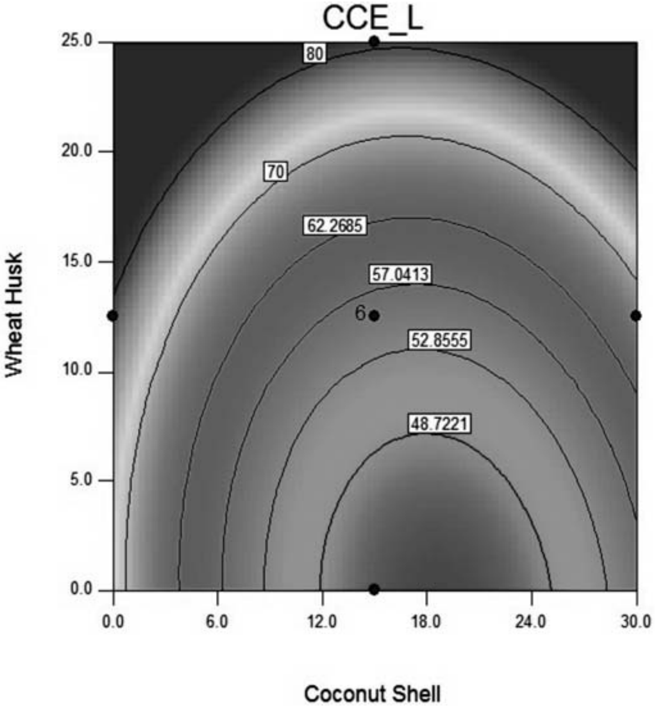
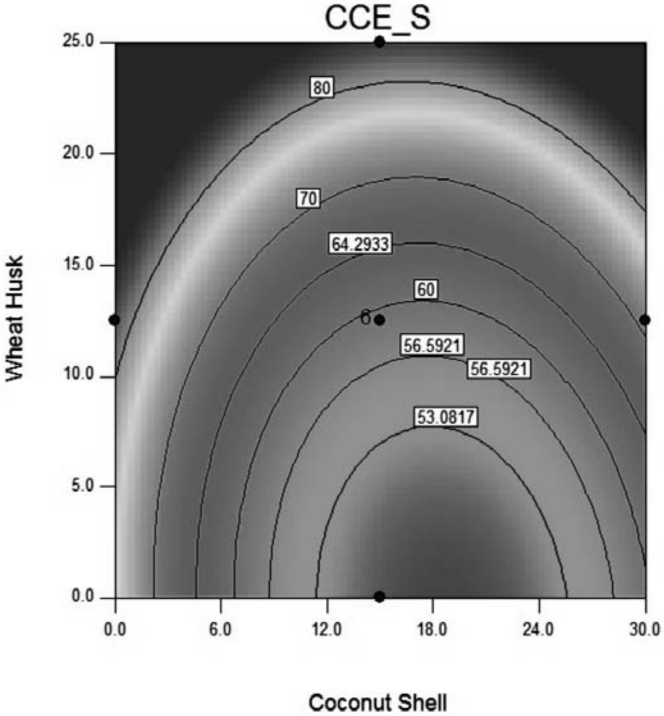


Figure 3: Response Contour Plots Showing the Effect of Interaction Factors (Coconut Shell & Corn stalks)

The gasification behavior of the biomass blends over different combinations of the independent variables is shown through a two-dimensional view of the contour plots. The contour plots are represented as a function of two factors at a time, holding the other factors at a fixed level. All the contour plots revealed that at low and high levels of the variables, the gasification behavior is minimal; however, it is noted that there existed a region with a color difference, where neither an increasing nor a decreasing trend in the gasification behavior was observed. This phenomenon confirms that there was an optimum for the gasification variables, in order to maximize the gasification resistance capacity. Fig. 3 shows the interaction effects of the Corn Stalk and the coconut shell on the gasification behavior of the biomass blends. It is observed that, the stationary point is far outside the region of exploration for fitting the second order model. The contour surface is assumed to be a rising ridge. In this type of ridge system, the least or most number of contours was assumed to be an optimal degree of solution. Elliptical contours exist in the interaction plots for all the gasification tests. It can be seen that an inverse relationship between Corn Stalk and the coconut shell on the gasification behavior of the biomass blends was found in all the plots. Fig. 3 shows the effect of Corn Stalk and the coconut shell on the gasification behavior of the biomass blends. It was observed that on increasing Corn Stalk and the coconut shell on the gasification behavior of the biomass blends, the gas efficiency increases. It was authenticated by the fact that the interaction between Corn Stalk and the coconut shell on the gasification behavior of the biomass blends shows an appreciable level of significance. Also it suggested that, the Corn Stalk was more sensitive than coconut shell on the gasification behavior of the biomass blends. Thus, the contour plots, clearly show the effect of gasification behavior of the biomass blends; and independently show that the gas efficiencies increased on increasing Corn Stalk and the coconut shell. Fig 4 shows the interaction effects of the coconut shell and the wheat husk on the gasification behavior of the biomass blends. It shows the wheat husk also played an important role on the gasification behavior of the biomass blends; this was evident from the equation and contour plots. The interaction between the coconut shell and the wheat husk was distorted, which was reflected by the corresponding p-values, but, it was clear that, the wheat husk was more sensitive than the coconut shell. Further, it was seen that, on increasing the wheat husk and coconut shell the gasification behavior increase. Circular contours were found and the optimal value falls at the center of the concentric circles. Fig. 5 shows the effects of the Corn Stalk and the wheat husk on the gasification behavior of the biomass blends. It was observed that the interaction of the Corn Stalk and the wheat husk was appreciably significant on the gasification behavior of the biomass blends. This was evident from the corresponding p-values, and deduced from the curvature of the contour. It was noted that, on the gasification behavior of the biomass blends especially carbon conversion efficiency decreased with increasing Corn Stalk and with the increment in the wheat husk. The trend observed in the other responses was different as increases with increase in the composition and blends. As an interactive factor, the Corn Stalk is more sensitive than the wheat husk during the gasification.





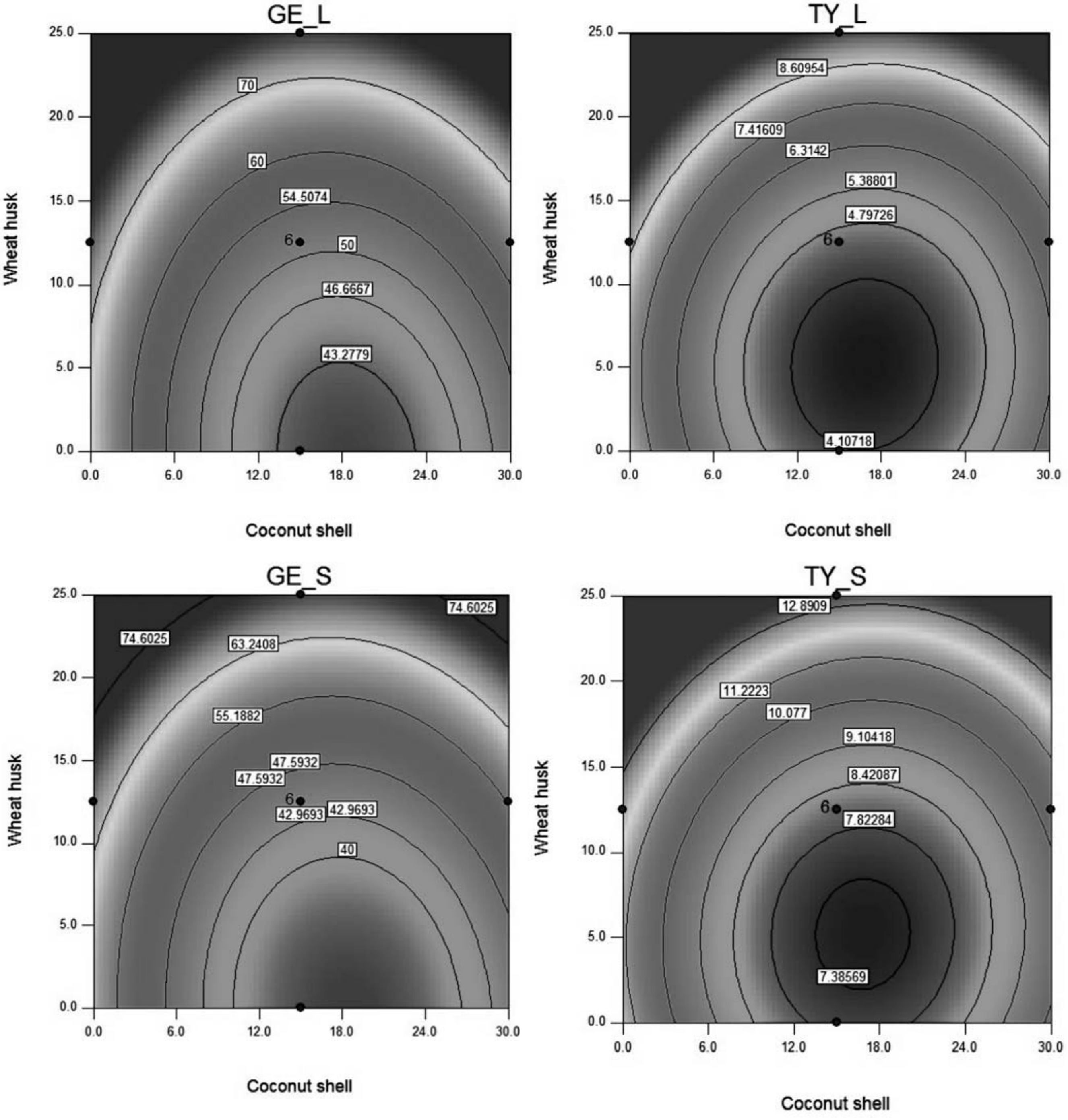


Figure 4: Response Contour Plots Showing the Effect of Interaction Factors (Coconut Shell & wheat husk)

3.2. Effect of Coconut shell

Two series of tests have been performed with silica and limestone as bed material. The main difference in both series is the blending ratio (BR) used. As a biomass blend, coconut shell plays a vital role in biomass gasification process. In this present work, though it was an autothermal gasifier, the fuel gas was evaluated at various intermediate coconut shell ratio in the biomass blend until it reached the maximum ratio for a given Corn Stalk and wheat husk. Table 4 shows the experimental data of gas species taken at coconut shell ratio between 0 to 30% of the total blend. It was seen that the calculated values fits good from the experimental data, although the similar trends (increase or decrease) were observed regarding the changes of species concentrations. It is found that with the increase of coconut shell ratio, the carbon conversion efficiency, gas efficiency and tar yield increases. It is noted that for both the bed materials the carbon

Table 4

Experimental Results

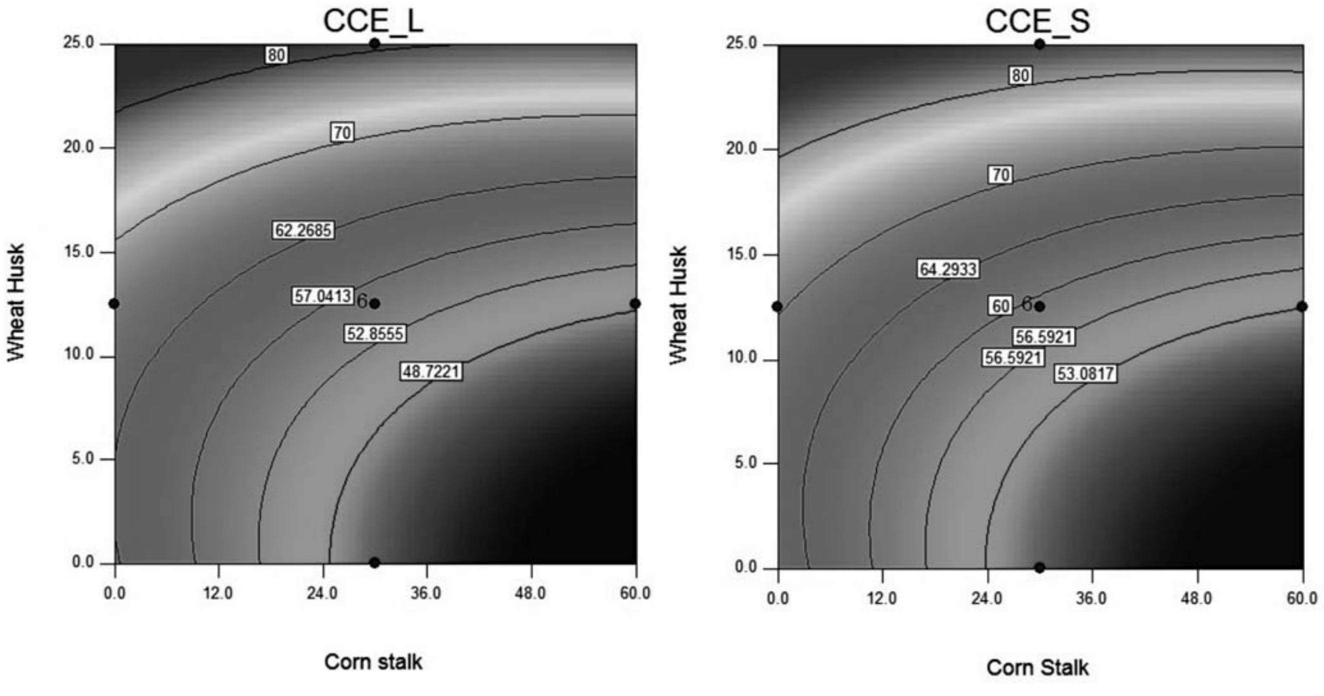
EX. No	*Coconut Shell (%)*	*Corn stalks (%)*	*Wheat husk (%)*	*Carbon Conversion Efficiency-Silica (%)*	*Carbon Conversion Efficiency-Limestone (%)*	*Gas Efficiency Silica (%)*	*Gas Efficiency Limestone (%)*	*Tar Yield Silica (%)*	*Tar Yield Limestone (%)*
1	6	12	5	67.63	71.5	63.48	55.16	7.036	10.556
2	24	12	5	53.23	57.1	49.58	42.3	4.156	7.676
3	6	48	5	58.95	62.82	54.8	48.57	5.3	8.82
4	24	48	5	39.29	43.16	35.64	29.86	3.368	6.888
5	6	12	20	83.05	86.92	78.9	72.65	10.12	13.64
6	24	12	20	70.05	73.92	66.4	59.14	7.52	11.04
7	6	48	20	79.79	83.66	75.64	67.96	9.468	12.988
8	24	48	20	65.45	69.32	61.8	54.82	6.6	10.12
9	0	30	12.5	69.95	73.82	65.8	57.98	7.5	11.02
10	30	30	12.5	78.15	82.02	74.5	65.58	9.14	12.66
11	15	0	12.5	70.75	74.62	66.6	60.37	7.66	11.18
12	15	60	12.5	47.05	50.92	43.4	36.17	4.92	8.44
13	15	30	0	46.25	50.12	42.1	35.84	4.76	8.28
14	15	30	25	82.85	86.72	79.2	71.74	10.08	13.6
15	15	30	12.5	53.85	57.72	49.7	43.4	4.28	7.8
16	15	30	12.5	64.85	68.72	60.7	52.38	6.48	10
17	15	30	12.5	53.85	57.72	49.7	44.58	4.28	7.8
18	15	30	12.5	55.85	59.72	51.7	44.42	4.68	8.2
19	15	30	12.5	51.85	55.72	47.7	40.72	3.88	7.4
20	15	30	12.5	51.15	55.02	47	41.72	8.18	7.26

Table 5
ANOVA Test Results

Source	*Carbon Conversion Efficiency (Silica)*		*Carbon Conversion Efficiency (Limestone)*		*Gas Efficiency (Silica)*		*Gas Efficiency (Limestone)*		*Tar Yield (Silica)*		*Tar Yield (Limestone)*	
	F value	*p-value Prob>F*	*F value*	*p-value Prob>F*	*F value*	*p-value Prob>F*	*F value*	*p-value Prob>F*	*F value*	*p-value Prob>F*	*F value*	*p-value Prob>F*
Model	5.68	0.0047	5.76	0.0057	5.88	0.0053	6.24	0.0042	4.66	0.0123	4.27	0.0101
A-Coconut shell	3.08	0.1021	3.23	0.1025	2.91	0.1191	3.39	0.0952	2.29	0.1612	2.11	0.1587
B-cornstalks	6.95	0.0231	7.05	0.0241	7.00	0.0245	7.77	0.0192	3.07	0.1105	3.00	0.1008
C-Wheat husk	25.4	0.0002	28.25	0.0003	29.08	0.0003	31.79	0.0002	21.03	0.0010	19.24	0.0009
AB	0.10	0.7244	0.11	0.7515	0.11	0.7494	0.084	0.7775	0.032	0.8617	0.030	0.8601
AC	0.09	0.7315	0.11	0.7471	0.11	0.7451	0.068	0.7997	0.030	0.8665	0.024	0.7844
BC	0.48	0.4698	0.53	0.4833	0.54	0.4797	0.28	0.6071	0.063	0.8075	0.060	0.8044
A^2	11.01	0.0058	11.04	0.0077	11.54	0.0068	10.87	0.0080	10.68	0.0084	10.01	0.0077
B^2	0.2	0.6078	0.24	0.6376	0.29	0.6040	0.34	0.5743	1.55	0.2421	1.32	0.2358
C^2	2.05	0.1500	2.38	0.1537	2.57	0.1401	2.86	0.1218	5.62	0.0392	4.98	0.0228

conversion efficiency, gas efficiency and tar yield increases with the increase in coconut shell ratio. This may be explained with Le Chatelier's principle which states that higher concentration of coconut shell ratio favors the reactants in exothermic reactions and the products in endothermic reaction. Therefore, the endothermic reaction was strengthened with increasing coconut shell ratio, which resulted in more H_2 and less CH_4 concentrations.

It is well-known how the addition of limestones to the bed changes the product distribution in processes of combustion, incineration, gasification, and pyrolysis of biomass. These calcinated solids mainly react with some contaminants like HCl, SO_2, PAHs, etc., and eliminate them in some extent from the fuel gas. The in-bed use of limestone in biomass gasification seems also to have found commercial application. Many researches [37, 38, 39] used in-bed limestone and dolomite, respectively, for biomass gasification with steam, and in the earlier research [37] dolomite for biomass gasification with air but under pressure. Since there was some lack of knowledge in biomass gasification with air at atmospheric pressure, hence the present research was made for this purpose. All the runs were made with silica and limestone to study the effect of biomass blending ratio on the gas efficiency, carbon conversion efficiency and tar yield. The biomass blends used with the limestone bed materials shows better performance than the silica bed materials. This is due to the low heating value (LHV) of the gas decreases somewhat with lime stone. This is attributed to the in-bed tar elimination reactions which increase the H_2, CO, and CH_4 contents in the producer gas. For the just said reasons, gas yield increases with limestone bed materials. Thus it reduces the tar yield because the rates of the in-bed char elimination reactions (partial oxidation, steam, and dry (CO_2) gasification, etc.) increase on limestone bed materials. As is observed, the carbon conversions of the producer gas with limestone bed materials vary significantly as tabulated in the Table 4. The high reactivity of limestone can be explained by its high initial porosity. Limestone has also earlier been found to behave differently than the other silica under gasification. When comparing the porosity with the reactivity of the sorbents, the higher the porosity, the higher the final conversion. This is in agreement with the work of previous research [40]. Due to the decomposition of CaCO3 to CaO, the porosity of the limestone was increased, thus increasing the conversion rate.



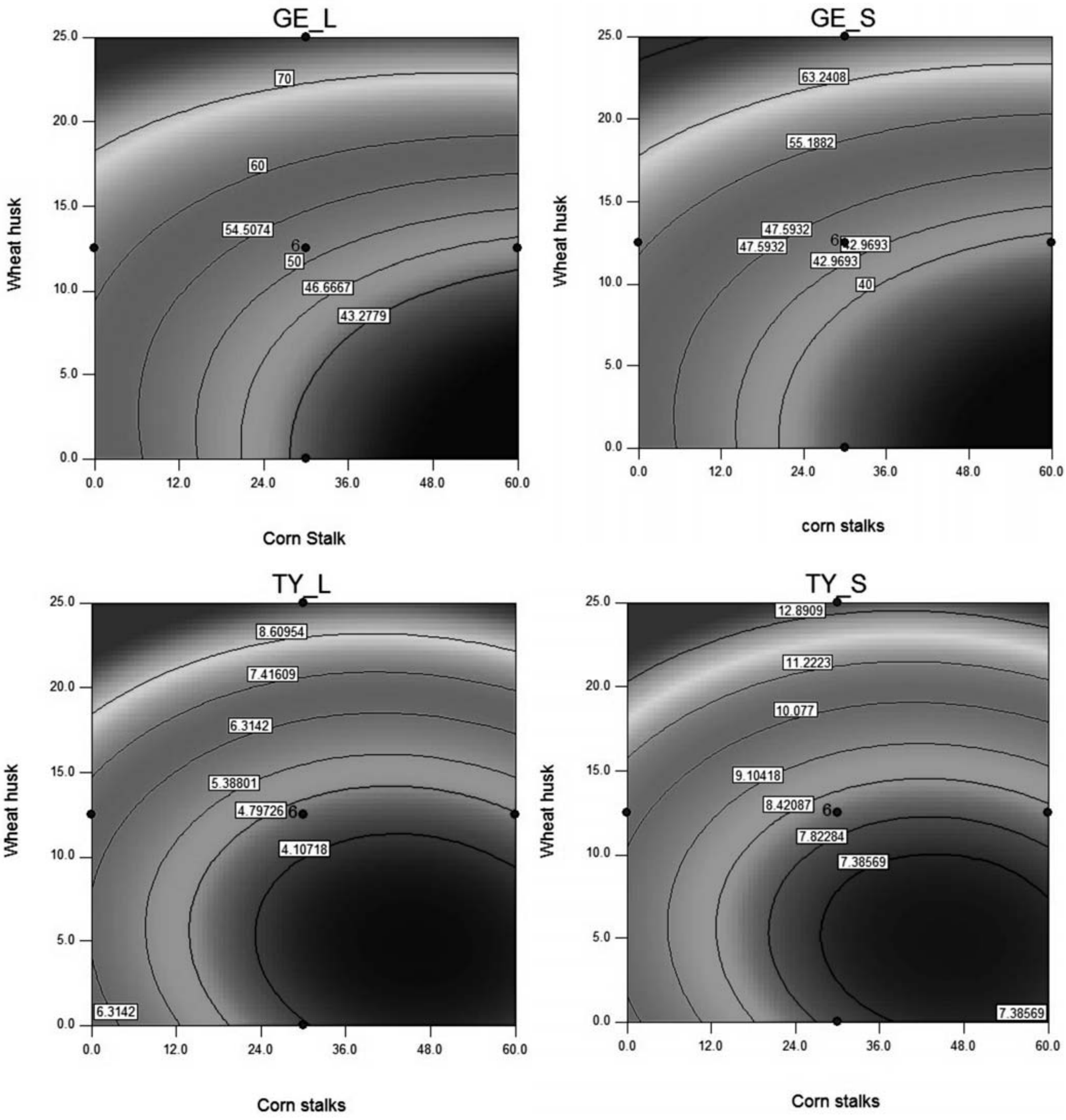


Figure 5: Response Contour Plots Showing the Effect of Interaction Factors (Coconut stalks & wheat husk)

3.3. Effect of Corn Stalk

Corn Stalk is a predominant biomass used for the gasification. Table 4 shows both theoretical values and experimental data of gas species taken at Corn Stalk ratio between 0 to 60% of the total blend. The influences of addition of rice clearly demonstrated that, because of the thermal instability of carbon, a higher percentage of Corn Stalk results in a lesser degree of carbon conversion in both silica and limestone bed material. However, the carbon conversion with lime stone as a bed material is comparatively higher than the silica bed materials. Compared to thermodynamic equilibrium the syngas contains less CO. The syngas also contains 1.3% CH_4 which is not predicted at all at equilibrium (~10-4 %). A possible explanation could be that the heterogeneous reactions involved in char gasification are too slow to be completed within the residence time of the reactor at the current gasification conditions. This will thereby result in less CO_2 and CO. The syngas can also have become shifted in the quench, which could also explain differences between the measured syngas composition after the quench compared to the syngas composition at equilibrium. Generally, increasing the Corn Stalk will increase the gas efficiency since the heating value of the produced gas will increase with pressure [41] as a result of CH_4 production through the steam reforming reaction. On the other hand, with silica bed material increasing Corn Stalk will decrease the heating value of produced gas and hence lower the gas efficiency.

In terms of tar yield, with the increase of Corn Stalk, the tar yield increases. On comparing the bed materials, the limestone bed material possesses lesser tar yield. According to the course of the catalytic reaction, the tar needs to be absorbed first by the active sites of the bed material, which is not only affected by the physical properties of the bed material but also by the transfer behavior of the volatiles. In this experiment, calcium oxide was fine and was prone to enter the freeboard, which had no bubbles, with good contact between the bed material and the tar; thus, the tar cracking would be improved. The tar conversion increases apparently as Corn Stalk rises. The addition of Corn Stalk favors the conversion of tar. It is well-known that the polarities of the active site of silica could not affect the π-electron cloud's stability of condensed aromatic compounds in tar, so the addition of silica decelerates the cracking of condensed aromatic compounds and results in the quick decrease of tar yield.

3.4. Effect of Wheat husk

Major constituents of wheat husk such as hydrogen, nitrogen, oxygen and minerals such as calcium. It is observed for each gasification trial and are represented in Table 4. The data with the increase of wheat husk, the carbon conversion efficiency, gas yield increases. High reactivity of biomass causes an increase in volatile matter, which subsequently gets converted to free radicals and therefore improves the decomposition, oxidation and gasification reactions. It is reported that due to both high reactivity and high contents of hydrogen and oxygen in biomass, carbon conversion during co-gasification is greater than other biomass gasification alone and this tends to increase with increasing biomass content in the fuel.

It is reported that higher conversion of fuel during co-gasification causes an increase in the gas yield [42]. In the co-gasification, higher gas yield is reported with an increase in wheat husk composition in the fuel as a consequence of higher concentration of hydrocarbons. In earlier research [43], gas yield increases with an increase in biomass ratio due to transfer of hydrogen radicals from biomass that causes more decomposition of fuel. In addition, gas yield reaches to a maximum value when the fuel blend consists of 30% of wheat. This is due to the reaction of oxygen content and carbon content in biomass, CO increases. They also state that by increasing the cracking of tar by means of volatiles present in biomass such asH_2O andH_2 radicals, CH_4 increases. The wheat husk as a biomass plays a key role in the production of tar during co-gasification in comparison with other feedstock components. It is observed that in co-gasification of wheat husk with Corn Stalk with, tar contents are decreased, although it is reported that the structure of tar that is formed is harder than that formed by individual biomass. It is also claimed that the synergetic effects of wheat husk with coconut shell causes a decrease in tar contents during cogasification. It is also observed that the use of high air/fuel ratio with higher contents of biomass during co-gasification, due to which less tar yield is produced. It is further confirmed that tar production in co-gasification of biomass is lower than in the gasification of individual fuels as a result of synergetic effects between both fuels. The investigation of wheat contents in cogasification shows a decrease in tar production, when wheat proportion increases in fuel blends as wheat has less complex structure than biomass [44].

4. CONCLUSIONS

1. The present study was focused on the co-gasification of biomass blends in a pilot scale fluidized bed reactor installed in the laboratory. The gasifier was operated at bed temperatures ranging from 750 °C to 950 °C with varying equivalence ratios of 0.35 to investigate the fuel gas compositions.

2. The empirical relation was developed in order to quantify the gas efficiency of fuel gas. This model gave results with high accuracy showing similar trends in predicting the variation of gas species concentrations in line with experimental data.
3. It was noticed that the carbon conversion efficiency, gas efficiency and tar yield increases with the increase in Corn Stalk, wheat husk and coconut shell. However, with the increase of Corn Stalk, the carbon conversion efficiency reduces.
4. On comparing the efficiency of the producer gas, the lime stone bed material shows better performance than the silica bed material.

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