Prediction of Gas Composition of a Fluidized Bed Gasifier in a Sugarcane Bagasse- Modeling

P Manikandan\textsuperscript{1} and V Christus Jeya Singh\textsuperscript{2}

\textsuperscript{1} Department of Mechanical Engineering, Vins Christian College of Engineering, Nagercoil, Tamilnadu, 629180, India
\textsuperscript{2} Department of Mechanical Engineering, St. Xavier’s Catholic College of Engineering, Nagercoil, Tamilnadu, 629003, India

*Corresponding e-mail: manips53@gmail.com

Abstract. The assessment of the performance of various biomass fuel sources in gasifier is a significant zone of study for the execution of this innovation in different applications, pertinent to remote villages. This paper reveals the prediction of the composition of producer gas in a fluidized bed gasifier using Sugarcane Bagasse as feedstock where air to be used as gasifying agent. The model dependent on equilibrium constant and material balance has been created to assess the syngas compositions. The developed model has been used to predict the composition of constituent gases by varying equivalence ratio (ER) between 0.1 and 0.35 and keeping the moisture content (MC) constant. The outcomes show that the mole portion of CO from sugarcane bagasse is higher as compared to rice husk and coir pith and the composition of H\textsubscript{2} and CH\textsubscript{4} where absorbed very close to rice husk. Hence it recommended that the sugarcane bagasse and coir pith shall replace the rice husk and coir pith in fluidized bed gasifier for rural applications.

1. Introduction

India produces more than 40 million metric tons (MMT) of sugarcane bagasse waste and this raw material are used less percentage in the paper industry. Through this the sugarcane bagasse can also be used to produce electricity at low cost, and the utilization of the biomass resources as fuel shall reduce greenhouse emissions. Therefore, biomass could play a vital role for generation of clean energy by replacing fossil fuels [1].

Many of the large scale industries produce more air pollution, which deteriorates the environment, human health and causes damage of property and landscape. The air pollution is mainly generated by the burning of fossil fuels for different applications. The fossil fuel also causes climate change and global warming and hence we have to find out new and cleaner strategies and fuel especially from sustainable power sources [2]. The share of the fossil fuels among the world total energy demand is reported as 80\% contribute where biomass resources only 10-15\% [3]. India has a huge opportunity for energy breeding from the accessible 500 metric tons of biomass per year. The agricultural areas of India depend on accepted biomasses much as firewood, animal couch, agricultural and other related applications. It is likewise seen that the biomass imperative control may add to 33\% of complete energy usage in India [4&5].

One of the thermochemical process measure the biomass gasification is to change over biomass into sustainable energizes. Moreover the gasification process to deliver energy for warmth and force, syngas and condensed energizes, for example, diesel and gas, elective powers [6]. The idea of united turn and power creation from biomass is principally valuable to trim developing based process industries and rural power generation in emerging countries [7&8].

Biomass gasification is one of the widely using methods for producing syngas from the biomass in this process pollution is lesser than the burning of biomass fuel. There are different kinds of biomass gasifiers are utilized in power creation applications. The gasification process is relatively difficult and presently lots of researchers have been motivated on modeling of gasifier based on the gasification reactions the design, simulation and optimization of performance of gasifier [7].

The fluidized bed gasification were also analyzed technology is preferred because of its different preferences which incorporate the variety of fuel used, great heat transfer rate, even and well-regulated temperature of bed, encouraging gas–solid mixing, etc [9].
The dynamic displaying of a bubbling fluidized bed biomass gasifier was studied and this model has been validated to measurements from transient tests in a small-scale fluidized bed biomass gasifier. The results were compared to experimental results of a pilot-scale (FBG) and previous literature models. The transient response model is studied different working conditions, for example, biomass feed rate, equivalence ratio (ER), ambient temperature, and primary char amount in the bed [10].

An empirical and non-equilibrium model was developed in a fluidized bed biomass gasifier and the model predict the performance of gasifier and are to be compared n a 80kWh bubbling fluidized bed air biomass gasifier experimental results. A chemical balance model created by Pio (2020) overestimated the concentrations of H$_2$ and CO and underestimated CH$_4$. However, the efficiency was estimated accurately [11].

The synthetic balance model (CEM) and limited substance harmony technique (RCEM) for bubbling fluidized bed gasifier (BFBG) were developed for almond shell gasification using Aspen Plus and the estimated values were compared to the experimental results. In this modeling the increased cold gas efficiency has the higher gasification temperature of the process and to improve in production of H$_2$ with the increase in steam to biomass (S/B) ratio and increase in biomass moisture content of the biomass [12].

NASA has developed a simulation model with non-stoichiometric balance dependent on minimization of Gibbs free energy procedure. The model results showed that in a specific equivalence proportion as the gasification temperature increments, the mole fraction CO raises and a reverse trend was absorbed for CO$_2$. In a coal and biomass mixture, the percentage of coal increases at a specific equivalence ratio the mole portion of CO increments, with the expansion in gasification temperature and a reverse trend is reported in experimental work for CO$_2$. In a fuel mixture the increase in coal percentage at a specific equivalence ratio reduces the mole concentration of H$_2$ for all gasification temperature [13].

The gasifying agent was picked either air or steam based on the application. The gas composition and calorific values were predicted using a thermodynamic equilibrium model, depend upon the impact of gasification temperature, Oxygen to biomass proportion, and Steam to biomass proportion. The developed model was solved by commercial MATLAB software using ‘Fsolve’ function. The study carried out in the state of Punjab in India, using four agricultural biomasses [14].

The gas composition and the higher and lower heating estimations of the syngas created dependent on balance based model was created in Aspen Plus software. The equilibrium model estimated the syngas species, the char and tar yield and the elemental energy balances based on the water-gas shift reaction (WGS) and methanation reaction of gasification process. The equilibrium model was used to examine two biomasses with various moisture content and various gasification conditions and the predicted values were compared with experimental data [15].

A mathematical stoichiometric thermodynamic equilibrium model developed was used to estimate the exhibition of biomass gasification measure about the syngas yield and composition. The thermodynamic balance models are exact and helpful instruments for the assessment and comparison of gasification process. The performance of gasification process was estimated and it was approved for steam gasification and air-steam gasification [16].

2. Modeling

The overall chemical formula of sugarcane bagasse based on one mole of carbon is written as CH$_{1.55}$O$_{0.77}$N$_{0.001}$. The prediction of the physical characteristics char gasification carried out based on Equilibrium modeling [17].

The proximate and ultimate analysis used to determine the composition of individual elements of the biomass materials considered in this study shown in Table 1.

Table 1. Proximate and Ultimate analysis of the selected Biomass Materials
It is accepted that all gasification responses follow the thermodynamic equilibrium conditions, and the major components of the producer gas are H₂, CO, CO₂, H₂O, CH₄, N₂, and char content. This modeling assumed that the ash to be inert in the gasification reactions. The overall gasification reaction with air can be composed as:

\[
\text{CH}_m\text{O}_n\text{N}_o + m_w \text{H}_2\text{O} + m_O \text{O}_2 + 3.76 m_a \text{N}_2 = x_1 \text{H}_2 + x_2 \text{CO} + x_3 \text{CO}_2 + x_4 \text{H}_2\text{O} + x_5 \text{CH}_4 + x_6 \text{N}_2
\]  

(1)

Where \(m, n, \text{ and } o\) are the mole number of Hydrogen, Oxygen and Nitrogen present in the biomass per one mole of biomass carbon, \(m_w\) is the moisture content present in the biomass and \(m_a\) is the mole of air supplied. In the above general equation, the moles of six unknown species of syngas are represented as \(x_1, x_2, x_3, x_4, x_5, \text{ and } x_6\). An equilibrium condition the mole numbers of reactants are equal to the mole numbers of the products. In order to estimate the six species concentrations, six equations are developed. The elemental balancing of Carbon, Hydrogen, Oxygen and Nitrogen in the general equation obtained the four linear equation and other two nonlinear equations are attained from the equilibrium constants [18].

From eqn. (1), the mole balancing for C, H, O and N are:

- **Carbon balance**
  
  \[1 = x_2 + x_3 + x_5\]  
  (2)

- **Hydrogen balance**
  
  \[m + 2m_w = 2x_1 + 2x_3 + 4x_5\]  
  (3)

- **Oxygen balance**
  
  \[n + m_w + 2m_a = x_2 + 2x_3 + x_4\]  
  (4)

- **Nitrogen balance**
  
  \[o + 7.52m_a = 2x_6\]  
  (5)

In this model all chemical reactions are assumed to be in equilibrium condition, and the following reactions are playing vital role in the gasification process.

- **Boudouard reaction:**
  
  \[\text{C} + \text{CO}_2 = 2\text{CO} \quad (+ 172.6 \text{ kJ / mol})\]  
  (6)

- **Steam gasification:**
  
  \[\text{C} + \text{H}_2\text{O} = \text{CO} + \text{H}_2 \quad (+ 131.4 \text{ kJ / mol})\]  
  (7)

- **Water gas shift reaction:**
  
  \[\text{CO} + \text{H}_2\text{O} = \text{CO}_2 + \text{H}_2 \quad (- 41.2 \text{ kJ / mol})\]  
  (8)

- **Methanation reaction:**
  
  \[\text{C} + 2\text{H}_2 = \text{CH}_4 \quad (- 74.9 \text{ kJ / mol})\]  
  (9)

It is assumed that all these chemical reactions are obey the perfect gas characteristics and the gasification is held at atmospheric condition. The following equations have no temperature component.

The water–gas shift reaction of equilibrium constant is given by

\[
K_1 = \frac{P_{\text{CO}_2}P_{\text{H}_2}}{P_{\text{CO}}P_{\text{H}_2}^2} = \frac{x_2x_3}{x_1x_4}
\]  

(10)

The methane formation of equilibrium constant is given by
The values of above constants $K_1$ and $K_2$ are also calculated by the Gibbs free energy

$$K_1 = \exp\left(-\frac{G^0_{T,H_2} + G^0_{T,CO_2} - G^0_{T,CO} - G^0_{T,H_2,O}}{R_a T}\right)$$

$$K_2 = \exp\left(-\frac{G^0_{T,CH_4} - 2G^0_{T,H_2}}{R_a T}\right)$$

Where, $R_a$ is the general gas constant and $G^0_T$ is the standard Gibbs function at gasification temperature, $T$ (K) of the gas species.

To evaluate the gas concentrations of the six unknowns, initially calculate the values of $K_1$ and $K_2$ at the particular temperature, and the values of $K_1$ and $K_2$ values are substituted in eqn. (10) and (11). A program was developed in SCILAB an open source software using the tool “Fsolve” to solve the six equations (2), (3), (4), (5) (10), and (11).

3. Results and discussion

The equilibrium model is used to predict the production of producer gas in a fluidized bed gasifier from the sugarcane bagasse. The impact of equivalence ratio on the gasification at temperature of 850°C and density of biomass is 194 kg/m$^3$ has been the choice of equivalence ratio was kept between 0.1 and 0.35 for this study based on the previous literature. The variation of the syngas concentrations of $H_2$, $CO$, $CO_2$, $CH_4$ and $N_2$ on dry basics are studied and reported shown in Figs. 1-5. It is seen that expansion in ER reduces the concentration of $H_2$, $CO$ and $CH_4$ percentage drops while $CO_2$ and $N_2$ increased.

![Figure 1. Variation of species concentration of $H_2$ with equivalence ratio](image)

A common trend of decrease in the concentration of $H_2$ in producer gas for increase of equivalence ratio has been observed for all the biomasses (fig.1). The $H_2$ yield is maximum of around 12% when ER kept at 0.1 for all biomasses. This due to that the increase in ER beyond the value of 0.1, reduces the rate of reactions of steam gasification and water gas shift reactions.
The analysis shows that the increase in equivalence ratio reduces the concentration of CO in product gas (Figure 2). All the three biomass materials, Sugarcane Bagasse, Rice Husk and Coir Pith have been reported with the same trend, when the ER was varied between 0.1 and 0.35. The CO yield at an equivalence ratio of 0.1 is observed with the maximum value of 29% for sugarcane bagasse as compared to the other two biomasses. This is due to the fixed carbon species in sugarcane bagasse is more than rice husk and coir pith.

In Figure 3, In this prediction the equivalence ratio is increased the CO\textsubscript{2} yield is increased in Sugarcane Bagasse, Rice Husk and Coir Pith Estimated CO\textsubscript{2} yield is decreased. The CO\textsubscript{2} yield is 16.5% when ER is 0.35 in this prediction for Sugarcane Bagasse is maximum yield of CO\textsubscript{2}. The variation of the species concentration of CO\textsubscript{2} with equivalence ratio for three biomasses is shown in Fig.3. An increasing trend for sugarcane bagasse and coir pith and a reducing trend were observed for rice husk when the equivalence ratio was varied 0.1 to 0.35. The fixed carbon content in sugarcane bagasse also promotes the production of CO\textsubscript{2} when the equivalence ratio is increased. However the CO\textsubscript{2} yield is obtained close to 15% at equivalence ratio is 0.1.
The variation of concentration of CH$_4$ obtained for different equivalence ratios, for Sugarcane bagasse, Rice husk and Coir pith are presented in Figure 4. When the equivalence ratio is increased, the CH$_4$ yield is decreased, and the CH$_4$ yield for sugarcane bagasse is 11.5% when ER is kept at 0.1. It is observed from the study that the increase in equivalence ratio affects the methanation reaction.

The inert gas Nitrogen yield is increased when increasing the equivalence ratio for all the three biomass materials and this has been shown in Figure 5. This is due to the content of N$_2$ in air supplied is increased when the equivalence ratio is increased. However, the concentration of N$_2$ was reported as minimum for Sugarcane bagasse, Rice husk and Coir pith.

### 4. Conclusion
In this study the prediction of gas composition sugarcane bagasse, coir pith and rice husk using equilibrium model in a fluidized bed gasifier from has been analyzed. The gas compositions of the producer gas have been studied by keeping the various equivalence between 0.1 and 0.35. The study showed that the maximum production of H$_2$, CO and CH$_4$ where obtained at the minimum equivalence ratio of 0.1. On the other hand the composition of CO$_2$ and N$_2$ were increased with
increase in equivalence ratio. The maximum combustible gas was obtained at various equivalence ratios for sugarcane bagasse as compared to rice husk and coir pith. Hence it is suggested that the sugarcane bagasse can replace the other two biomasses where it is available abundantly.

References

[1] Kalpana Bisht 2016 Bagasse Power an Untapped Potential in India -A Review International Journal of Engineering Sciences & Research Technology 2277-9655.
[2] Chanchal Loha 2011 Performance of fluidized bed steam gasification of biomass – Modeling and experiment Energy Conversion and Management 52 1583-1588.
[3] Faaïj A 2006 Modern biomass conversion technologies Mitigation and Adaptation Strategies for Global Change 11 343-375.
[4] Sreejith C C 2013 Performance prediction of steam gasification of wood using an ASPEN PLUS thermodynamic equilibrium model International Journal of Sustainable Energy 33 416-434.
[5] Kumar A 2009 Thermochemical biomass gasification: A Review of the Current Status of the Technology Energy 2 556-81.
[6] Report of Pacific Northwest National Laboratory (PNNL) & National Renewable Energy Laboratory (NREL) 2004.
[7] Son Yi 2006 A Study on measurement of the light tar content in the fuel gas produced from small-scale gasification and power generation systems Proceedings of the 15th Annual Meeting of the Japan Institute of Energy Japan August 3rd 4th.
[8] Thomas B R 1998, Hand Book of Biomass Downdraft Gasifier Engine System Golden Colorado The Biomass Energy Foundation Press.
[9] Cui H 2007 Fluidization of biomass particles: a review of experimental multiphase flow aspects Chem Eng Sci 62 1 45–55.
[10] Suarez-Almeida M 2020 Modeling the transient response of a fluidized-bed biomass gasifier, Fuel 270 – 117226
[11] Pio D T 2020 Empirical and chemical equilibrium modelling for prediction of biomass gasification products in bubbling fluidized beds Energy 202 – 117654
[12] Mahmut Caner Acar 2019 Simulation of biomass gasification in a BFBG using chemical equilibrium model and restricted chemical equilibrium method Biomass and Bioenergy 125 131–138
[13] Samar Das 2018 Thermodynamic optimization of coal-biomass co-gasification process by using non-stoichiometric equilibrium modeling Materials Today Proceedings 5 23089–23098
[14] Vinícius Shirke 2018 Equilibrium Model for Biomass Gasification: Study of effect of Biomass properties and Operating parameters Materials Today Proceedings 5 22983–22992
[15] Gagliano A 2017 Development of an equilibrium-based model of gasification of biomass by Aspen Plus Energy Procedia 111 1010 – 1019
[16] Joel George 2016 Stoichiometric Equilibrium Model based Assessment of Hydrogen Generation through Biomass Gasification Procedia Technology 25 982 – 989
[17] Venkata Ramanan M 2008 Performance Prediction and Validation of Equilibrium Modeling for Gasification of Cashew Nut Shell Char Brazilian Journal of Chemical Engineering 585 – 601
[18] Chanchal Loha 2011 Thermodynamic analysis of hydrogen rich synthetic gas generation from fluidized bed gasification of rice husk Energy 36 4063-4071