THERMODYNAMIC ANALYSIS OF DOWNDRAFT BIOMASS GASIFIER TO STUDY THE EFFECT OF TEMPERATURE USING DIFFERENT FEEDSTOCK

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Abstract. In the present paper, effect of gasification temperature on gasification process in a downdraft gasifier using different biomass feedstock has been examined. An equilibrium model of the downdraft biomass gasifier has been developed to carry out the study. The model has been validated with experimental results. The producer gas yield has been analysed by using stoichiometric equilibrium model. The lower heating value (LHV) calculation has been done for different biomass with respect to temperature. It has been observed that the hydrogen production rate and CO production rate increases with respect to increase in temperature. On the other hand the Methane production decreases with increase in temperature. The lower heating value (LHV) for the studied sample has been observed to decrease with respect to the increase in gasification temperature.

Keywords: Downdraft biomass gasifier, equilibrium model, effect of temperature

1. Introduction
In the present context of world environment and need of energy, it is important to develop sustainable and renewable energy option. For such criteria of energy demand the biomass gasification is very important. Therefore, in the present study a downdraft biomass gasifier model has been considered and the gasification process has been analysed according to the schematic given in the block diagram of figure 1.

![Figure 1: Block diagram of downdraft biomass gasifier for the present model of biomass gasification.](image)

In gasification process the equivalence ratio of oxygen and gasification temperature have been found with great influence. The gasification process has been modelled in different ways in different studies [1-3]. However, for thermodynamic analysis the stoichiometric equilibrium model [4-5] and minimization of Gibbs free energy has been found convenient and reliable with respect to the producer gas yield. Therefore, in the present study the modified stoichiometric equilibrium model has been used to check the different gas yield and lower heating value (LHV) of produced gas.

2. Model description and methodology
In the present study stoichiometric equilibrium model has been applied with modified reaction constants, which vary with respect to gasification temperature. The developed model has been
validated with experimental literature and then the model has been utilized to predict the composition of produced gas mainly hydrogen, carbon mono oxide and methane for different biomass feed stock. For biomass ultimate analysis Douglas fir, Paper, Maple wood and Redwood feedstock has been utilized. The ultimate analysis of this biomass has been given in the table 1.

Table 1: Ultimate analysis of biomass on dry basis (wt %)

| Biomass       | C   | H   | O    | N   | Ash | HHV(MJ/Kg) |
|---------------|-----|-----|------|-----|-----|------------|
| Maple wood    | 50.6| 6   | 41.7 | 0.3 | 1.4 | 19.958     |
| Douglas fir   | 52.3| 6.3 | 40.5 | 0.1 | 0.8 | 21.051     |
| Paper         | 43.4| 5.8 | 44.3 | 0.3 | 6.2 | 17.613     |
| Redwood       | 53.5| 5.9 | 40.3 | 0.1 | 0.2 | 21.028     |

To run the calculation Carbon, Hydrogen, Oxygen and Nitrogen ratio along with the moisture content of the biomass has been considered as important input. The moisture content of the different biomass has been given in table 2. After biomass consideration model has been developed in section 2.1;

Table 2: moisture content of different biomass (wt % of dry biomass)

| Biomass       | Maple wood | Douglas fir | Paper | Redwood |
|---------------|------------|-------------|-------|---------|
| MC            | 35         | 27          | 45    | 25      |

2.1. Assumptions and model formulation

The analysis has been done with the thermodynamic equilibrium model i.e. stoichiometric equilibrium model (calculation has been done on the basis of equilibrium constant and stoichimetric ratios). To develop such a model following assumptions has been made. The reaction time has been considered very high so that all reactions are in steady state and all carbon molecules converts into gas. Tar content has been neglected and ash has been considered as inert in every gasification reactions. Along with this all the produced gas has been considered as ideal gas. To analyse the process the main gasification equation has been considered in a very simplified form and it has been given in eq. (1);

\[
\text{CH}_x\text{O}_y\text{N}_z + w_1\text{H}_2\text{O} + m (\text{O}_2 + 3.76\text{N}_2) \rightarrow \dot{\text{N}}_{\text{H}_2} + \dot{\text{N}}_{\text{CO}} + \dot{\text{N}}_{\text{CO}_2} + \dot{\text{N}}_{\text{H}_2\text{O}} + \dot{\text{N}}_{\text{CH}_4} + \dot{\text{N}}_{\text{N}_2}
\]

Here the unknown parameters are $\dot{N}_{\text{H}_2}$, $\dot{N}_{\text{CO}}$, $\dot{N}_{\text{CO}_2}$, $\dot{N}_{\text{H}_2\text{O}}$, $\dot{N}_{\text{CH}_4}$, $\dot{N}_{\text{N}_2}$. These values of unknown parameter will give the composition of producer gas yield. To get these unknown, the mass balance of carbon, hydrogen, oxygen and nitrogen has been used along with methanation reaction and water-gas shift reaction.

\[
\dot{N}_{\text{CO}} + \dot{N}_{\text{CO}_2} + \dot{N}_{\text{CH}_4} = 1
\]
\[
2\dot{N}_{\text{H}_2} + 2\dot{N}_{\text{H}_2\text{O}} + 4\dot{N}_{\text{CH}_4} = x + 2w_k
\]
\[
\dot{N}_{\text{CO}} + 2\dot{N}_{\text{CO}_2} + \dot{N}_{\text{H}_2\text{O}} = y + w_k + 2m
\]
\[
2\dot{N}_{\text{N}_2} = z + 7.52m
\]
\[
w_k = \frac{M_B \times MC}{(1-MC) \times 18}
\]
\[
m = ER(1 + 0.25x - 0.5y)
\]

The value of different parameter of eq. (6 and 7) has been calculated from the ultimate analysis of different biomass feedstock.

\[
\text{C} + \text{CO}_2 \rightarrow 2\, \text{CO}
\]
\[
\text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2
\]

The first two reactions shown above eq. (8 and 9) can be combined into eq. (10) known as water-gas shift reaction:

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2
\]
\[
\text{C} + 2\text{H}_2 \rightarrow \text{CH}_4
\]
The main reactions in gasification process have been considered as water-gas shift reaction eq. (10) and methanation reaction eq. (11). The reaction rate constants have been given in eq. (12-17):

\[
K_{mn} = \frac{N_{CH_4}}{(N_{H_2})^2}
\]

(12)

\[
K_{wgs} = \frac{N_{H_2} \times N_{CO_2}}{N_{CO} \times N_{H_2O}}
\]

(13)

It has been found that the equilibrium constants ( \(K_{mn}\) and \(K_{wgs}\)) are functions of reaction temperature \(T\) and Gibbs free energy (\(\Delta g_{mn}^0, \Delta g_{wgs}^0\)) of the corresponding reactions. On the other hand the Gibbs free energy has been found as a function of reaction temperature. Therefore the reaction constants have been calculated from the gasification temperature by using the simplified reaction rate constant equation of Zainal et al. [5].

\[
K'_{mn} = \exp\left(\frac{-\Delta g_{mn}^0}{RT_G}\right)
\]

(14)

\[
K'_{wgs} = \exp\left(\frac{-\Delta g_{wgs}^0}{RT_G}\right)
\]

(15)

\[
K_{mn} = \exp\left(\frac{5878}{T} + 1.86 \ln T - 0.27 \times 10^{-3}T - \frac{58200}{T^2} - 18\right)
\]

(16)

\[
K_{mn} = \exp\left(\frac{7082.842}{T} - 6.567 \ln T + \frac{7.467 \times 10^{-3}}{T} - \frac{2.167 \times 10^{-6}}{T^2} + \frac{0.702 \times 10^{-5}}{T^2} + 32.541\right)
\]

(17)

The six eq. (2, 3, 4, 5 and 12, 13) has been solved by the standard Newton-Raphson method. After calculation of six unknown \(N_{H_2}, N_{CO}, N_{CO_2}, N_{H_2O}, N_{CH_4}, N_{N_2}\) the lower heating value (LHV) of the producer gas has been calculated from eq. (18)

\[
LHV = 10.78 \times \% H_2 + 12.63 \times \% CO + 35.88 \times \% CH_4 \text{ [}MJ/m^3\]}

(18)

3. Model validation

The produced hydrogen gas percentage from model calculation has been compared with experimental results of Sittisun et al. [6], and the root mean square error (RMSE) has been calculated to check the deviation. The root mean square error has been found as 5.92 for present study. To compensate the non-equilibrium conditions present in gasification, the reaction constants \(K_{mn}\) and \(K_{wgs}\) have been multiplied by non-equilibrium coefficients 20 and 0.91 for minimization of errors. In several literatures such method has been applied to develop their models and resulted in better prediction [6]. The result of present study as compared with the experimental result has been given in figure 2.

![Figure 2: Hydrogen production with respect to the equivalence ratio.](image-url)
4. Results and Discussions
The percentage of $H_2$, $CO$ and $CH_4$ has been calculated using the developed model based on the thermodynamic equilibrium model and stoichiometric equilibrium model. Figure 3 represents the gas production percentage and LHV with respect to the temperature for different biomass.

![Figure 3: Effect of gasification temperature on gas production for (a) Douglas fir (b) Maple (c) Paper (d) Redwood (e) Effect of gasification temperature on LHV of produced gas.](image)
Composition analysis of different gas with respect to temperature has been done. The equivalence ratio has kept fixed as 0.25 and the temperature have varied from 973K to 1173K. The LHV calculation has also been made for different biomass with respect to temperature. It has been observed that the hydrogen production rate and CO production rate increases with respect to increase in temperature. On the other hand the Methane production decreases with increase in temperature. The LHV for the studied sample have found to decrease with respect to the increase in temperature.

5. Conclusions
From the present work it can be concluded that the LHV for different biomass is decreasing with temperature,
- Because there is less production of \(CH_4\) at higher temperature and \(CH_4\) contributes a large factor nearly 40 times of its percentage in the produced gas for the calculation of LHV. This is due to the fact that with the increase in temperature the methanation reaction rate constant has decreased sharply from 33.45 to 16.33, as a result less reaction took place producing less \(CH_4\).
- On the other hand the \(H_2\) and \(CO\) production rate increases because with the increase in temperature the oxidation rate of carbon to \(CO_2\) has increased rapidly due to less requirement of reaction activation energy along with more char and moisture conversion to \(CO_2\) and \(H_2O\).
- But the increase in \(H_2\) and \(CO\) is not sufficient with respect to the decrease in \(CH_4\) production. More precisely their contribution to LHV is nearly 10-12 times of their percentage in produced gas, which is comparatively very less than that of \(CH_4\) contribution (nearly 40 times of its percentage in total gas). Hence overall LHV is decreasing with increase in temperature.

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References
[1] Jarunghammachote S and Dutta A 2007 Thermodynamic equilibrium model and second law analysis of a downdraft waste gasifier Energy 32(9) 1660-1669
[2] Barman N S Ghosh S and De S 2012 Gasification of biomass in a fixed bed downdraft gasifier a realistic model including tar Bioresource technology 107 505-511
[3] Janajreh I and Al Shrah M 2013 Numerical and experimental investigation of downdraft gasification of wood chips Energy Conversion and Management 65 783-792
[4] Mendiburu A Z Carvalho Jr J A Zanzi R Coronado C R and Silveira J L 2014 Thermochemical equilibrium modeling of a biomass downdraft gasifier constrained and unconstrained non-stoichiometric models Energy 71 624-637
[5] Zainal Z A Ali R Lean C H and Seetharamu K N 2001 Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials Energy conversion and management 42(12) 1499-1515
[6] Sittisun P Tippayawong N and Pang S 2019 Biomass gasification in a fixed bed downdraft reactor with oxygen enriched air a modified equilibrium modeling study Energy Procedia 160 317-323

Nomenclature
\(x\) Hydrogen to carbon mole ratio in dry biomass
\(y\) Oxygen to carbon mole ratio in dry biomass
\(z\) Nitrogen to carbon mole ratio in dry biomass
\(w_k\) Number of water molecule in dry biomass
\(m\) Number of oxygen molecule
\(M_B\) Mass of dry biomass
\(MC\) Moisture content