DEVELOPMENT OF AN EMPIRICAL RELATIONSHIP AND INFLUENCE OF PROCESS PARAMETERS ON BIOMASS GASIFICATION SYSTEM

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ABSTRACT

The present research incorporated the parametric study of process parameters such as bed temperature (T), pressure (P), equivalence ration (R), feed rate (F) and particle size (S) which influence the composition of the producer gas, tar yield and cold gas efficiency. Six major components of the producer gas such as O_2, H_2, CO, CO_2, CH_4, and N_2 were analyzed in the laboratory along with the evaluation of tar yield and cold gas efficiency. It was observed that the concentrations of hydrogen, oxygen nitrogen and carbon monoxide were increased with rise in gasification temperature, pressure and equivalent ratio (0.2-0.35). On the other hand, higher equivalence ratios (0.4-0.5) caused to decrease the concentrations of hydrogen, oxygen, nitrogen and carbon monoxide. Higher equivalence ratio also resulted in more gas yields and cold gas efficiency due to increase in the exothermic reactions. Empirical relationship was developed to predict the process of generating fuel gas with better quality through gasification of biomass in a fluidized bed reactor using response surface methodology. The developed model was made a good prediction for the experimental data as observed for the gas species concentrations.

Keyword: Equivalent ratio, Fluidized bed gasifier, Producer gas, Response surface methodology and Sugarcane bagasse.

I. INTRODCTION

Today in many countries, most of the surplus sugarcane bagasses 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]. 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]. The gasification technologies are broadly of two types – fixed bed and fluidized bed. According to Ergudenler [7],sugarcane bagasse has low contents of sulfur and of heavy metals and is relatively nonpolluting [8]. It can serve as a more environmentally friendly fuel than fossil fuels because, even when it is burned, all the emitted carbon can be the carbon accumulated in the plant body by photosynthesis; in other words, it is carbon neutral. Conversion of

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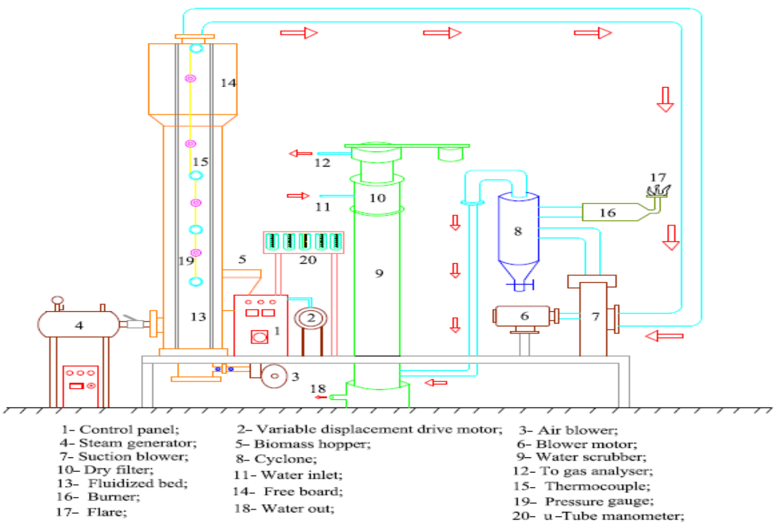
sugarcane bagasse into heat, steam, gases, or liquid fuels could bring benefits to countries that have no conventional energy resources [9]. It power plants [10-13], but so far no such plants have been built in India, possibly because of low electricity prices and a lack of sufficient incentives to adopt renewable energy [14].Several studies have investigated equilibrium modelling of gasification and most of them used the relatively simple Gibbs free energy minimization method [15–17]. Ptasinski.etal. [18] and Prins et al. [19] studied the effect of varying feedstock compositions on gasification efficiency. Mahishi and Goswami [20] used equilibrium modelling to study the effects of operating conditions on hydrogen yields using both steam and oxygen as gasifying agents.

II. EXPERIMENTAL SET UP

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. The electric heating was switched onto and the gasifier was allowed to run until the bed temperature was 450°C.The cyclone at the outlet of gasifier was used to separate the solid particles from the fuel gas mixture. A second orifice meter (50 mm diameter) was positioned in the fuel gas pipe (108 mm diameter) to estimate the gas yields. The As sugarcane bagasse has high ash content, it requires larger fraction of the fuel to be burnt – this ultimately demands a higher equivalence ratio [22]. In Hartiniati et al. [23], 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 sugarcane bagasse. Later on, Mansaray et al. [24] also investigated the sugarcane bagasse 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.



Fig, 1 Experimental Set Up

2.1 Feedstock and Inert Bed Materials

The proximate and ultimate analyses of sugarcane bagasse used as feed stock are presented. Considering the major elements and on the basis of dry and ash free condition, the sugarcane bagasse was represented as $CH_{1.49}O_{0.64}$ on molar basis. The inert bed material used was sand and its particle size distribution was selected as 0.400 mm using sieve analysis. [21]. 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.

2.2 Identifying the Important Factors and the Feasible Working Limit

The predominant factors that have a greater influence on the quality of the producer gas and the cold gas efficiency have been identified review from the literature [25-34] and the following conclusions have been arrived at If the bed temperature was less than 650°C, the catalyst was required for higher production of hydrogen and nitrogen. The temperature at the bottom part of the gasifier is stable for all the fuels at around 650°C [25]. the bed temperature was greater than 950°C, expected that the gas composition will change with temperature inside the gasifier, but no clear trend was observed for the individual gas components during gasification [26].If the pressure is less than 1 bar, the high purity of the produced gas is not required [27]. If the pressure is greater than 5 bar, the process control for chemical cycles due to the production of hydrogen in high pressure is to some extent difficult [28].If the feed rate was less than 5 kg/hr, but as time passes, feed stock and ned materials gather on the bottom, forming a solid bed. [29]If the feed rate was less than 20 kg/hr, may decrease the residence time of the material inside it and thus decrease its exposure to melting inside it. Hence, the gasifier used for the present work id designed with the maximum feed rate of 20 kg/hr [30]. If the equivalent ratio is less than 0.2, the change is temperature is very insensitive. If the equivalent ratio is greater than 0.5, It is noted from the data that, at increased values of ER, the higher heating value of synthetic gas was reduced which is in good agreement with the results of the study conducted [26, 31]. If the particle size is less than 70 µm, implied higher conversions, and with lower solid temperatures into the bed and lower concentration of some gases, this means lower combustion richness [32].If the particle greater than 500 µm, reduces the pre-treatment costs, but the devolatilization time increases, and thus for a defined throughput the gasifier size increases [33].

2.3 Experimental Design Matrix

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 assay conditions for the reaction parameters were taken at zero level (center point) and one level (-1) and (+1). The design was extended up to a $\pm \alpha$ (axial point) of 2.378. The design would consist of the 10 corner points of the 2^5 cube, the 16 star points, and 6 center points. The star points would have a = 32^ (1/4) = 2.378 For the convenience of recording and processing experimental data, the upper and lower levels of the factors were coded here as +2.378 and -2.378 respectively. The coded values of any intermediate value could be calculated using following relationship

$$Xi = (2.378 \times \{2X- [Xmax - Xmin]\})/(Xmax - Xmin) \quad \text{.................................} \quad (1)$$

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where,Xi is the required coded value of a variable X and X is any value of the variable from Xmin to Xmax ;

Design matrix consisting of 32 sets of coded conditions (comprising a full replication five factorial of 16 points, 10 corner points and six centre points) was chosen in this investigation.

TABLE 1-IMPORTANT FACTORS AND THEIR LEVELS

Factors	Units	Notation	Factors levels				
			-2.378	-1	0	+1	+2.378
Bed Temperature	Celsius	T	650	725	800	875	950
Pressure	MPa	P	1	2	3	4	5
Feed rate	Kg/h	F	5	8.75	12.5	16.25	20
Particle size and Shape	µm	S	70	142.5	215	357.5	500
Equivalence ratio		E	0.2	0.275	0.35	0.425	0.5

2.4 Experimental Testing

During experimentation, special care was taken to maintain the desired bed temperatures as the selected feedstock was sugarcane bagasse which had 17.09% ash, higher than any woody biomass and its ash had more than 95% silica. One of the important features of sugarcane bagasse gasification is that the bed temperature can be kept as low as 600–650°C, thereby preventing sintering and agglomeration of this ash which would otherwise cause serious operational problems during the conversion process[33] also indicate that oxidation of sugarcane bagasse 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. In view of this, the gasifier was operated in the range of 600–950°C when the experiments were carried out with equivalence ratio 0.2 and 0.5. The energy content of the gas is assessed through the variable CGE (cold gas 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 ($HHV_{RiceHusk}$) without taking into account the heat input in the reactor:

$$\mathbf{CGE = HHV_{gas}/HHV_{RiceHusk}} \quad \ldots\ldots (1)$$

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 sugarcane bagasse

$$\mathbf{Y_{Tar}\% = [(M_{Tar}) / (M_{RiceHusk})]x100} \ \ldots.. (2)$$

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III. DEVELOPING THE EXPERIMENTAL DESIGN MATRIX

RSM provides a quantitative form of relationship between the desired response (Quality of the Producer gas) and the independent input variables, bed temperature (T), pressure (P), the feed rate of the feed stock (F), the equivalence ratio (E) and particle size (S), and can be expressed as a function, as in Equation (3)

Producer gas (G) = f (T, P, F, E, S)..... (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 five factors, the selected polynomial could be expressed as

Quality of the Producer Gas (G) = {b_0 +b_1 (T) + b_2 (P) +b_3 (F) +b_4 (E) +b_5(S) + b_{11}(T^2) + b_{22}(P^2) + b_{33}(F^2) + b_{44}(E^2) + b_{55}(S^2) + b_{12} (TP) + b_{13} (TF) + b_{14}(TE) b_{15}(TS) + b_{23}(PF) + b_{24}(PE) + b_{25}(PS) + b_{34}(FE) + b_{35}(FS) + b_{45}(ES)} ….. (5)

where b_0 is the average of responses (corrosion rate) 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,

Bi = (∑ (Xi,Yi))/n ……………………………..… (6)

. The final empirical relationship obtained by the above procedure to estimate producer gas generation of sugarcane bagasse under fluidized bed gasification is given below;

<u>For Oxygen</u>

Producer Gas (O_2) = + 0.11 - 0.012 *(T) +5.375x10^{-3} *(P) + 2.292 x10^{-3} *(F) + 3.125x10^{-3}*(E) - 5.625x10^{-3} *(S) + 1.562 x10^{-3} * (TP) +0.021 *(TF) +9.375 x10^{-4} * (TE) +0.019 * (TS) +0.038 * (PF) -0.0122 * (PE) -3.125 x10^{-4} * (PS) -2.812 x10^{-3} * (FE) +0.0203 * (FS) - 2.187 x10^{-3} * (ES) +0.013 * (T^2) +0.029 * (P^2) +0.032 * (F^2) +6.352 x10^{-3} * (E^2) -2.398 x10^{-3}*(S^2)

<u>For Hydrogen</u>

Producer Gas (H_2) = + 0.11 - 0.012 *(T) +5.375x10^{-3} *(P) + 2.292 x10^{-3} *(F) + 3.125x10^{-3}*(E) - 5.625x10^{-3} *(S) + 1.562 x10^{-3} * (TP) +0.021 *(TF) +9.375 x10^{-4} * (TE) +0.019 * (TS) +0.038 * (PF) -0.0122 * (PE) -3.125 x10^{-4} * (PS) -2.812 x10^{-3} * (FE) +0.0203 * (FS) - 2.187 x10^{-3} * (ES) +0.013 * (T^2) +0.029 * (P^2) +0.032 * (F^2) +6.352 x10^{-3} * (E^2) -2.398 x10^{-3}*(S^2)

<u>For Nitrogen</u>

Producer Gas (H_2) = + 0.11 - 0.012 *(T) +5.375x10^{-3} *(P) + 2.292 x10^{-3} *(F) + 3.125x10^{-3}*(E) - 5.625x10^{-3} *(S) + 1.562 x10^{-3} * (TP) +0.021 *(TF) +9.375 x10^{-4} * (TE) +0.019 * (TS) +0.038 * (PF) -0.0122 * (PE) -3.125 x10^{-4} * (PS) -2.812 x10^{-3} * (FE) +0.0203 * (FS) - 2.187 x10^{-3} * (ES) +0.013 * (T^2) +0.029 * (P^2) +0.032 * (F^2) +6.352 x10^{-3} * (E^2) -2.398 x10^{-3}*(S^2)

<u>For Carbon-monoxide</u>

Producer Gas (H_2) = + 0.11 - 0.012 *(T) +5.375x10^{-3} *(P) + 2.292 x10^{-3} *(F) + 3.125x10^{-3}*(E) - 5.625x10^{-3} *(S) + 1.562 x10^{-3} * (TP) +0.021 *(TF) +9.375 x10^{-4} * (TE) +0.019 * (TS) +0.038 * (PF) -0.0122 *

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$$\mathbf{(PE) - 3.125\times10^{-4} * (PS) - 2.812\times10^{-3} * (FE) + 0.0203 * (FS) - 2.187\times10^{-3} * (ES) + 0.013 * (T^2) + 0.029 * (P^2) + 0.032 * (F^2) + 6.352\times10^{-3} * (E^2) - 2.398\times10^{-3} * (S^2)}$$

For Carbon-di-oxide

$$\mathbf{Producer\ Gas\ (H_2) = + 0.11 - 0.012 *(T) + 5.375\times10^{-3} *(P) + 2.292\times10^{-3} *(F) + 3.125\times10^{-3} *(E) - 5.625\times10^{-3} *(S) + 1.562\times10^{-3} * (TP) + 0.021 *(TF) + 9.375\times10^{-4} * (TE) + 0.019 * (TS) + 0.038 * (PF) - 0.0122 * (PE) - 3.125\times10^{-4} * (PS) - 2.812\times10^{-3} * (FE) + 0.0203 * (FS) - 2.187\times10^{-3} * (ES) + 0.013 * (T^2) + 0.029 * (P^2) + 0.032 * (F^2) + 6.352\times10^{-3} * (E^2) - 2.398\times10^{-3} * (S^2)}$$

For Methane

$$\mathbf{Producer\ Gas\ (H_2) = + 0.11 - 0.012 *(T) + 5.375\times10^{-3} *(P) + 2.292\times10^{-3} *(F) + 3.125\times10^{-3} *(E) - 5.625\times10^{-3} *(S) + 1.562\times10^{-3} * (TP) + 0.021 *(TF) + 9.375\times10^{-4} * (TE) + 0.019 * (TS) + 0.038 * (PF) - 0.0122 * (PE) - 3.125\times10^{-4} * (PS) - 2.812\times10^{-3} * (FE) + 0.0203 * (FS) - 2.187\times10^{-3} * (ES) + 0.013 * (T^2) + 0.029 * (P^2) + 0.032 * (F^2) + 6.352\times10^{-3} * (E^2) - 2.398\times10^{-3} * (S^2)}$$

For CGE

$$\mathbf{Producer\ Gas\ (H_2) = + 0.11 - 0.012 *(T) + 5.375\times10^{-3} *(P) + 2.292\times10^{-3} *(F) + 3.125\times10^{-3} *(E) - 5.625\times10^{-3} *(S) + 1.562\times10^{-3} * (TP) + 0.021 *(TF) + 9.375\times10^{-4} * (TE) + 0.019 * (TS) + 0.038 * (PF) - 0.0122 * (PE) - 3.125\times10^{-4} * (PS) - 2.812\times10^{-3} * (FE) + 0.0203 * (FS) - 2.187\times10^{-3} * (ES) + 0.013 * (T^2) + 0.029 * (P^2) + 0.032 * (F^2) + 6.352\times10^{-3} * (E^2) - 2.398\times10^{-3} * (S^2)}$$

For Tar yield

$$\mathbf{Producer\ Gas\ (H_2) = + 0.11 - 0.012 *(T) + 5.375\times10^{-3} *(P) + 2.292\times10^{-3} *(F) + 3.125\times10^{-3} *(E) - 5.625\times10^{-3} *(S) + 1.562\times10^{-3} * (TP) + 0.021 *(TF) + 9.375\times10^{-4} * (TE) + 0.019 * (TS) + 0.038 * (PF) - 0.0122 * (PE) - 3.125\times10^{-4} * (PS) - 2.812\times10^{-3} * (FE) + 0.0203 * (FS) - 2.187\times10^{-3} * (ES) + 0.013 * (T^2) + 0.029 * (P^2) + 0.032 * (F^2) + 6.352\times10^{-3} * (E^2) - 2.398\times10^{-3} * (S^2)}$$

TABLE 2-EXPERIMENTAL RESULTS

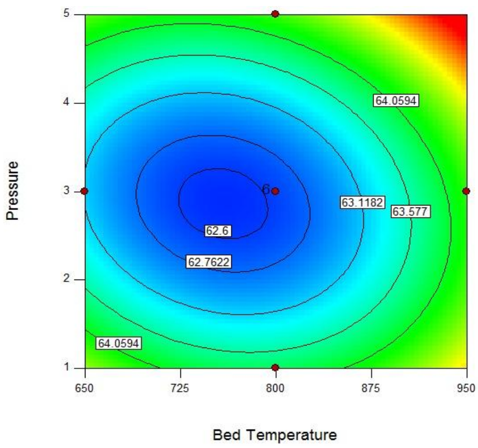
Ex. No	Input parameters					Gas Composition							
	Bed Temperature(°C)	Pressure (bar)	Feed Rate(kg/hr)	Equivalent ratio	Particle size (µm)	Oxygen	Hydrogen	Carbon monoxide	Carbon-di-oxide	Methane	Nitrogen	Tar yield	Cold gas efficiency
1	725	2	8.75	0.275	392.5	0.21	5.89	12.83	10.8	1.25	54.6	4.6	64.1
2	875	2	8.75	0.275	177.5	0.35	7.15	11.89	12.1	1.4	54.5	4.5	64.5
3	725	4	8.75	0.275	177.5	0.25	6.16	12.24	11.2	1.31	54.6	4.65	64.6
4	875	4	8.75	0.275	392.5	0.36	7.99	11.11	12.8	1.41	54.0	4.02	65.1
5	725	2	16.25	0.275	177.5	0.28	6.38	12.90	11.5	1.32	53.9	3.99	63.9
6	875	2	16.25	0.275	392.5	0.16	4.81	11.89	10.1	1.21	54.9	4.91	64.9
7	725	4	16.25	0.275	392.5	0.24	5.11	12.28	12.9	1.28	54.8	4.86	64.8
8	875	4	16.25	0.275	177.5	0.22	5.03	12.1	11.1	1.26	53.9	3.95	65.9
9	725	2	8.75	0.425	177.5	0.33	8.06	12.27	11.9	1.37	54.4	4.44	64.4
10	875	2	8.75	0.425	392.5	0.18	4.99	11.79	10.6	1.22	53.8	3.81	63.8
11	725	4	8.75	0.425	392.5	0.32	7.68	12.14	13.8	1.36	54.1	4.15	64.1
12	875	4	8.75	0.425	177.5	0.11	4.75	12.13	9.9	1.15	54.1	4.11	64.1
13	725	2	16.25	0.425	392.5	0.15	5.77	12.21	10.3	1.19	54.5	4.53	64.5
14	875	2	16.25	0.425	177.5	0.18	5.34	12.16	10.6	1.23	54.2	4.25	64.2
15	725	4	16.25	0.425	177.5	0.25	6.6	12.2	11.6	1.29	54.4	4.45	64.4
16	875	4	16.25	0.425	392.5	0.24	5.45	12.26	11.1	1.28	54.7	4.78	64.7
17	650	3	12.5	0.35	285	0.25	5.61	12.42	11.4	1.29	54.5	4.51	62.5
18	950	3	12.5	0.35	285	0.32	7.21	11.05	13.3	1.21	53.2	3.23	65.1

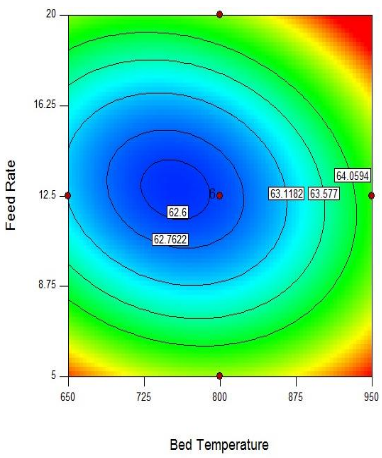
19	800	1	12.5	0.35	285	0.18	3.77	12.14	10.6	1.28	54.1	4.19	64.1
20	800	5	12.5	0.35	285	0.36	6.13	11.92	12.2	1.3	53.0	3.06	64.2
21	800	3	5	0.35	285	0.24	6.45	12.01	11.1	1.28	53.5	3.54	65.5
22	800	3	20	0.35	285	0.18	4.11	12.17	10.6	1.24	54.3	4.34	64.0
23	800	3	12.5	0.2	285	0.16	4.6	12.34	10.4	1.25	54.6	4.68	64.6
24	800	3	12.5	0.5	285	0.2	6.44	12.21	10.8	1.22	54.5	4.53	64.9
25	800	3	12.5	0.35	70	0.32	6.64	12.04	12.1	1.36	53.6	3.68	63.6
26	800	3	12.5	0.35	500	0.18	4.91	11.89	10.6	1.22	52.9	2.93	63.9
27	800	3	12.5	0.35	285	0.22	5.16	11.98	10.5	1.26	53.3	3.39	63.3
28	800	3	12.5	0.35	285	0.13	3.33	11.78	9.25	1.15	52.3	2.69	62.6
29	800	3	12.5	0.35	285	0.13	3.33	11.78	9.25	1.26	52.3	2.39	62.3
30	800	3	12.5	0.35	285	0.13	3.33	11.78	9.25	1.19	52.3	2.39	62.3
31	800	3	12.5	0.35	285	0.13	3.33	11.78	9.89	1.19	52.3	2.39	62.3
32	800	3	12.5	0.35	285	0.13	3.33	11.78	9.25	1.19	52.3	2.39	62.3

The Analysis of Variance (ANOVA) technique was used to find the significant main and interaction factors.. The determination coefficient (r^2) indicated the goodness of fit for the model. The Model F-value of (Oxygen = 3.84, Hydrogen = 5.85, Nitrogen = 5.23, Carbon-monoxide = 4.41, Carbon-di-oxide = 5.33, Methane = 4.15, Cold Gas Efficiency = 4.97 and Tar Yield = 8.11) implies the model is significant.

IV. RESULTS AND DISCUSSION

4.1 EFFECT OF TEMPERATURE: Higher temperatures favoured the formation of O_2, N_2, H_2 and CO coupled with increased reforming of methane. However, if the temperature is further increased, H_2 is converted to CO and H_2O by the reverse water gas shift reaction, In this case, the maximum H_2/CO ratio occurred at between 750-950°C, but this varied according to the other operating variables. According to previous studies composition and heating value as bagasse, occurs at around 850°C,which would correspond to the optimum gasifier temperature.





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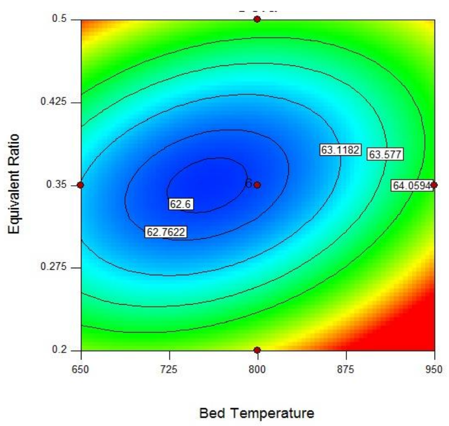

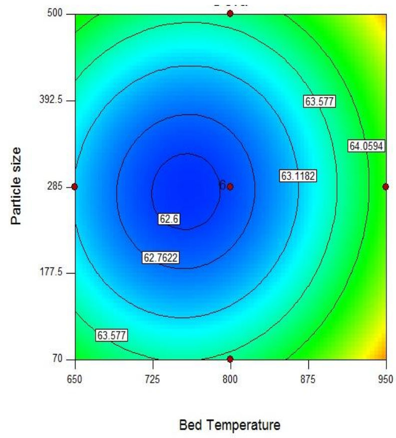

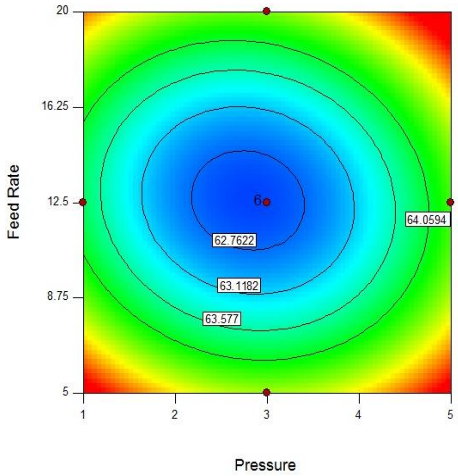

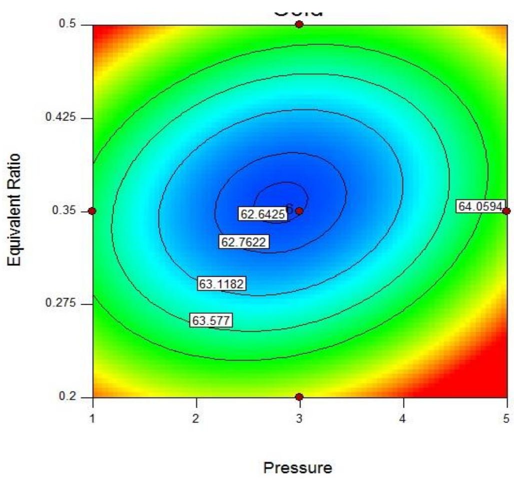

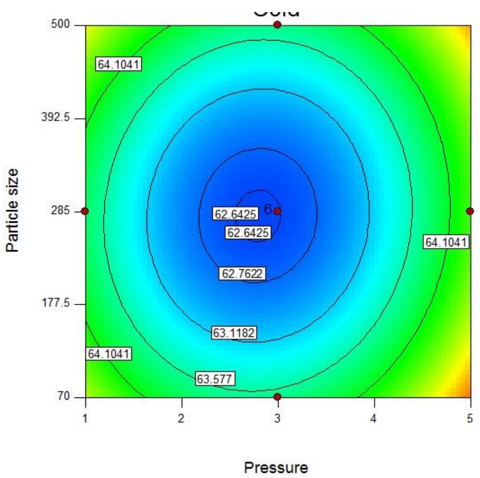

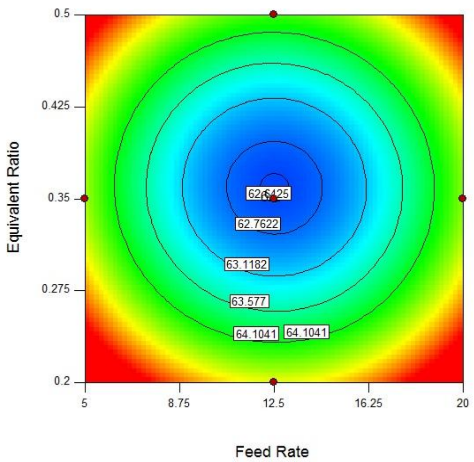

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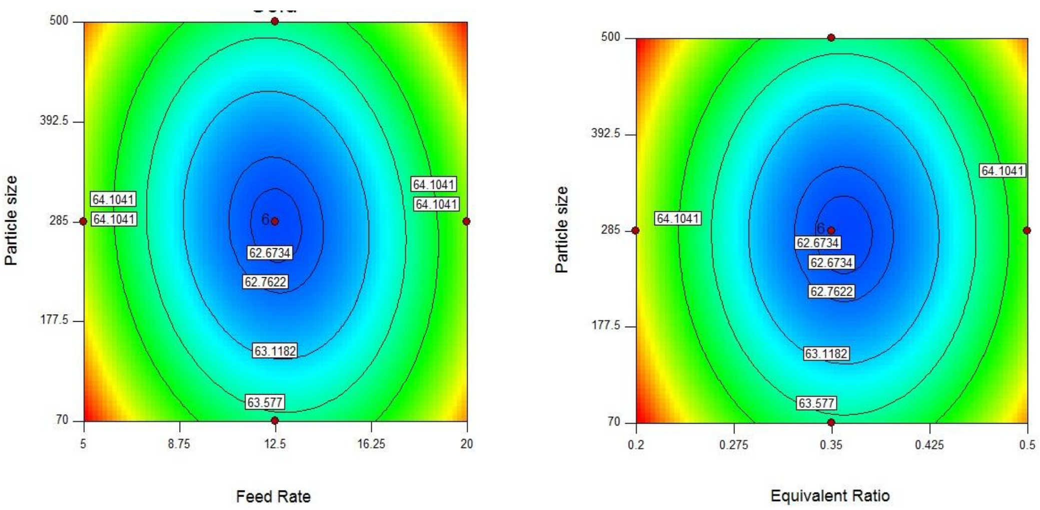

Fig. 4 .1 Response Contour Plots for the Cold Gas Efficiency

4.2 EFFECT OF PRESSURE : The composition of the syngas at equilibrium was determined at 5 bar, 0.36 % O_2 and 53% N_2. The calculations are performed by determining the minimum of Gibbs free energy of a specific system based on a database containing thermodynamic data for various chemical species and phases. Compared to thermodynamic equilibrium the syngas contains less CO but more CO2. The syngas also contains 1.3% CH_4 which is not predicted at all at equilibrium.

4.3 EFFECT OF FEED RATE: The overall range of methane content was 1–1.3% in all the trials of fluidized bed gasification. With the increase of rate of feed stock, the percentage of oxygen and hydrogen was decreased. The same pattern of change of synthetic gas constituents was observed in the earlier study conducted

4.4 EFFECT OF EQUIVALENCE RATIO: It is found the theoretical optimum conditions for maximum efficiency and hydrogen production from atmospheric gasification of dry biomass to be 825°C and an equivalence ratio of 0.35.However, they did not account for practical considerations such as tar formation. It has been reported in literature that a 20% secondary air injection above the gasifier freeboard can reduce tar formation . The results from the study [33] showed a good correlation between experimental and predicted results for bagasse gasification with no tar formation at equivalence ratios of 0.35 and the effect of ER variation (0.2-0.4) is one of the most important operation parameters on the quality of the producer gas. H_2 production peaked at ER of 0.35. Lower heating value of the producer gas was obtained at high ER which was due to the promotion of the oxidation reaction and dilution of the producer gas with N_2.

4.5 EFFECT OF PARTICLE SIZE : Therefore, a balance should be considered while investigating the effect of biomass particle size on the gasification efficiency. The non-uniformity of the biomass particles will influence gasification reaction rate. However, due to intense mixing caused by the fluidized sand, temperature longitudinally does not vary much and are almost similar, indicating that the irregular shapes and size of wood chips do not effect the temperature.

V. CONCLUSIONS

The empirical relation was developed in order to quantify the composition 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. It was noticed that the amount of CH_4 produced during the gasification process was more in comparison to the predicted values. The possible reason could be that the equilibrium state might not have reached for not having enough bed temperature in gasifier. It was seen that hydrogen, oxygen, nitrogen and carbon monoxide contents in fuel gas were increased with rise in bed temperatures, equivalent ratios. The cold gas efficiency was found to increase at higher temperature, equivalence ratio and pressure due to presence of more CO_2 and O_2 in the fuel gas.

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