Abstract
Gasification of high ash coals and controlling resulting emissions is a challenging task. Effective utilization of these coals depends on proper selection of operating conditions. This paper is aimed at comprehensive analysis of effect of operating conditions on the gasification of a high ash Indian (Jharia) coal with two-fold objectives of maximizing syngas heating value and reducing CO2 emissions. An ASPEN Plus model is developed to simulate the gasification process and simulation results are validated with experimental data available in literature. The simulated results are in good agreement with experimental results with less than 10% error.

In the first stage the sensitivity analysis of four operating conditions viz., Equivalence Ratio (ER), Steam-to-Coal Ratio (SCR), Gasifier Temperature, and Gasifier Pressures is performed. A design specification Limiting Air Flow Rate (LAFR) is used for effective carbon conversion and reduced emissions. Gasification temperature is the most influencing parameter among all parameters, followed by ER and SCR. Gasification pressure has no significant effect on syngas composition. The results clearly indicate that a lower ER and SCR are favorable for formation of maximum amount of combustible gases (H2, CO) and minimum amount of CO2. Different combination of ER and SCR in the specified ranges were examined. In all cases, the maximum efficiency is attained in a temperature range of 600 °C to 900 °C. In the second stage these parameter are optimized with an objective of maximizing the heating value of syngas and minimizing CO2 emissions. Both normal and constraint based optimization is performed. In constraint based optimization, a constraint of CO2 mole fraction less than 1% is imposed. Optimum parametric domains for maximum efficiency are presented.

Keywords: Coal gasification, high ash coals, sensitivity analysis, optimization, equivalence ratio, steam to coal ratio, limiting air flow rate, minimum steam flow rate

Nomenclature

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER</td>
<td>Equivalence Ratio</td>
</tr>
<tr>
<td>SCR</td>
<td>Steam to Coal Ratio</td>
</tr>
<tr>
<td>HHV</td>
<td>Higher Heating Value (MJ/Nm³)</td>
</tr>
<tr>
<td>CGE</td>
<td>Cold Gas Efficiency</td>
</tr>
<tr>
<td>M</td>
<td>Moisture (wt.%)</td>
</tr>
<tr>
<td>VM</td>
<td>Volatile Matter (wt.%)</td>
</tr>
<tr>
<td>FC</td>
<td>Fixed Carbon (wt.%)</td>
</tr>
<tr>
<td>ΔHo</td>
<td>Enthalpy of formation (kJ/mol)</td>
</tr>
<tr>
<td>GCV</td>
<td>Gross Calorific Value of coal (MJ/kg)</td>
</tr>
<tr>
<td>LAFR</td>
<td>Limiting Air Flow Rate</td>
</tr>
</tbody>
</table>

INTRODUCTION
Gasification is process of converting carbonaceous fuels into high calorific value gases like H2, CO and CH4. It is most efficient and eco-friendly process of utilizing fossil fuels and biomass fuels [1]. The product gas of gasification process is called syngas consisting of mainly H2, CO and other gases like CH4, CO2, SO2 and NOx in smaller quantities. This syngas is used for power generation and for producing petrochemical products. Indian coals contain high amount of ash and makes them difficult to use for direct combustion. Gasification is a good alternative to exploit these resources for power generation. One of the metrics of gasification process is the gasification efficiency which primarily depend on amount of...
fuel gases H2 and CO present in sygas. Gasification involves complex chemical reactions and depends on several factors like gasifier design, fuel properties, gasifying agent, operating conditions like flow rate of gasifying agent, gasification temperature, pressure, equivalence ratio, etc.

In the past decade many researchers worked on understanding the effect of various parameters and operating conditions on gasification process. Majority of the work is based on biomass fuels. Seldom work is done on understanding gasification process of coals especially low rank coals available in India. The presence of excess ash and other unwanted constituents and releasing of pollutants like CO2, SO2, and NOx, etc., makes these coals an unattractive option for gasification [2]. However, with careful analysis and by proper selection of critical parameters these drawbacks can be overcome.

Yaji Haung et al [3] studied the effect of operating conditions and coal properties and reported that high rank coals like anthracite are more suitable for gasification than low rank bituminous coals. V. Satyam Naidu, et al [4] studied the gasification kinetics of low rank coals and concluded that coals with higher inorganic matter has higher reactivity. Maan Al-Zareer et al [5] studied effect of gasification parameters using kinetic based model and Gibbs free energy model on three coals. They reported that kinetic based gives accurate results than Gibbs free energy based model, but later one is more suitable due to its compatibility to all coal types. They concluded that syngas composition is highly dependent on air and steam flow rates. Vijay Kumar. K et al [6] conducted experimental study on high-ash Indian coal in bubbling fluidized bed using air and steam. They have varied equivalence ratio from 0.25 to 0.35 and steam-coal-ratio from 0.25 to 0.35 and studied their effect on syngas composition. They concluded that steam flow rate is has positive effect on calorific value and gasification efficiency. Neeraj Singh et al [7] conducted mathematical modeling of gasification high-ash Indian coals in moving bed gasification system. They have reported that steam-coal-ratio is dependent on amount of oxidizing agent and that for air based system SCR is 0.4 and for O2 based system it is 1.5. According to them operating pressure has significant effect on gasification performance and pressure of 8 bar and above is suitable for high ash coals. Nourredine Abdouloumouine et al [8] studied the effect of temperature and equivalence ratio on mass balance and energy analysis on biomass gasification. They reported that as the temperature and ER increases the mass balance increases. The increase in temperature has positive effect on cold gas efficiency and hot gas efficiency. In contrast the efficiencies are decreased with increase in equivalence ratio. Zhi-Hua Wang et al [9] investigated characteristics of Shenhua bituminous (SH) and Baorixile lignite coal (BRXL) using both thermogravimetric analyzer and tubular furnace. They reported that both the gasification temperature and atmospheric composition greatly gasification. They concluded that reactivity is lowest under CO2 gasification atmosphere and increased continuously with increase in the H2O partial pressure. They emphasized that there will be a particular combination of gasification atmosphere and temperature which is specific to a given coal. Haibin Li et al [10] developed an integrated gasification fuel cell with zero emission and studied the effect of gas flow rate, pressure, pre-heating temperature, heat losses. They reported that as pressure increases lower heating value is reduced and reaction temperature is increased. O2 preheating has greater influence on reaction temperature and lower heating value when compared to CO2 preheating.

In the present work, the effect of four parameters viz., ER, SCR, Gasifier Temperature and Gasifier Pressure on gasification of Jharia coal is studied in a comprehensive manner. Gasification process consists of complex chemical reactions. Identification of influencing parameters and understanding their synergetic effect is very important. In this work, the interdependency of the parameters and their effect on efficiency is assessed. The optimum parametric domains are presented for maximum gasifier efficiency and minimum emissions, which was not done in previous works.

MODEL DESCRIPTION:

The model is developed based on Gibbs free energy principle and corresponding flow sheet is given in Figure.1 for simulation. Table.1 presents the details of components along with functionality and also operating conditions. The model consists of two reactors, DECOMP for decomposing the wet coal into primary components and GASIFIER to carry out the chemical reactions. The main reactions for different processes along with the enthalpy values are shown in Table.2. The yield of the DECOMP reactor is calculated using FORTRAN subroutine from the ultimate analysis on dry basis. The output of yield reactor is then sent to GASIFIER where the chemical reactions will take place based on minimization of Gibbs free energy principle. Oxygen is produced from air using air separation unit and steam is produced from heater. The heat required for converting water into steam is supplied from gasifier. The product gas is then sent to cyclone separator where the ash is separated and clean syngas is sent for further process.

The following assumptions and model settings are made for conducting the analysis

• The system is operating under steady state conditions
• Coal supplied in the form of particles and the particles have uniform temperature
• There is no pressure drop in the heat exchanger, splitters and cyclone separator
• Coal heat capacity is based on Kirov’s correlation (ASPEN option: HCOALGEN)
• Density calculation based on IGT (Institute of Gas Technology) equations (ASPEN option: DCOALIGT)
• Thermodynamic property method used for real components and mixture (ASPEN option: RK-SOAVE)
• Tar formation is neglected
Figure 1: Flow sheet of gasification plant for simulation

Table 1: Components of gasification plant and representation in ASPEN Plus

<table>
<thead>
<tr>
<th>Block/Stream</th>
<th>Type</th>
<th>Function</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECOMP</td>
<td>RYield Reactor</td>
<td>Decompose the coal into primary form</td>
<td>1 atm, 25 °C</td>
</tr>
<tr>
<td>Air Separation Unit (ASU)</td>
<td>Component Separator</td>
<td>Separate O₂ from Air</td>
<td>1 atm, 25 °C</td>
</tr>
<tr>
<td>GASIFIER</td>
<td>RGibbs Reactor</td>
<td>React all component inputs based on Gibbs free energy principle</td>
<td>1 atm, 300 to 1500 °C, Rigorous with all possible components</td>
</tr>
<tr>
<td>HEATER</td>
<td>Heat exchanger</td>
<td>Convert water into steam at specified temperature and pressure</td>
<td>1 atm, 300 °C</td>
</tr>
<tr>
<td>CYC-SEP</td>
<td>Cyclone Separator</td>
<td>Separate ash from product gas</td>
<td>1 atm, Gasifier Temperature</td>
</tr>
</tbody>
</table>

Table 2: Main reactions taking place in the RGibbs reactor

<table>
<thead>
<tr>
<th>Process</th>
<th>Reaction</th>
<th>Reaction #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation</td>
<td>[ C + 0.5O_2 \rightarrow CO, \Delta H^\circ = -268 \text{ kJ/mol} ]</td>
<td>R1</td>
</tr>
<tr>
<td></td>
<td>[ C + O_2 \rightarrow CO_2, \Delta H^\circ = -406 \text{ kJ/mol} ]</td>
<td>R2</td>
</tr>
<tr>
<td></td>
<td>[ H_2 + 0.5O_2 \rightarrow H_2O, \Delta H^\circ = -258.8 \text{ kJ/mol} ]</td>
<td>R3</td>
</tr>
<tr>
<td>Water Gas Shift Reaction</td>
<td>[ C + H_2O \rightarrow CO + H_2, \Delta H^\circ = +131 \text{ kJ/mol} ]</td>
<td>R4</td>
</tr>
<tr>
<td>Boudouard Reaction</td>
<td>[ C + CO_2 \rightarrow 2CO, \Delta H^\circ = +172 \text{ kJ/mol} ]</td>
<td>R5</td>
</tr>
<tr>
<td>Shift Reaction</td>
<td>[ CO + H_2O \leftrightarrow CO_2 + H_2, \Delta H^\circ = -42 \text{ kJ/mol} ]</td>
<td>R6</td>
</tr>
<tr>
<td>Methanation</td>
<td>[ C + 2H_2 \rightarrow CH_4, \Delta H^\circ = -75 \text{ kJ/mol} ]</td>
<td>R7</td>
</tr>
<tr>
<td></td>
<td>[ CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O, \Delta H^\circ = -206 \text{ kJ/mol} ]</td>
<td>R8</td>
</tr>
</tbody>
</table>

Table 3: Properties of Illinois #06 coal [11]

<table>
<thead>
<tr>
<th>Proximate Analysis</th>
<th>Ultimate Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>FC</td>
</tr>
<tr>
<td>0.2</td>
<td>58.01</td>
</tr>
</tbody>
</table>
Model Validation

The model is validated with the experimental data from the work done by Wen et al., [11] for the Illinois #06 coal. They have investigated the effect of various parameters on syngas composition and compared the experimental results with the Texaco entrained flow gasifier plant data. The ultimate and proximate analysis of Illinois No.6 coal is given in table 3. The proposed model is given input for three runs and the gas components are compared with the experimental results. Table 4 shows the input conditions and output gas components. Since model input streams are different from those of experiment, while giving inputs for O₂ and SCR, the air and steam flow rates are adjusted by using applicable factors to match the inputs of experiment. The operating conditions are gasifier pressure of 24 atm, and steam temperature of 490 °C for all cases.

Simulation Methodology

The proximate and ultimate analysis of Jharia coal is presented in Table 5. The wet coal is fed to the DECOMP reactor which decomposes it into its primary components. The heat required for the DECOMP reactor (Q-DECOM) is supplied from the Gasifier. A constant coal feed rate (10 kg/s) is maintained and the air flow such that gasifier operating conditions are sustained and the excess heat has to be recovered by other means. Therefore in order to control the combustion such that the reactions are self-sustained and the heat requirement of gasification plant are met, a design specification for the GASIFIER block LAFR is introduced. The design specification controls the air flow such that gasifier produces just enough heat to meet the plant requirements while keeping the Q-Gasifier and CO₂ formation to a minimum value. The steam flow rate and gasifier temperature are then varied and syngas composition is analyzed. The HHV and CGE for different combinations of parameters are studied and optimum values of parameters are identified. CGE and HHV are calculated using Eq. (3) and (4) respectively.

\[
\left(\frac{\text{Air}}{\text{Fuel}}\right)_{\text{stoch}} = 4.23 \times [2.67C + (8H - O) + S] \quad (1)
\]

Where C, H, O and S are wt.% of Carbon, Hydrogen, Oxygen, and Sulfur taken from Ultimate analysis.

\[
\text{Equivalence Ratio (ER)} = \frac{\left(\frac{\text{Air}}{\text{Fuel}}\right)_{\text{actual}}}{\left(\frac{\text{Air}}{\text{Fuel}}\right)_{\text{stoichiometric}}} \quad (2)
\]

\[
\text{Cold Gas Efficiency} = \frac{\text{Syn gas flow rate in } m^3/s \times \text{Gas HHV in } MJ/m^3}{\text{coal feed rate in } kg/s \times \text{coal HHV in } MJ/kg} \times 100 \quad (3)
\]

\[
\text{HHV}_{\text{syngas}} = \frac{V_{\text{CO}} \times CV_{\text{CO}} + V_{\text{H₂}} \times CV_{\text{H₂}} + V_{\text{CH₄}} \times CV_{\text{CH₄}}}{100} \quad (4)
\]

Where V is the volumetric percentage and CV is the calorific value of individual gas species.

Table 4: Input conditions, and validation of simulation data of Illinois #06 coal [11]

<table>
<thead>
<tr>
<th>Run No</th>
<th>Input Conditions</th>
<th>Product Gases (g/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coal (g/s)</td>
<td>O₂ (g/s)</td>
</tr>
<tr>
<td>Run-1</td>
<td>Experiment [9]</td>
<td>76.66</td>
</tr>
<tr>
<td></td>
<td>Model</td>
<td>5.68</td>
</tr>
<tr>
<td></td>
<td>%Error</td>
<td>5.49</td>
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<tr>
<td>Run-2</td>
<td>Experiment [9]</td>
<td>81.18</td>
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<tr>
<td></td>
<td>Model</td>
<td>6.04</td>
</tr>
<tr>
<td></td>
<td>%Error</td>
<td>3.04</td>
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<tr>
<td>Run-3</td>
<td>Experiment [9]</td>
<td>82.20</td>
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<tr>
<td></td>
<td>Model</td>
<td>5.77</td>
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<tr>
<td></td>
<td>%Error</td>
<td>7.10</td>
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Table 5: Properties of Jharia coal [12]

<table>
<thead>
<tr>
<th>Properties of Jharia coal</th>
<th>Proximate Analysis</th>
<th>Ultimate Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>MFC</td>
<td>6.94</td>
<td>49.3</td>
</tr>
<tr>
<td>VM</td>
<td>36.4</td>
<td>1.11</td>
</tr>
<tr>
<td>VM</td>
<td>28.5</td>
<td>0.08</td>
</tr>
<tr>
<td>ASH</td>
<td>28.2</td>
<td>0.31</td>
</tr>
<tr>
<td>C</td>
<td>4.81</td>
<td>9.25</td>
</tr>
<tr>
<td>H</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>9.25</td>
<td></td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Gasification temperature is the most influencing parameter followed by SCR and ER. Gasification pressure has a less significant effect. For each SCR there exists a limiting air flow rate (LAFR) which warrants maximum carbon conversion and minimum emissions. This air flow rate is estimated by a design specification. The effect of each parameter and their interdependency is presented below;

Effect of Equivalence Ratio

Figure 4(a) to 4(d) show the variation of individual gas components with respect to equivalence ratio. The graphs are plotted at four different steam flow rates (2, 6, 10, and 14 kg/s) at a temperature of 700 °C. Figure 4(a) depicts the H2 flow rate with equivalence ratio at all SCRs. It indicates that as the equivalence ratio increases the H2 is decreasing. This is due to increase in quantity of O2 which converts some H2 into H2O. This is evident from Figure 4(d) in which there is an increase in H2O with increase in equivalence ratio. It is also observed from Figure 4(a) that the rate of decrease in H2 formation depends on SCR. Figure 4(b) represent the variation of CO with equivalence ratio. It can be observed from the figure that as equivalence ratio increases CO is decreasing. This is due to the fact as equivalence ratio increases, O2 increases. The excess O2 tend to react with CO and convert into CO2. This can be seen from Figure 4(c) in which the CO2 increase with increase in equivalence ratio. It is evident from the results that an ER of less than 0.4 is favorable for higher H2 and CO formation irrespective of SCR.

Effect of Steam-Coal-Ratio

Figures 5(a) to 5(d) shows the effect of SCR on syngas components. The curves are plotted with equivalence ratio of 0.3 at four different temperatures ranging from 600 °C to 900 °C. From Figure 5(a) it is observed that as SCR increases H2 increases at all temperatures. Up to a certain SCR H2 yield will increase due to decomposition of steam into hydrogen and oxygen. After that the rate of H2 formation becomes slower. Figure 5(b) represent the variation of CO with SCR at different temperatures. It is observed that as SCR increases, the CO is decreasing. This is due to fact that as SCR increases O2 increases. This oxygen will react with CO forming CO2. This is evident from the Figure 5(c). A similar trend is show in H2O formation which shown in Figure 5(d). From the results it is seen that the favorable range of SCR is 0.2 to 0.6.

Figure 4(b): Equivalence Ratio Vs CO formation

Figure 4(c): Equivalence Ratio Vs CO2 formation
Effect of Gasifier Pressure

Effect of gasifier pressure on syngas components is shown in Figure 6(a). The curves are plotted at an equivalence ratio of 0.2, SCR of 0.2 and a temperature of 600 °C. The results show that H₂ and CO decreases with increase in pressure whereas CO₂, H₂O and CH₄ increases. The N₂ remains constant as it is only limited by the quantity present in the coal. Even though CH₄ is increasing with increase in gasifier pressure, H₂ and CO are decreasing. This results in decreasing of the HHV of syngas. Figure 6(b) shows the variation of HHV with increase in gasifier pressure. Thus a lower pressure is suitable for higher HHV.

Effect of Gasifier temperature

Most significant parameter is gasification temperature because all reactions are temperature dependent. Figure 7(a) to Figure 7(f) are plotted at different SCR values ranging from 0.2 to 1.4.
Equivalence ratio is maintained in such a way that the temperature remains in a specified value. Figure 7(a) shows the variation of H$_2$ with temperature. It indicates a sharp increase in quantity of H$_2$ initially followed by slow and gradual decrease beyond a certain temperature. Figure 7(b) represents the variation of CO with temperature. It indicates that after a threshold temperature, CO increases steeply and reaches its maximum value. After that it remains almost stable. As the SCR increases the amount of CO decreases indicating that H$_2$ and H$_2$O formation is predominant than CO. The favorable temperature range for maximum amount of H$_2$ and CO is 600 to 900 °C.
Figure 7(d): Temperature Vs H₂O formation

Figure. 7(e) depicts the char formation with temperature. Presence of char in syngas indicates incomplete carbon conversion. For maximum efficiency the char must be minimum / zero. It is clearly seen that a char formation occurs till a particular temperature and becomes zero after that. This temperature is threshold temperature of zero char formation and depends on SCR. Threshold temperature increases with decrease in SCR. However beyond 900 °C, char formation is zero irrespective of SCR.

Figure 7(f) shows the variation of gasifier efficiency with temperature. Syngas HHV and gasifier efficiency are given in Eq. (5) and (6). The heat required for generating steam is supplied from gasifier only. Hence the total heat output of the system is the sum of syngas HHV and Q Heater. The system efficiency is minimum at low temperature and raises steeply till a particular temperature and then starts decreasing gradually. It is also observed that as the SCR increases the maximum efficiency decreases which indicates that a lower SCR is favorable for higher efficiency.

\[
HHV = (H_2 \times 30.52 + CO \times 30.18 + CH_4 \times 95) \times 4.1868 \text{ MJ} / (Nm^3)
\]

(5)

\[
\text{Gasifier Efficiency} = \frac{HHV_{product\ gas} + Q_{Heater}}{GCV_{fuel} \times \text{mfuel}} \times 100
\]

(6)

Table 6: Optimum values for operating variables

<table>
<thead>
<tr>
<th>Manipulated Variable</th>
<th>Range</th>
<th>Optimum Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without</td>
<td>With</td>
</tr>
<tr>
<td></td>
<td>Constraint</td>
<td>Constraint (CO₂ Mol Frac. &lt; 1%)</td>
</tr>
<tr>
<td>ER</td>
<td>0.1 - 0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>SCR</td>
<td>0 – 2</td>
<td>0.438</td>
</tr>
<tr>
<td>Gasifier Temp. (°C)</td>
<td>500 – 1500</td>
<td>918.006</td>
</tr>
<tr>
<td>Gasifier Pres. (atm)</td>
<td>1 – 30</td>
<td>1</td>
</tr>
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</table>

Table 7: Optimization results

<table>
<thead>
<tr>
<th>Objective</th>
<th>Optimum Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Constraint</td>
</tr>
<tr>
<td>HHV (MJ/Nm³)</td>
<td>6.1075</td>
</tr>
<tr>
<td>CO₂ (Mole Frac.)</td>
<td>3.3167 x 10⁻²</td>
</tr>
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Table 8: Optimum parametric domains for different objectives

<table>
<thead>
<tr>
<th></th>
<th>H₂ (↑)</th>
<th>CO (↑)</th>
<th>CO₂ (↓)</th>
<th>Gasfr. Eff. (↑)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ER</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>SCR</td>
<td>0.8 – 1.2</td>
<td>0.2 – 0.4</td>
<td>0.2 – 0.8</td>
<td>0.4 – 0.6</td>
</tr>
<tr>
<td>TEMP (°C)</td>
<td>600 – 800</td>
<td>600 – 800</td>
<td>800 – 1200</td>
<td>600 – 900</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Gasification studies of Jharia coal were conducted using ASPEN Plus model. The effects of operating conditions ER, SCR, Gasifier temperature, Gasifier pressure are studied. The conclusions of the study are as follows:

ER, SCR, gasifier temperature are more significant than gasifier pressure. Synergic composition depends on the gasification atmosphere and effect of parameters are interdependent. To assess this synergistic effect LAFR is used. For each SCR and gasifier temperature there exists a LAFR.

H₂ formation is enhanced by increase in SCR whereas it is reduced by increase in ER and gasifier pressure. A lower ER and pressure are favorable for H₂ formation. From the results it can be concluded that an ER below 0.4 is suitable for maximum H₂ formation. Even though higher SCR promotes higher H₂ formation, beyond an SCR of 1.2 no significant increase H₂ quantity is observed. CO decreases with increase in ER and SCR whereas it is increased by increase in gasifier temperature. A lower ER and higher temperature is favorable for CO formation. Maximum amount of CO is formed in the temperature window of 600 to 900 °C.

The variation of CO₂ and H₂O is similar. As ER and SCR increases both CO₂ and H₂O increases. CO₂ increases with temperature till a maximum value and then starts decreasing. Whereas H₂O decreases with increase in temperature, reaches it minimum value and then starts increasing. CO₂ peak and H₂O trench occurs in the same temperature window. For maximum efficiency, a lower ER, SCR and higher temperature are favorable.

At lower temperatures carbon conversion is incomplete. A threshold temperature is to be maintained for char free gas which ranges between 600 and 900 °C depending on SCR. The HHV and hence the efficiency depends on the amount of H₂ and CO produced. The results indicate that the efficiency increases with temperature, reaches a maximum value then decreases gradually. Maximum efficiency occurs in the temperature range of 600 to 900 °C.

Optimization studies were conducted to obtain ideal combination of operating conditions with objective of maximizing HHV and minimizing CO₂ emissions. It is observed that the optimum value of equivalence ratio is 0.1 in both cases of with and without constraint on CO₂ emissions. The optimum value of steam-to-coal ratio is 0.417 and 0.438 with and without constraints respectively. The optimum value of temperatures are 1085.23 °C and 918.006 °C with and without constraint respectively.

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