Modelling the Influence of Moisture Content in High Temperature Gasification (HTAG) of Biomass

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ABSTRACT

Moisture content is a biomass property that is influenced by harvesting period, processing, and storage. While gasifying at high temperature, moisture does take part in the secondary gasification reactions that produces more syngas. However, excessive moisture negatively affects the gasification process. Modeling the influence of moisture content on the gasification process is therefore important in understanding its limiting factors to the process design and performance. This paper presents the model that has been developed to investigate the influence of moisture content in high temperature gasification of biomass. The model determines the equilibrium concentration of the product gas components by the concept of minimizing total Gibbs free energy of the species taking part in the main gasification reactions. Findings of the study show that above 20% moisture content, the molar concentrations of CO, CH_4, and H_2 decrease tremendously, with comparatively higher effects on the CO. For instance, at a preheat temperature of 700ºC and gasifier temperature 800ºC and moisture content of 20, 40, and 60%, the molar concentrations of CO in the syngas was 22.4, 13.6, and 5.7% whereas the respective molar concentrations of H_2 was 23.2, 22.4, and 16.3%. A similar trend was observed in steam gasification. There were marginal effects on the concentration of CH_4. As a result of this effect, the heating value of the syngas and the cold gas efficiency of the gasification process are lowered by increasing the biomass moisture.

Keywords: Biomass Energy; Biomass Moisture Content; Gibbs Energy Equilibrium; High Temperature Gasification (HTAG)

1. INTRODUCTION

Equilibrium models are independent of design of the gasifier and can predict thermodynamic limits of gasifier performance under different conditions, which forms a useful basis for design and optimization of the process (Jarungthammachote and Dutta, 2008; Li *et al.,* 2001). Input data required for equilibrium models (Gibbs free energy, enthalpy of formation, heat capacity) is also easily available in literature. Major limitation of equilibrium models is that actual performance of gasifier (in terms of composition and quality of producer gas) may deviate from that predicted by the model, as total equilibrium conditions may not be achieved in the gasifier. But overall trends in molar composition and low heating value (LHV) of the producer gas predicted by the model for different combination of operating parameters stay essentially unchanged. Consequently, the Gibbs free energy minimization approach has been widely utilized by researchers (Pellegrini and de Oliveira Jr., 2007; Sadaka *et al*., 2002; Mahishi and Goswami, 2007) to simulate performance of biomass gasification process. The approach utilizes the concept of chemical reaction equilibrium in application of the second law of thermodynamics. From the concept of chemical reaction equilibrium, as the reacting systems approach equilibrium, all spontaneously reacting systems occur in the direction of maximum entropy while the total Gibbs free energy is minimized, and the condition for equilibrium is given by equation (1).

$$G = \sum_{i=1}^{n} \nu_i . \mu_i = 0 \qquad (1)$$

Where, G is the total Gibbs free energy, ν_i and μ_i, respectively, are the stoichiometric coefficients and chemical potentials of species *i*. If all gases are assumed to be ideal gases at one atmosphere pressure, then the problem is to find the values of ν_i that minimize the objective function under the constraint of material and energy balances.

Layout of the model for determining the influence of moisture in the high temperature gasification (HTAG) process is presented in Figure 1 where the dotted rectangle indicates area of concentration under the current study. Input to the gasifier is the biomass whose moisture is varied. The gasifier is a downdraft, which is connected to syngas treatment facilities that include cyclone, heat exchanger, and fabric filter. The treatment facilities ensure that syngas incident to the engine is of acceptable quality free from entrained particles. Fabric filters are effective (removal efficiency to 99.9%) in removing particles with an aerodynamic diameter < 1.5 μm where as cyclones can achieve efficiency up to 99% to remove particles with aerodynamic diameter > 1.5 μm (Hasler and Nussbaumer, 1999). In practice, part of the syngas will be burned to preheat the gasification air. A recuperator or regenerator is put in line with the hot flue gas for the purpose of exchanging heat with the gasification air. Widely used are the honeycomb regenerators made of ceramic materials such as Al_2O_3/SiO_2. The honeycomb regenerators have a larger heat exchange surface area per unit cross section area. At a switching time of 15 to 60 seconds their heat exchange efficiency is more than 85%, which is two-fold larger than those of conventional recuperator systems (Suzukawa *et al.*, 1997; Rafidi and Blasiak, 2005).

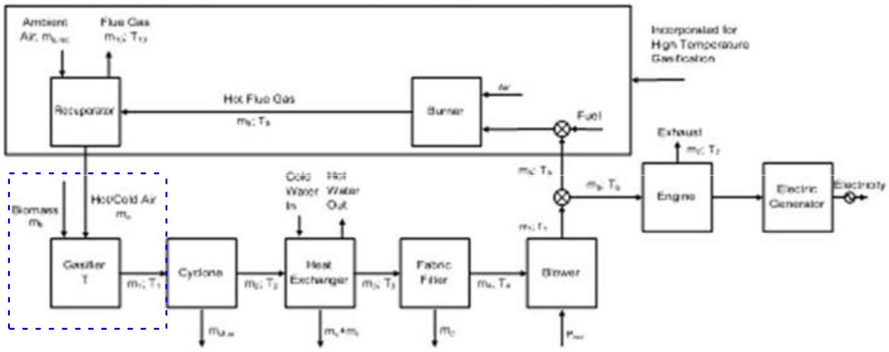

Figure 1: Schematic model for high temperature biomass gasification

1.2 Model Description

The mass fractions of carbon (C), hydrogen (H), and oxygen (O) in the biomass material are obtained through its ultimate analysis and its simplified formula is shown in Equation 2. The global gasification reaction of biomass material is therefore presented in Equation 3.

$$C_xH_yO_z \qquad (2)$$

$$C_xH_yO_z + j(0.21O_2 + 0.79N_2) + \alpha H_2O \rightarrow aCO + bCO_2 + cH_2 + dH_2O + eCH_4 + fC + gN_2 \qquad (3)$$

Where *j* is the molar quantity of air used in the gasification process; α is the molar quantity of water per mole of biomass; and *a, b, c, d, e, f,* and *g* are the coefficients of the respective products (CO, CO_2, H_2, H_2O, CH_4, C, and N_2) of the gasification process. The coefficients are obtained from the mass balance of the global gasification reaction (3):

$$\text{Carbon balance: } x = a + b + e + f \qquad (4)$$

$$\text{Hydrogen balance: } y + 2\alpha = 2c + 2d + 4e \qquad (5)$$

$$\text{Oxygen balance: } z + \alpha + 2 * 0.21j = a + 2b + d \qquad (6)$$

$$\text{Nitrogen balance: } 2*0.79j = 2g \tag{7}$$

The concept of thermodynamic equilibrium of the gasifying process need be considered for developing the additional equations. This will involve main reactions under the gasification process. The enthalpy variation for a given reaction at a given temperature is calculated from Equation (8) as:

$$\Delta H_T^o = J + R(\Delta A.T + \Delta.B.\frac{T^2}{2} + \Delta C.\frac{T^3}{3} - \frac{\Delta D}{T}) \tag{8}$$

Where, *A, B, C*, and *D* are constant characteristic of particular species as tabulated in thermodynamics tables. Equation (8) offers a general method for calculating the heat capacity of a given reaction as a function of temperature. From the equation, the integration constant *J* can be established since the values of standard heat of formation at 298.15K are tabulated in thermodynamic tables.

Assuming that carbon remains in equilibrium, the three main reactions taking place during the gasification process are Boudouard, methanation, and primary water-gas reaction, represented respectively in Equations (9 – 11):

$$C + CO_2 \rightarrow 2CO \tag{9}$$

$$C + 2H_2 \rightarrow CH_4 \tag{10}$$

$$C + H_2O \rightarrow CO + H_2 \tag{11}$$

From the general gasification reaction (3) and utilizing the product gas coefficients (*a, b, c, d, e, f,* and *g*), the equilibrium constant for reactions (9 – 11), respectively $k_1 - k_3$, are established from the mixture partial pressures as:

$$k_1.n.b - a^2 p = 0 \tag{12}$$

$$k_2.c^2.p - e.n = 0 \tag{13}$$

$$k_3.d.n - a.p.c = 0 \tag{14}$$

Here, it is assumed that there are *n* moles of the gaseous products having total pressure *P* and that the partial pressure of carbon is zero. Consequently, the system of equations required to be solved for obtaining the equilibrium gas composition will constitute of mass balance equations (4 – 7) and equilibrium constant equations (12 – 14). In this work, a code written in Engineering Equation Solver (EES) environment was developed. EES provides built-in mathematical and thermophysical property (for example JANAF table and transport properties of gases) functions, which eases engineering calculations. The input variables of the code include thermodynamic properties of the chemical species considered in the model and biomass material's composition.

2 RESULTS AND DISCUSSION

The model results from the variation of biomass moisture level in the range of 3, 5, 6, 7, 10.1, 20, 40, and 60%; and gasification temperature in the range of 500, 600, 700, 800, 900, to 1,000 °C are presented. The oxidizer was either air, or air and steam with their respective preheating to temperatures of 340, 500, and 700 °C. The parametric study investigated and reported the syngas quality in terms of components of CO, CO_2, H_2, including its low heating value (LHV). Furthermore, the cold gasification efficiency of the gasification process was investigated.

2.1 Biomass Material

The high temperature gasification model prediction bases on the coffee husk material, which was obtained from Tanganyika Coffee Curing Company (TCCCo) in Moshi, Tanzania. From the coffee husks ultimate analysis presented in Table 1, the simplified coffee husk formula is $CH_{1.47}O_{0.63}$.

Table 1: Coffee husks ultimate analysis (dry basis)

Proximate Analysis		**Ultimate Analysis**	
Ash content (550 °C),	2.50	Carbon (C), %	49.40
Volatiles content, %	83.20	Hydrogen (H), %	6.10
Fixed carbon, %	14.30	Oxygen (O), %	41.20
HHV, MJ/kg	18.34	Nitrogen (N), %	0.81
		Sulphur (S), %	0.07
		Chlorine (Cl), %	0.03

2.2 Carbon Monoxide

Carbon monoxide evolution profile as a function of gasifier temperature and moisture content shows a consistent common trend. As shown in Figure 2, initially the carbon monoxide increases with temperature to a peak concentration after which it decreases.

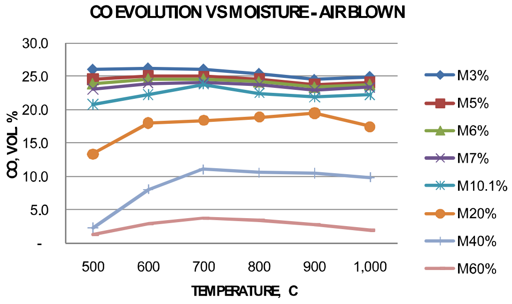

Figure 2: CO evolution profile for air blown gasification

As the moisture content increases, the CO evolution deteriorates further. From this model output, it shows that CO evolution for moisture levels below 20% is relatively comparable whereas there was a considerable difference in CO concentration for moisture levels above 20%. Thus taking an example of the information presented in Figure 2, for materials with moisture below 20% the peak CO was about 30 Vol.% whereas the respective peak CO for materials with 20, 40, and 60% moisture were 19.50, 11.10, and 3.80 Vol. % respectively. Steam injection had no enhancing effects on CO evolution compared to the air blown condition. Generally, the CO reduction as an effect of steam injection to biomass up to 40% moisture was observed to range from 6.87 to 20%. On the other hand, preheating air/steam had positive effects of increasing CO evolution and the effect was more pronounced in higher range of biomass moisture content. For instance, while preheating air (from ambient to 340, 500, and 700 °C) at 6% moisture content biomass, increased CO evolution by 8.54, 13.01, and 18.29%, the respective increment to 60% biomass moisture was 21.05, 31.58, and 50%. However, for each equivalence ratio (ER) there exists a critical temperature above which air preheating has negligible influencing effect. In agreement with other researchers (Sharma, 2008; Jarungthammachote and Dutta, 2008) the CO concentration decreases with increased moisture content. This is due to the fact that the evaporation of moisture from biomass decreases the gasifier's reaction temperature. The lowered reaction temperature has a negative consequence on the progress of endothermic Boudouard ($CO_2 + C \rightarrow 2CO$) and primary water-gas ($C + H_2O \rightarrow CO + H_2$) reactions, which are mainly responsible for the production of carbon monoxide.

2.3 Hydrogen

Though hydrogen yield increased with moisture addition, the trend is consistent up to 40% moisture after which the yield drops. Furthermore, the hydrogen evolution peaks increased consistently with steam injection. For the materials with moisture content 20% and below, the increment due to steam injection ranged from 13.14 to 24.71%. At 40% moisture content the increment dropped below 4% and there were virtually no increment at 60% moisture content. Preheating air/steam had positive effects on hydrogen evolution. The effect was more pronounced to the higher moisture materials, which without preheating showed minimum hydrogen evolution. The average peak hydrogen increment due to preheating air to 340, 500, and 700 °C for up to 20% moisture content material was 3.54, 5.37, and 7.39% respectively. The respective percentage increment for 40% moisture rose to 6.59, 9.58, and 12.87% whereas the respective increment to the 60% moisture material increased further to 14.67, 21.33, and 29.33%. Hydrogen increases with moisture content since the moisture in biomass shifts the equilibrium of product gas towards the production of H_2 and CO_2 through the water-gas shift reaction ($CO + H_2O \rightarrow H_2 + CO_2$) and steam reforming of methane ($CH_4 + H_2O \rightarrow CO + H_2$). While hydrogen increases in the process the concentration of CO and CH_4 decreases simultaneously. Contrary to the exothermic water-gas shift reaction the steam reforming of methane is exothermic and it progresses well in the high temperature regime (and hence, during preheating).

2.4 Syngas Low Heating Value (LHV)

Figure 3 shows that the presence of excessive moisture (above 20%) produced syngas with much lower LHV compared to those with less moisture content. From the Figure it is clear that materials with moisture content of 10% and below produced comparable syngas LHV (above 6 MJ/nm^3) whereas those with moisture above 20% deviated and dropped significantly below 6 MJ/nm^3. Generally, steam injection decreased the syngas LHV. In the moisture range of 3 to 20% the percentage decrease ranged from 3.22 to 6.52% whereas at 40% moisture the range was from 1 to 2%. For the 60% moisture materials, there was an average increase of 0.75% of syngas LHV due to steam injection at the highly preheated air/steam (700 °C). On the other hand, air/steam preheating increased the syngas LHV for moisture range of 3 to 40% above which the effect was negligible. The respective average increment for preheating air/steam to 340, 500, and 700 °C was 6.03, 9.01, and 12.73%. Consequently, the higher the preheating the higher the syngas heating value.

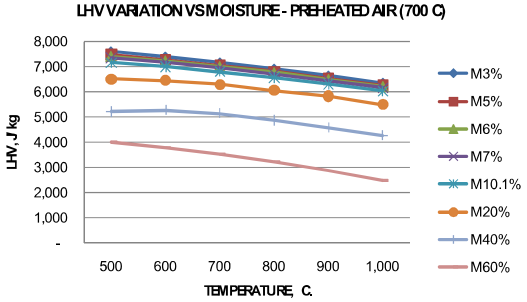

Figure 3: Syngas LHV variation with moisture

The primary cause of decreasing the LHV with increasing moisture is from the rising of water content in the product gas. The product gas is diluted with the moisture, which is not combustible. Furthermore, the rising water content in the product gas is degrading the syngas quality as it participates in the water-gas shift and steam reforming reactions, which reduces the concentration of combustible components namely carbon monoxide and methane. While the concentration of carbon dioxide and methane decreases, the concentration of carbon dioxide increases simultaneously. Carbon dioxide is not combustible hence its presence lowers the syngas heating value.

2.5 Cold Gasification Efficiency (η_{gas})

Equation 15 defines the cold gasification efficiency of a gasifier:

$$Cold\ gas\ efficiency = \frac{LHV\ of\ gas\,(kJ/Nm^3 \times fuel\ gas\ production\,(Nm^3/kg)}{LHV\ of\ Biomass\ fed\ in\ the\ system\,(kJ/kg)} \tag{15}$$

The variation of cold gasification efficiency with moisture content is shown in Figure 4. Though the efficiency drops with increasing moisture, the Figure shows that materials with moisture content below 20% resulted in a comparable cold gasification efficiency of above 70%. The gasification efficiency dropped below 60% for 40% moisture and it dropped consistently below 50% for materials with 60% moisture content.

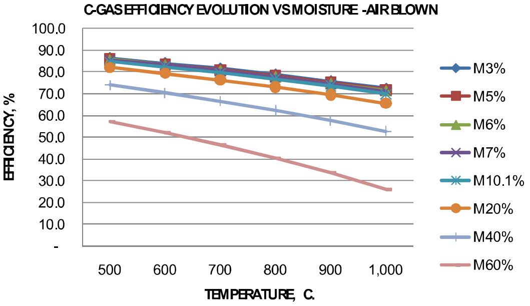

Figure 4: Cold gasification efficiency variation with moisture content

There was a marginal decrease (averaged 0.41%) of gasification efficiency due to steam injection whereas preheating air/steam influenced positively the cold gasification efficiency. On the average, there was a gasification efficiency increase of between 2.94 and 14.20% for preheating air in the range of 340, 500 and 700 °C. Relatively higher increment of gasification efficiency was recorded to higher moisture materials (that exhibited poorer gasification efficiency) compared to the lower moisture counterparts. For instance, at 3% moisture content the gasification efficiency increment due to preheating air to 340, 500, and 700 °C was 2.92, 4.22, and 5.79%. The increment at 10.1% moisture was 3.09, 4.40, and 5.99% whereas the respective increment for the 60% moisture material rose to 7.72, 10.73, and 14.20%. The cold gasification efficiency (Equation 15) decreases with moisture primarily due to the decreased syngas heating value as a result of syngas dilution with water and carbon dioxide. Furthermore, the moisture has to be evaporated from the biomass resulting in a high energy demand and hence less energy is available to support endothermic reactions that produce hydrogen and carbon monoxide. As supported by findings from other researchers (Pellegrini and de Oliveira Jr., 2007; Schuster *et al*., 2001), moisture content above 40% leads to poor gasification efficiency as most of the product gas has to be re-circulated in the combustion zone for supporting the process.

3 CONCLUSIONS

It is generally concluded that though the presence of moisture is beneficial for hydrogen-rich syngas under HTAG process, there is a remarkable deterioration of other syngas component and characteristic for moisture content above 20%. Following are the specific conclusion:

(i) The CO evolution for moisture levels below 20% was comparable amongst the moisture levels whereas there was a considerable difference in CO concentration for moisture levels above 20%. Steam injection had no enhancing effects on CO evolution since the observed CO reduction as an effect of steam injection to biomass up to 40% moisture ranged from 6.87 to 20%. On the other hand, preheating air (from ambient to 340, 500, and 700 °C) at 6% moisture content biomass, increased CO evolution by 8.54, 13.01, and 18.29%, the respective increment to 60% biomass moisture was 21.05, 31.58, and 50%.

(ii) Though hydrogen yield increased with moisture addition, the trend is consistent up to 40% moisture after which the yield drops. Furthermore, the hydrogen evolution peaks increased consistently with steam injection. Preheating air/steam had positive effects on hydrogen evolution. The average peak hydrogen increment due to preheating air to 340, 500, and 700 °C for up to 20% moisture content material was 3.54, 5.37, and 7.39% respectively.

(iii) The presence of excessive moisture (above 20%) produced syngas with much lower LHV compared to those with less moisture content. Materials with moisture content of 10% and below produced comparable syngas LHV (above 6 MJ/nm^3) whereas those with moisture above 20% deviated and dropped significantly below 6 MJ/nm^3. Generally, steam injection decreased the syngas LHV whereas air/steam preheating increased the syngas LHV for moisture range of 3 to 40% above which the effect was negligible.

(iv) Though the cold gasification efficiency decreased with increasing moisture, it was evident that materials with moisture content below 20% resulted in a comparable cold gasification efficiency of above 70%. The gasification efficiency dropped below 60% for 40% moisture and it dropped consistently below 50% for materials with 60% moisture content.

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