



## Modeling and Simulation of Downdraft Biomass Gasifier

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### Abstract

Gasification is one of the efficient ways to convert the energy embedded in biomass. In the present study, equilibrium modeling is used to predict the performance of a downdraft gasifier. The composition of the producer gas and, hence, the calorific values are determined. The effects of the oxygen factor and the moisture content of wood on gas composition, reaction temperature and calorific values are investigated. The calorific values of the producer gas decreases as the oxygen factor increases and also as the moisture content increases.

**Keywords:** Biomass; Gasification; Equilibrium Modeling; Downdraft Gasifier; Simulation; Renewable Energy

### 1. Introduction

Bio-energy is now accepted as having the potential to provide the major part of the projected renewable energy provisions of the future. Wood and other forms of biomass including energy crops and agricultural and forestry wastes are some of the main renewable energy resources available. Biomass fuels and residues can be converted to energy via thermal, biological and physical processes. In the thermo-chemical conversion technologies, biomass gasification has attracted the highest interest as it offers higher efficiencies compared to combustion and pyrolysis [1]. Gasification is the conversion of solid carbonaceous fuel into combustible gas by partial combustion. The mixture of combustible gases thus produced is called producer gas [2]. In view of the considerable interest in the gasification process worldwide, it is necessary to model and predict the performance of the gasifier *in priori*. Babu and Chaurasia in their studies [3,4,5,6,7,8] reported extensive results on pyrolysis, which is one of the part of biomass gasifier. Modeling of biomass gasification implies the representation of chemical and physical phenomena constituting pyrolysis, combustion, reduction, and drying in the

mathematical form. In other words, whole process is to be represented as a system of equations which taken together can provide valuable quantitative information about the process.

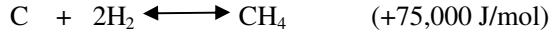
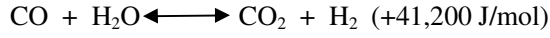
The residence time for the biomass in a gasifier is long enough. It will allow pyrolysis products burn and subsequently to achieve an equilibrium state in the reduction zone before leaving the gasifier [9,10]. An equilibrium model has been developed and the variation with moisture content for fixed temperature was found out. An equilibrium model based on minimization of Gibbs free energy for wood waste (saw dust), has been simulated by Altafini et al. [11]. The effect of one of the most important parameter such as  $O_2$  factor has not been reported in the literature.

Hence the present study focuses on developing equilibrium model and studying the effects of oxygen factor on composition, reaction temperature and calorific values of the gases. For fixed oxygen factor the effects of moisture content on the reaction temperature is also studied.

### 2. Model

The equilibrium model assumes that all the reactions are in thermodynamic equilibrium. It is

expected that the pyrolysis product burns and achieves equilibrium in the reduction zone before leaving gasifier; hence an equilibrium model can be used in the downdraft gasifier [9]. The reactions are as follows:



The equilibrium constant for methane generation ( $K_1$ ) is

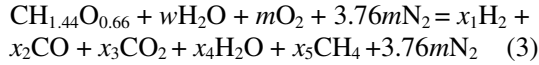
$$K_1 = \frac{P_{\text{CH}_4}}{(P_{\text{H}_2})^2} \quad (1)$$

And equilibrium constant for shift reaction ( $K_2$ ) is

$$K_2 = \frac{P_{\text{CO}_2} P_{\text{H}_2}}{P_{\text{CO}} P_{\text{H}_2\text{O}}} \quad (2)$$

The typical chemical formula of woody material, based on a single atom of carbon, is  $\text{CH}_{1.44}\text{O}_{0.66}$

The global gasification reaction can be written as follows:



Where  $w$  is the amount of water per kmole of wood,  $m$ , the amount of oxygen per kmole of wood,  $x_1$  to  $x_5$ , the coefficients of constituents of the products. For the known moisture content, the value of  $w$  becomes a constant &  $m$  can be found out from the airflow rate per kmol of wood. From the global reactions, there are six unknowns  $x_1$  to  $x_5$ , and  $T$ , representing the five unknown species of the product and the temperature of the reaction. Therefore six equations are required, which can be obtained from the following balances.

Carbon Balance:

$$1 = x_2 + x_3 + x_5 \quad (4)$$

Hydrogen Balance:

$$2w + 1.44 = 2x_1 + 2x_4 + 4x_5 \quad (5)$$

Oxygen Balance:

$$w + 0.66 + 2m = x_2 + 2x_3 + x_4 \quad (6)$$

The heat balance for gasification process (assumed to be adiabatic) is:

$$\left[ \begin{aligned} &H_{f\text{wood}}^0 + w(H_{f\text{H}_2\text{O}(l)}^0 + H_{(\text{vap})}) + mH_{f\text{O}_2}^0 \\ &+ 3.76mH_{f\text{N}_2}^0 \end{aligned} \right] = \left[ \begin{aligned} &x_1H_{f\text{H}_2}^0 + x_2H_{f\text{CO}}^0 + x_3H_{f\text{CO}_2}^0 \\ &+ x_4H_{f\text{H}_2\text{O}(\text{vap})}^0 + x_5H_{f\text{CH}_4}^0 + \Delta T(x_1C_{p\text{H}_2} + \\ &x_2C_{p\text{CO}} + x_3C_{p\text{CO}_2} + x_4C_{p\text{H}_2\text{O}(\text{vap})} + x_5C_{p\text{CH}_4} \\ &+ 3.76mC_{p\text{N}_2}) \end{aligned} \right] \quad (7)$$

Where  $\Delta T = T_2 - T_1$ ,

$T_1$ , the temperature of the inlet,

$T_2$ , the temperature of the reduction zone

From Eq. (4)

$$x_5 = 1 - x_2 - x_3 \quad (8)$$

From Eq. (5)

$$x_4 = w + 0.72 - x_1 - 2x_5 \quad (9)$$

Substituting the value of  $x_5$  from the Eq. (4) into Eq. (5)

$$x_4 = -x_1 + 2x_2 + 2x_3 + w - 1.28 \quad (10)$$

From Eq. (1)

$$x_1^2 K_1 = 1 - x_2 - x_3 \quad (11)$$

Substituting the value of  $x_4$  from the Eq. (10) into Eq. (6)

$$-x_1 + 3x_2 + 4x_3 = 2m + 1.94 \quad (12)$$

Substituting the value of  $x_4$  from the Eq. (10) into Eq. (2)

$$x_1x_3 = K_2x_2[-x_1 + 2x_2 + 2x_3 + w - 1.28] \quad (13)$$

From Eq. (7),

$$T_2 = T_1 + \frac{\left[ \begin{aligned} &H_{f\text{wood}}^0 + w(H_{f\text{H}_2\text{O}(l)}^0 + H_{(\text{vap})}) + \\ &H_{f\text{O}_2}^0 + 3.76mH_{f\text{N}_2}^0 - x_1H_{f\text{H}_2}^0 \\ &+ x_2H_{f\text{CO}}^0 + x_3H_{f\text{CO}_2}^0 + x_4H_{f\text{H}_2\text{O}(\text{vap})}^0 \\ &+ x_5H_{f\text{CH}_4}^0 \end{aligned} \right]}{\left( \begin{aligned} &x_1C_{p\text{H}_2} + x_2C_{p\text{CO}} + x_3C_{p\text{CO}_2} \\ &+ x_4C_{p\text{H}_2\text{O}(\text{vap})} + x_5C_{p\text{CH}_4} + 3.76mC_{p\text{N}_2} \end{aligned} \right)} \quad (14)$$

The general equation for  $\ln K_1$  [3] is given by

$$\ln K_1 = \left[ \begin{aligned} &\frac{7082.848}{T} + (-6.567) \ln T \\ &+ \frac{7.466 \times 10^{-3}}{2} T + \frac{-2.164 \times 10^{-6}}{6} T^2 + \\ &\frac{0.701 \times 10^{-5}}{2(T)^2} + 32.541 \end{aligned} \right] \quad (15)$$

The general equation for  $\ln K_2$  [3] can be given by

$$\ln K_2 = \left[ \begin{array}{l} \frac{5870.53}{T} + 1.86 \ln T \\ -2.7 \times 10^{-4} T - \frac{58200}{(T)^2} - 18.007 \end{array} \right] \quad (16)$$

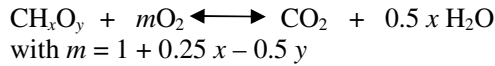
The set of equations (11) to (16) can be solved using following algorithm.

1. Specify the value of  $m$  and  $w$ .
2. Assume temperature  $T_2$ , find  $K_1$  &  $K_2$  using Eq. (15) and Eq. (16).
3. Find  $x_1$ ,  $x_2$ , &  $x_3$  using Eq. (11), Eq. (12), & Eq. (13) respectively.
4. Find  $x_4$  &  $x_5$  using Eq. (8) & Eq. (10) respectively.
5. Calculate the new value of  $T_2$  using Eq. (14).
6. Repeat the above steps until successive value of  $T_2$  become constant.

### 3. Results and Discussion

A sensitivity analysis of the model results is carried out when two parameters are varying namely: the oxygen factor ( $F$ ), and the moisture content of inlet biomass.

#### 3.1 The oxygen factor $F$



It is defined as the  $\text{O}_2$  fraction of stoichiometric  $\text{O}_2$  amount used in a neutral and theoretical combustion process. For wood the values are  $x = 1.44$  and  $y = 0.66$ , which gives  $m = 1.03$  (stoichiometric value). The gasification process is taking place when there is a lack of  $\text{O}_2$ , lets take an  $\text{O}_2$  amount equal to the  $\frac{1}{4}$  of the stoichiometric in a theoretical amount in a theoretical combustion, that is  $F = 25.75\%$  [4].

#### 3.2 The influence of the $\text{O}_2$ factor

Fig. 1 shows how the composition of the gas changes with  $F$ . Mostly all the variations of the molar fractions versus  $F$  are more or less linear. The mole fraction of  $\text{N}_2$  increases with increasing  $F$  as expected. The composition of methane produced is very low. The percentage of hydrogen in the fuel gas decreases continuously with  $F$  from about 21% to 7% for an increase of  $F$  from 30% to 70%. A similar trend is also observed for carbon monoxide. It is interesting to know that carbon dioxide and water vapour percentages are increasing as hydrogen and carbon monoxide percentage are decreasing.

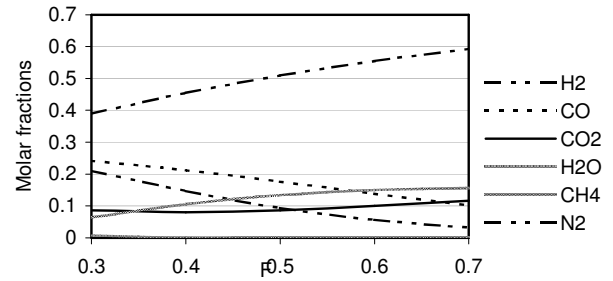


Fig. 1 Molar fractions of the gas components versus the  $\text{O}_2$  factor  $F$

Fig. 2 shows that the reaction temperature goes up from 1050 K to 1950 K when  $F$  increases from 30% up to 70%. This is due to the increased generation of  $\text{CO}_2$  with  $F$ . By increasing  $F$  combustion rate increases resulting in decreases in the amount of partially oxidized product.

Fig. 3 shows the decreasing trend of the calorific values of fuel gas.

Fig. 4 shows that the reaction temperature decreases as moisture content increases for the same amount of air supply.

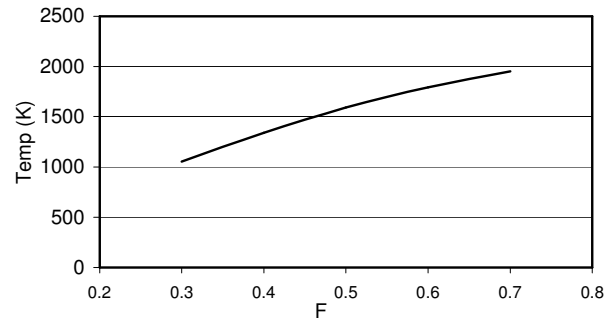


Fig. 2 Reaction Temperature versus the Oxygen Factor

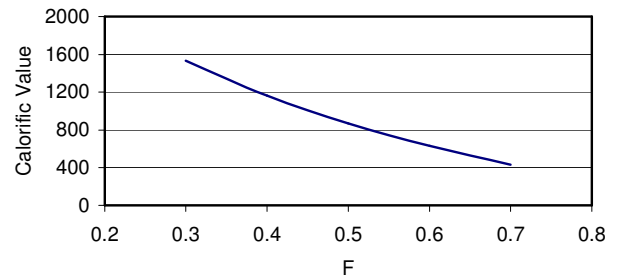


Fig. 3 Calorific Values ( $\text{kJ}/\text{m}^3$ ) versus oxygen factor

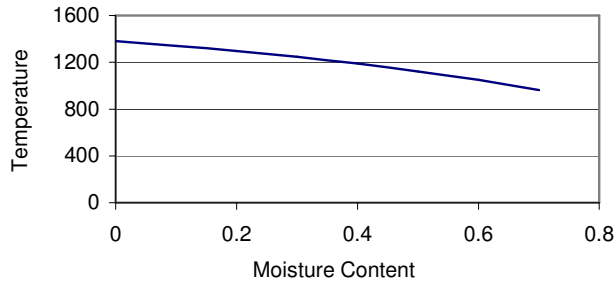


Fig. 4 Temp (K) versus Moisture content for F = 40 %

Fig. 5 shows the trend of compositions of different components of gas with moisture content for a fixed supply of oxygen content of 40%. The composition of inert nitrogen is almost constant with moisture content. The composition of methane is very less and almost constant. The percentage of hydrogen in the fuel gas increases continuously with moisture content from about 15% –25 % for an increase in moisture content from 0% to 60%. A similar trend is observed for the carbon dioxide content; however, the increase is from about 8% to 23%. It is interesting to note that the percentage of carbon monoxide reduces from about 26% to 5% for the same variation of moisture content. This is because of the increase in percentage of carbon dioxide with moisture content.

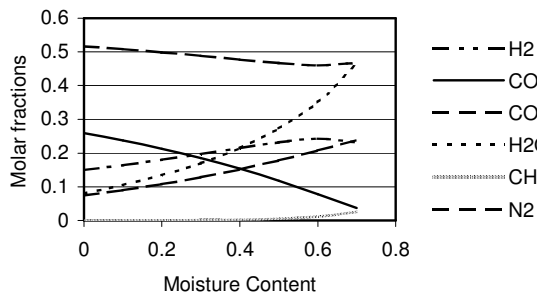


Fig. 5 Molar fraction of the gas components versus moisture content for a F = 40%

#### 4. Conclusions

The modeling of gasification process in a downdraft gasifier is performed using an equilibrium model. The calculations of the composition and the calorific value of the producer gas with wood as a raw material are illustrated. From the sensitivity analysis for the oxygen factor and moisture content, following conclusions are drawn:

1. The content of hydrogen in producer gas decreases with oxygen factor and increases with moisture content.

2. The carbon monoxide content in producer gas decreases with increasing moisture content and oxygen factor.
3. The methane content in producer gas increases with moisture content and decreases with oxygen factor.
4. The reaction temperature increases with oxygen factor and decreases with moisture content, almost in a linear fashion.
5. The calorific value decreases with increasing oxygen factor and moisture content.

These conclusions suggest that there must be an optimum oxygen factor depending upon moisture content. The results of this study are very useful in the design of a downdraft biomass gasifier.

#### Nomenclature

$C_{p,i}$	Specific heat of component i (kJ/mol)
$F$	Oxygen factor
$H_{f,i}^0$	Heat of formation of component i (kJ/mol)
$K$	Equilibrium constant
$m$	Moles of oxygen per mole of wood
$P_i$	Partial pressure of component i (kPa)
$T$	Temperature (K)
$w$	Moles of water per mole of wood

#### References

- [1]. A.V. Bridgwater, 4th International Symposium on Waste Treatment Technologies (Thermal, Non-Thermal and Clean-up), Sheffield, UK. 29 June - 2 July 2003
- [2]. G. Bhawe, Technical notes in the Proceedings of Intensive workshop on - Testing Evaluation of Biomass Gasifier Systems and Related Laboratory Investigation, (SPRERI), Vallabh Vidyanagar, (Apr, 2001).
- [3]. B.V. Babu, A.S. Chaurasia, Energy Conversion and Management, 44(2003) 2135-2158.
- [4]. B.V. Babu, A.S. Chaurasia, Energy Conversion and Management, 44(2003) 2251-2275.
- [5]. B.V. Babu, A.S. Chaurasia, Energy Conversion and Management, 45(2004) 53-72.
- [6]. B.V. Babu, A.S. Chaurasia, Energy Conversion and Management, 45(2004) 1297-1327.
- [7]. B.V. Babu, A.S. Chaurasia, Chemical Engineering Science, 59(2004) 611-622.
- [8]. B.V. Babu, A.S. Chaurasia, Chemical Engineering Science, 59(2004) 1999-2012,
- [9]. Z. A. Zainal, R. Ali, C.H. Lean, K. N. Seetharamu, Energy Conversion and Management, 42(2001) 1499-1515.
- [10]. M. Philippe, R. Dubuisson, Energy Conversion and Management, 43(2002) 1291-1299
- [11]. R. Altafini, P. Wnader, R. M. Barreto, Energy and Conversion Management, 44(2003) 459-469.