

Full Length Research Paper

Equilibrium modeling for a downdraft biomass gasifier for cotton stalks biomass in comparison with experimental data

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Equilibrium modeling has been used to predict the composition of the fuel gas produced in a downdraft gasifier for cotton stalks biomass at 800 °C with the moisture content from 0 to 30%. The calorific value of the fuel gas has been determined. The predicted values are in good agreement with the experimental data. The moisture content in the cotton stalks biomass and the variability in calorific value, have been investigated. It has been found that the calorific value of the producer gas decreases with the increase in moisture content of the cotton stalks.

Key words: Gasification, biomass, downdraft gasifier, modeling.

INTRODUCTION

Biomass is one of the most promising renewable energy sources. Biomass is in various forms and it is abundant in many areas of the world. Due to its abundance, its energy content, and the low emissions to the atmosphere, it could play a major role in meeting world energy demand (Gao et al., 2008).

Biomass gasification is one of the effective technologies for its thermo chemical conversion. The conversion is achieved by reactions between a feed gas and a feedstock. The primary goal of biomass gasification is optimal energy conversion of the solid biomass into a combustible gaseous product known as producer gas. In a gasifier, there are three main thermal conversion layers: the combustion zone, the pyrolysis zone and the reduction zone. In a downdraft fixed bed, the biomass undergoes combustion, pyrolysis and gasification, one after the other (Gao et al., 2008).

Wang and Kinoshita (1993) quoted that the char reduction reactions are slow due to the fact that they are

surface phenomena and the overall biomass gasification rate can be controlled by the char reduction zone. The reaction temperature, residence time and thus volume of the reaction zone decide the reaction rates and their direction and thus the calorific value of gas as well as the efficiency of conversion. In order to obtain the optimal energy conversion, it is important to understand the chemistry of heterogeneous and homogeneous reactions taking place in the downdraft biomass gasifier and specifically in the reduction zone.

Giltrap et al. (2003) developed a model of the reduction zone of a downdraft biomass gasifier to predict the composition of the producer gas under steady state operation.

The accuracy of the model is limited by the availability of data on the initial conditions at the top of the reduction zone. Moreover, it is assumed that the char reactivity factor (CRF), a factor representative of the char reactivity which is a key variable, is constant throughout the reduction zone.

Babu and Sheth (2006) suggested an exponentially varying char reactivity factor in order to predict better simulation of the temperature profile in the reduction reaction zone. They have also compared the role of

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constant, linearly varying, and exponentially varying char reactivity factors on the model predictions.

Melgar et al. (2007) combine the chemical equilibrium and thermodynamic equilibrium of the global reaction to predict the final composition of the producer gas.

Srivastava et al. (1996) predict the concentration profiles in the cases of pyrolysis of different biomass materials in isothermal and non-isothermal conditions.

Koufopoulos et al. (1989) presented a two step mechanism scheme for describing the kinetics of biomass pyrolysis, and Babu and Chaurasia (2003) attempted to find the optimum kinetic modeling parameters for the pyrolysis process.

Zainal et al. (2001) have studied an equilibrium gasification model based on equilibrium constants, to simulate the gasification process in a downdraft gasifier. They have confirmed that the residence time of the reactants can be considered to be high enough to reach chemical equilibrium.

In this work, the equilibrium model of Zainal et al. (2001) of the gasification process is used as a basis in order to predict the composition of the fuel gas produced and its associated calorific values. The equilibrium model is used for the gasification of cotton stalks at 800 °C with the moisture from 0 to 30%. The model predictions are compared with the experimental data reported by Kantarelis et al. (2009)

ANALYSIS

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 the gasifier.

The reactions that take place are the following:



Equations 1 and 2 can be combined to give the shift reaction



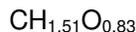
For Equation 3 (methane formation) the equilibrium constant is:

$$K_1 = \frac{P_{CH_4}}{(P_{H_2})^2} \quad (5)$$

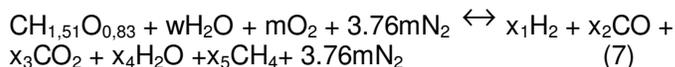
The equilibrium constant for the shift reaction is:

$$K_2 = \frac{P_{CO_2} P_{H_2}}{P_{CO} P_{H_2O}} \quad (6)$$

The chemical formula of cotton stalks biomass, based on a single atom of carbon is (Kantarelis et al., 2009):



The general equation can be written as follows:



where w is the amount of water per mol of cotton stalks; m is the amount of oxygen per mol of cotton stalks, and x_1, x_2, x_3, x_4 and x_5 are the coefficients of constituents of the products.

If MC is taken to be the content of moisture per mole of biomass, then

$$MC = \frac{\text{mass of water}}{\text{mass of dry biomass}} (100\%) \Rightarrow MC = \frac{18w}{24 + 18w} (100\%)$$

Then

$$w = \frac{26.8MC}{18(1 - MC)}$$

Since the moisture content is known, the value of w becomes a constant.

From Reaction (7), there are six unknowns, x_1, x_2, x_3, x_4, x_5 , the species of the product, and m , the oxygen content for the reaction. Therefore, six equations are required based on the following:

Carbon balance:

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

Hydrogen balance:

$$2w + 1.51 = 2x_1 + 2x_4 + 4x_5 \Rightarrow w + 0.755 = x_1 + x_4 + 2x_5 \quad (9)$$

Oxygen balance:

$$w + 0.83 + 2m = x_2 + 2x_3 + x_4 \quad (10)$$

Equilibrium constant from methane formation (Equation (5)):

$$K_1 = \frac{x_5}{x_1^2} \quad (11)$$

Equilibrium constant from shift reaction (Equation (6)):

$$K_2 = \frac{x_1 x_3}{x_2 x_4} \quad (12)$$

The gasification process is assumed to be adiabatic. The equation for the heat balance is:

$$H_{f,wood}^{\circ} + w(H_{f,H_2O(l)}^{\circ} + H_{(vap)}) + mH_{f,CO_2}^{\circ} + 3,76mH_{f,N_2}^{\circ} = X_1H_{f,H_2}^{\circ} + X_2H_{f,CO}^{\circ} + X_3H_{f,CO_2}^{\circ} + X_4H_{f,H_2O(vap)}^{\circ} + X_5H_{f,CH_4}^{\circ} + \Delta T(X_1C_{p,H_2} + X_2C_{p,CO} + X_3C_{p,CO_2} + X_4C_{p,H_2O} + X_5C_{p,CH_4} + 3.76mC_{p,N_2}) \quad (13)$$

Since the values of H_{f,H_2}° , H_{f,N_2}° and H_{f,O_2}° , are zero at ambient temperature, equation (13) reduces to:

$$H_{f,wood}^{\circ} + w(H_{f,H_2O(l)}^{\circ} + H_{(vap)}) = X_2H_{f,CO}^{\circ} + X_3H_{f,CO_2}^{\circ} + X_4H_{f,H_2O(vap)}^{\circ} + X_5H_{f,CH_4}^{\circ} + \Delta T(X_1C_{p,H_2} + X_2C_{p,CO} + X_3C_{p,CO_2} + X_4C_{p,H_2O} + X_5C_{p,CH_4} + 3.76mC_{p,N_2}) \quad (14)$$

where, $H_{f,wood}^{\circ}$, is the heat of formation of wood; $H_{f,H_2O(l)}^{\circ}$, is the heat of formation of liquid water; $H_{(vap)}$, is the heat of vaporization of water; $H_{f,H_2O(vap)}^{\circ}$, is the heat of formation of water vapor; $H_{f,CO}^{\circ}$, H_{f,CH_4}° , are heats of formation of the gaseous products;

C_{p,H_2} , $C_{p,CO}$, C_{p,CO_2} , H_{f,CH_4}° , are heats of formation of the gaseous products; C_{p,H_2} , $C_{p,CO}$, C_{p,CO_2} , C_{p,H_2O} , C_{p,CH_4} , C_{p,N_2} , are specific heats of the gaseous products; $\Delta T = T_2 - T_1$, T_2 , are the gasification temperature at the reduction zone; T_1 , is the ambient temperature at the reduction zone. Equation (13) can be simplified to be:

$$H_{f,wood}^{\circ} + w(H_{f,H_2O(l)}^{\circ} + H_{(vap)}) = X_2H_{f,CO}^{\circ} + X_3H_{f,CO_2}^{\circ} + X_4H_{f,H_2O(vap)}^{\circ} + X_5H_{f,CH_4}^{\circ} + \Delta T(X_1C_{p,H_2} + X_2C_{p,CO} + X_3C_{p,CO_2} + X_4C_{p,H_2O} + X_5C_{p,CH_4} + 3.76mC_{p,N_2}) \quad (15)$$

Where, $dH_{(for\ any\ gas)}$, is the heat formation + enthalpy change

$$dH_{(for\ any\ gas)} = H_f^{\circ} + \Delta H, \quad \Delta H = \Delta T(C_{p(g)}), \quad (16)$$

$$dH_{H_2O(l)} = H_{f,H_2O(l)}^{\circ} + H_{(vap)},$$

$$dH_{biomass} = H_{f,biomass}^{\circ}$$

Equations (8) to (12) and (15) represent six equations with six unknowns. Two of the Equations, (11) and (12), are nonlinear equations while the rest are linear equations. The aforementioned system of equations can be reduced to three sets of equations, one linear and two nonlinear equations.

Based on Equation (8), the following holds

$$X_5 = 1 - X_2 - X_3 \quad (17)$$

From Equation (9),

$$X_4 = w + 0.755 - X_1 - 2X_5 \quad (18)$$

Substitution of Equation (17) into (18) gives

$$X_4 = w + 0.755 - X_1 - 2(1 - X_2 + X_3) \Rightarrow X_4 = -X_1 + 2X_2 + 2X_3 + w - 1.245 \quad (19)$$

From Equation (10), (20)

$$M = 1/2(X_2 + 2X_3 + X_4 - w - 0.83)$$

Substitution of Equation (18) into (20) gives:

$$M = 1/2(X_2 + 2X_3 - X_1 + 2X_2 + 2X_3 + w - 1,245 - w - 0.83)$$

$$\Rightarrow m = 1/2(-X_1 + 3X_2 + 4X_3 - 2.075) \quad (21)$$

From Equation (11),

$$x_5 = x_1^2 K_1 \quad (22)$$

Substitution of Equation (17) into (22) gives:

$$1 - X_2 - X_3 = x_1^2 K_1 \Rightarrow x_1^2 K_1 + X_2 + X_3 - 1 = 0 \quad (23)$$

From Equation (12),

$$X_1 X_3 = X_2 X_4 K_2 \quad (24)$$

Substitution of Equation (18) into (24) gives:

$$X_1 X_3 - X_2(-X_1 + 2X_2 + 2X_3 + w - 1,245) K_2 = 0$$

$$\Rightarrow -K_2(X_1 X_2) + (w - 1,245) K_2(X_2) + 2K_2(X_2)^2 - (X_1 X_3) + 2K_2(X_2 X_3) = 0 \quad (25)$$

Substitution of Equations (17), (19) and (21) into (15) gives:

$$X_1 dH_{H_2} + X_2 dH_{CO} + X_3 dH_{CO_2} + (-X_1 + 2X_2 + 2X_3 + w - 1.245) dH_{H_2O(g)} + (1 - X_2 - X_3) dH_{CH_4} + 3.76 \cdot 1/2 \cdot (-X_1 + 3X_2 + 4X_3 - 2,08) dH_{N_2} - dH_{wood} - w dH_{H_2O(l)} = 0$$

$$\Rightarrow (dH_{H_2} - dH_{H_2O(g)} - 1.88 dH_{N_2}) X_1 + (dH_{CO} + 2dH_{H_2O(g)} - dH_{CH_4} + 5.64 dH_{N_2}) X_2 + (dH_{CO_2} + 2dH_{H_2O(g)} - dH_{CH_4} + 7.52 dH_{N_2}) X_3 + (dH_{H_2O(g)} - dH_{H_2O(l)}) w + dH_{CH_4} - 1.245 dH_{H_2O(g)} - 3.9104 dH_{N_2} - dH_{wood} = 0 \quad (26)$$

To simplify Equation (26), the known constants are simplified as follows:

$$A = dH_{H_2} - dH_{H_2O(g)} - 1,88 dH_{N_2},$$

$$B = dH_{CO} + 2dH_{H_2O(g)} - dH_{CH_4} + 5.64 dH_{N_2},$$

$$C = dH_{CO_2} + 2dH_{H_2O(g)} - dH_{CH_4} + 7.52 dH_{N_2},$$

$$D = dH_{H_2O(g)} - dH_{H_2O(l)}$$

$$E = dH_{CH_4} - 1.245 dH_{H_2O(g)} - 3.91 dH_{N_2} - dH_{wood}$$

Therefore, Equation (26) is simplified as follows:

$$A X_1 + B X_2 + C X_3 + D w + E = 0 \quad (27)$$

The systems of remaining equations are 3, two nonlinear Equations (23) and (25), and one linear Equation (27).

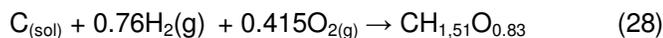
$$x_1^2 K_1 + x_2 + x_3 - 1 = 0 \quad (23)$$

$$-K_2(x_1 x_2) + (w-1.245)K_2(x_2) + 2K_2(x_2)^2 - (x_1 x_3) + 2K_2(x_2 x_3) = 0 \quad (25)$$

$$Ax_1 + Bx_2 + Cx_3 + Dw + E = 0 \quad (27)$$

The set of equations is solved using trial and error method.

The equation for calculating the heat of formation for 1 mol of solid biomass of cotton stalks ($\text{CH}_{1.51}\text{O}_{0.83}$), which contains solid carbon, hydrogen and oxygen, is:



The reaction cannot occur in reality. The formation of ($\text{CH}_{1.51}\text{O}_{0.83}$) is based on the following reactions:



Therefore, the heat of formation is $-126513.59 \text{ kJ/Mol}$. At constant pressure, the dependence of specific heat on temperature is given by the empirical equation (Perry, 1984)

$$C_{pmh} = R \left(A + BT_{am} + \frac{C}{3}(4T_{am} - T_1 T_2) + \frac{D}{T_1 T_2} \right) \quad (29)$$

Where, $T_{am} = (T_1 + T_2)/2$ is the arithmetic mean temperature; A, B, C and D are the constants for the properties of the gases concerned (Perry, 1984), and R is the universal gas constant (8.314 J/molK).

Substituting the values of A, B, C and D for the gases concerned, the specific heat of the gas can be obtained as follows:

$$C_{p\text{H}_2\text{O}} = 37.36 \text{ kJ/kmolK}$$

$$C_{p\text{H}_2} = 29.63 \text{ kJ/kmolK}$$

$$C_{p\text{CO}} = 31.16 \text{ kJ/kmolK}$$

$$C_{p\text{CO}_2} = 48.33 \text{ kJ/kmolK}$$

$$C_{p\text{N}_2} = 30.75 \text{ kJ/kmolK}$$

$$C_{p\text{CH}_4} = 56.55 \text{ kJ/kmolK}$$

Therefore, following the gasification process, the temperature of the gas increases from $T_1 = 298\text{K}$ to the gasification temperature $T_2 = 1073 \text{ K}$. The enthalpy change ΔH can be obtained using Equation (30)

$$\Delta H = C_{pmh}(T_2 - T_1) \quad (30)$$

Therefore

$$\Delta H_{\text{H}_2\text{O}} = 28954 \text{ kJ/mol}$$

$$\Delta H_{\text{H}_2} = 22963.25 \text{ kJ/mol}$$

$$\Delta H_{\text{CO}} = 24304 \text{ kJ/mol}$$

$$\Delta H_{\text{CO}_2} = 37455.75 \text{ kJ/kmol}$$

$$\Delta H_{\text{N}_2} = 23831.25 \text{ kJ/mol}$$

$$\Delta H_{\text{CH}_4} = 43826.25 \text{ kJ/mol}$$

The term $dH_{(\text{of any gas})}$ in Equation (16) can be determined from the value of the enthalpy change ΔH , of the gases. The equilibrium constant K is a function of temperature only, and is written as follows (Perry, 1984)

$$-RT \ln K = \Delta G^\circ \quad (31)$$

where: ΔG° is the standard Gibbs function of formation (Perry, 1984) and ΔH° is the heat of formation. The dependence of ΔG° to the temperature T, can be expressed as follows:

$$\frac{d(\Delta G^\circ / RT)}{dT} = \frac{-\Delta H^\circ}{RT^2} \quad (32)$$

The manipulation of Equation (31) leads to:

$$\frac{\Delta G^\circ}{RT} = -\ln K$$

$$\frac{\Delta G^\circ}{RT} = -\ln K$$

Therefore,

$$\frac{d \ln K}{dT} = \frac{\Delta H^\circ}{RT^2} \quad (33)$$

Equation (33) gives the effect of temperature on the equilibrium constant. If ΔH° is negative, that is, if the reaction is exothermic, the equilibrium constant will be reduced if the temperature increases. The equilibrium constant K, increases with temperature, for an endothermic reaction.

Solution of Equation 33 leads to:

$$\ln K = \int \frac{\Delta H^0}{RT^2} dT + I \quad (34)$$

where, I is the constant of integration.

ΔH^0 is given from the following equation (Perry, 1984)

$$\frac{\Delta H^0}{R} = \frac{J}{R} + (\Delta A)T + \frac{\Delta B}{2}T^2 + \frac{\Delta C}{3}T^3 - \frac{\Delta D}{T} \quad (35)$$

where, J is a constant and ΔA , ΔB , ΔC , ΔD are the coefficients for determining specific heat.

Substitution of Equation (35) into (34) and integrating gives:

$$\ln K = \frac{-J}{R} + (\Delta A)\ln T + \frac{\Delta B}{2}T + \frac{\Delta C}{6}T^2 + \frac{\Delta D}{2T^2} + I \quad (36)$$

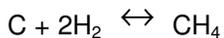
From Equation (31), $\Delta G^0 = -RT\ln K$. The multiplication of Equation (36) with the term (-RT) gives:

$$\Delta G^0 = J - RT \left(\Delta A \ln T + \frac{\Delta B}{2}T + \frac{\Delta C}{6}T^2 + \frac{\Delta D}{2T^2} + I \right) \quad (37)$$

Equations (35) to (37) will be used to find the equilibrium constant for any reaction temperature T since the specific heat is known and the constants J and K can be determined. Using Equation (35), we can determine the constant J at the temperature of 298K, where the value ΔH^0 is known. The constant I is determined from Equation (36) or (37) at the temperature at which the values of $\ln K$ or ΔG^0 are known, normally at 298K.

Two equilibrium equations are required to determine the equilibrium constants K_1 and K_2 . K_1 is the equilibrium constant for the reaction of Equation (3) and is solved as follows:

ΔA , ΔB , ΔC and ΔD can be obtained from the data of heat capacity. For the reaction from Equation (3),



$$\Delta = CH_4 - C - 2H_2$$

The equations to determine the values of ΔA , ΔB , ΔC and ΔD can be written as:

$$\Delta A = A_{CH_4} - A_C - 2A_{H_2},$$

$$\Delta B = B_{CH_4} - B_C - 2B_{H_2},$$

$$\Delta C = C_{CH_4} - C_C - 2C_{H_2}$$

$$\Delta D = D_{CH_4} - D_C - 2D_{H_2}$$

Therefore, from the data of heat capacity (Perry, 1984)

$$\Delta A = 1,702 - 1,771 - (2)(3.249) = 1,702 - 1,771 - 6.498 = -6.567$$

$$\Delta B = (9,081 - 0.771 - (2)0.422) \times 10^{-3} = 7,466 \times 10^{-3}$$

$$\Delta C = (-2,164 - (0 - 2)(0)(10^{-6})) = 2,164(10^{-6})$$

$$\Delta D = (0.867 - 0.1666)(10^5) = 0.701(10^5)$$

Calculation of the constant J and I for Equations (35) and (37) at 298K, requires the values for ΔH^0_{298} and ΔG^0_{298} . This data is available from the heat of formation data (Perry, 1984) and the Gibbs energy of formation (Perry, 1984).

$$\Delta H^0_{298} = (\Delta H^0_{298})_{CH_4} - (\Delta H^0_{298})_C - 2(\Delta H^0_{298})_{H_2}$$

$$\Delta H^0_{298} = -74520 - 0 - 2(0) = -74520 \text{ J/mol}$$

$$\Delta G^0_{298} = (\Delta G^0_{298})_{CH_4} - (\Delta G^0_{298})_C - 2(\Delta G^0_{298})_{H_2}$$

$$\Delta G^0_{298} = -50460 - 0 - 0 = -50460$$

Substituting the known values into Equation (36) for T = 298K, gives;

$$\frac{-74520}{8.314} = \frac{J}{R} + (-6.567)(298.15) + \frac{7.466 \times 10^{-3}}{2(298.15)^2} + \frac{(-2.164 \times 10^{-6})}{3} \times (298.15)^3 - \frac{0.701(10^5)}{298.15}$$

$$\begin{aligned} \delta & \quad J/R = -7083.18 \\ \delta & \quad J = -58889.6 \end{aligned}$$

Substituting the known values into Equation (37) for T = 298 K gives

$$-50460 = -58889.6 -$$

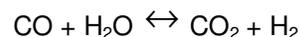
$$8.314 \times 29815 \left[(-6.567) \ln 29815 + \frac{7.466 \times 10^{-3}}{2} (29815) + \frac{(-2.164 \times 10^{-6})}{6} (29815)^2 + \frac{0.701 \times 10^5}{2(29815)^2} + I \right]$$

$$I = 32.544$$

Therefore, the general equation for $\ln K_1$ (using Equation (36)) is:

$$\ln K_1 = \frac{7082848}{T} + (-6,567) \ln T + \frac{7.466 \times 10^{-3}}{2} T + \frac{-2.164 \times 10^{-6}}{6} T^2 + \frac{0.701 \times 10^5}{2(T)^2} + 32.541 \quad (38)$$

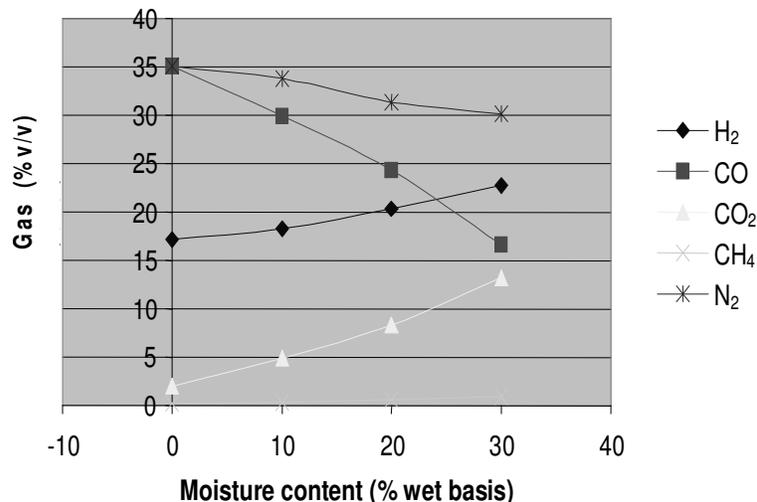
The equilibrium constant K_1 for any temperature T can be obtained by substituting the temperature T into Equation (38). A similar procedure is used to determine the equilibrium constant K_2 for the reaction of Equation (6), that is;



After going through the calculation steps, the general

Table 1. The composition of the producer gas (%v/v) against the moisture content for cotton stalks biomass gasification.

Moisture content (wet basis) (%)	H ₂ (%v/v)	CO (%v/v)	CO ₂ (%v/v)	CH ₄ (%v/v)	N ₂ (%v/v)
0	17.17	35.093	2.016	0.224	35.093
10	18.3	29.93	4.93	0.35	33.8
20	20.34	24.34	8.34	0.67	31.34
30	22.77	16.62	13.23	0.92	30.15

**Figure 1.** Effect of moisture content in the cotton stalks on gas composition at 800°C.

equation $\ln K_2$ is obtained as follows:

$$\ln K_2 = \frac{5872.45}{T} + 1.86 \ln T - 2.69 \times 10^{-4} T - \frac{58200}{T^2} - 18 \quad (39)$$

Similarly, the equilibrium constant K_2 for any temperature T can be obtained by substituting the value of temperature T into Equation (39).

The lower heating value of the produced gas was calculated by the following equation (Lv et al., 2004).

$$\text{LHV} = (30[\text{CO}] + 25.7[\text{H}_2] + 85.4 [\text{CH}_4] + 151.3[\text{C}_m\text{H}_n]) \times 4.2/1000 \text{ MJ/Nm}^3 \quad (40)$$

RESULTS AND DISCUSSION

The equilibrium model (Zainal et al., 2001) previously described is used for the gasification of cotton stalks biomass. The results which have been obtained are presented in Table 1.

The effect of moisture content in the cotton stalks on the composition of the producer gas when the bed is working at 800°C is shown in Figure 1. It can be observed from the figure that the composition of hydrogen in the

fuel gas increases continuously with the moisture content. A similar trend is also observed for the carbon dioxide. On the other hand, the percentage of carbon monoxide reduces for the same variation of moisture content. The composition of the inert nitrogen is almost constant with moisture content. The same is also observed for the composition of the methane.

The comparison between the predicted values and the experimental data can be seen in Figure 2.

The variation of calorific values for cotton stalks against moisture content is shown in Figure 3. It is observed that the calorific values decrease with increase in the moisture content, as expected.

Conclusion

In this work, it was attempted to apply an equilibrium model of gasification to the gasification process of cotton stalks. The equilibrium model was used for the gasification of cotton stalks at 800°C with the moisture from 0 to 30% in order to predict the composition of the fuel gas produced and its associated calorific values. The results obtained from the model are in close agreement with the actual measured values. The conclusions reached are the following:

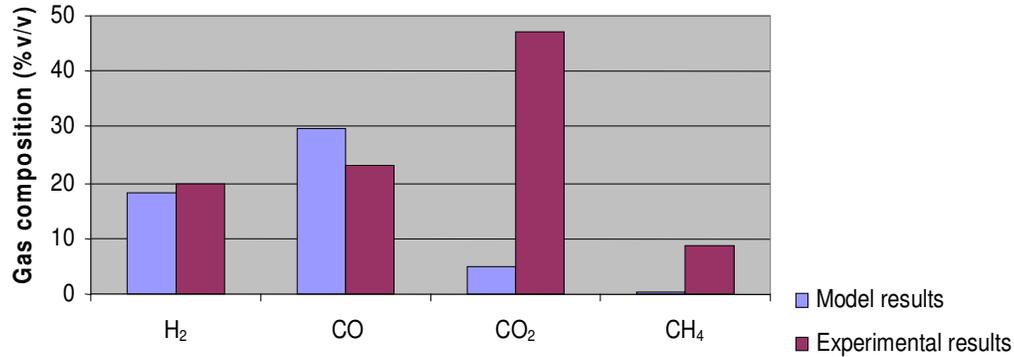


Figure 2. Comparison between model and experimental results for cotton stalks biomass and gasification temperature of 800°C.

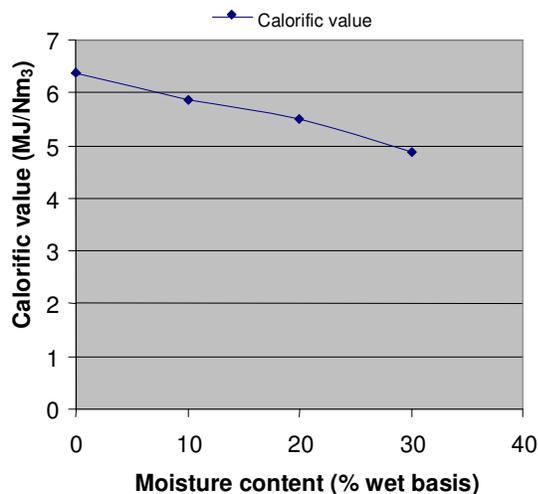


Figure 3. Calorific value against moisture content at 800°C for cotton stalks biomass.

1. The content of hydrogen in the produced gas increase with moisture content
2. The carbon monoxide content in the produced gas decreases with moisture content.
3. The methane content in the produced gas increases linearly with the moisture content
4. The calorific value of the produced gas decreases with the increase in moisture content due to the decrease of CO content and the increase of CO₂ content
5. There exists a good agreement between the model results and the experimental results for the hydrogen and carbon monoxide and not satisfying for carbon dioxide and methane.

The last point of the conclusions can be explained by taking into consideration the following: (a) The model assumes that gasification reaction rates are fast enough and residence time is sufficiently long to reach the

equilibrium state. The kinetics of gasification reactions are not simple. In the gasification process and the thermal pyrolysis process, homogeneous gas phase and heterogeneous gas-solid reactions take place, so that thousands of chemical reactions may occur. The steam and carbon dioxide reforming reactions of char are kinetically limited at temperatures lower than 1000°C. Furthermore, the product gas of fluidized bed gasifiers generally contains tar, which is not considered in equilibrium models, and furthermore, it contains many hydrocarbons (especially methane), many more than the ones predicted. (b) The gasifier is regarded as a perfectly insulated apparatus, heat losses are neglected. In practice, gasifiers have heat losses to the environment. (c) Perfect mixing and a uniform temperature are assumed for the gasifier. In practice are observed different hydrodynamics, depending on the design of the gasifier.

Nomenclature: w , amount of water per kmol of biomass; M , amount of oxygen per kmol of biomass; x_1 , coefficient of constituent of the hydrogen; x_2 , coefficient of constituent of the carbon monoxide; x_3 , coefficient of constituent of the carbon dioxide; x_4 , coefficient of constituent of the water; x_5 , coefficient of constituent of the methane; K_1 , equilibrium constant from methane formation (1/s); K_2 , equilibrium constant from shift reaction; H_{fwood}^o , the heat of formation of wood (kJ/kmol); $H_{fH_2O(l)}^o$, the heat of formation of liquid water (kJ/kmol); $H_{(vap)}$, the heat of vaporization of water; $H_{fH_2O(vap)}^o$, the heat of formation of water vapor; H_{fCO}^o , the heat of formation of the carbon monoxide; $H_{fCO_2}^o$, the heat of formation of the carbon dioxide; $H_{fCH_4}^o$, the heat of formation of the methane; C_{pH_2} , the specific heat of the hydrogen (kJ/kmol); C_{pCO} , the specific heat of the carbon monoxide (kJ/kmol); C_{pCO_2} , the specific heat of the carbon dioxide (kJ/kmol); C_{pH_2O} , the specific heat of the water (kJ/mol); C_{pCH_4} , the specific heat of the methane (kJ/mol); C_{pN_2} , the specific heat of the nitrogen; T_1 , the ambient temperature at the reduction zone (K); C_{pmh} , the

average specific heat over the temperature change; T_{am} , the arithmetic mean temperature; A,B,C,D, the constants for the properties of the gases concerned; R, universal gas constant (8.314 J/molK); ΔG° , the standard Gibbs function of formation; I, J, constants of integration; $\Delta A, \Delta B, \Delta C, \Delta D$, the coefficients for determining specific heat.

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