Appl Biochem Biotechnol (2009) 154:193–204
DOI 10.1007/s12010-008-8483-x

Modeling Biomass Gasification Using Thermodynamic Equilibrium Approach

Hua-Jiang Huang · Shri Ramaswamy

Received: 21 May 2008 / Accepted: 8 December 2008 /

Abstract In this paper, the thermodynamic equilibrium models for biomass gasification applicable to various gasifier types have been developed, with and without considering char. The equilibrium models were then modified closely matching the CH_4 only or both CH_4 and CO compositions from experimental data. It is shown that the modified model presented here based on thermodynamic equilibrium and taking into account local heat and mass considerations can be used to simulate the performance of a downdraft gasifier. The model can also be used to estimate the equilibrium composition of the syngas. Depending on the gasifier type and internal fluid flow, heat and mass transfer characteristics, with proper modification of the equilibrium model, a simple tool to simulate the operation and performance of varying types of biomass gasifier can be developed.

Keywords Biomass · Gasification · Chemical equilibrium · Modeling · Downdraft gasifier · Syngas

Nomenclature

a	number of atom H in the biomass formula $CH_aO_bN_cS_d$ based on 1 mol of carbon
A	coefficients of the heat capacity formula
ΔA	change in coefficient A of a reaction, see formula 17
b	number of atom O in the biomass formula $CH_aO_bN_cS_d$
B	coefficients of the heat capacity formula
ΔB	change in coefficient B of a reaction, similar to formula 17
c	number of atom N in the biomass formula $CH_aO_bN_cS_d$
C	coefficients of the heat capacity formula
C_P	heat capacity, J/mol·K
ΔC	change in coefficient C of a reaction, similar to formula 17
d	number of atom S in the biomass formula $CH_aO_bN_cS_d$
D	coefficients of the heat capacity formula

H.-J. Huang · S. Ramaswamy (✉)
Department of Bioproducts and Biosystems Engineering, University of Minnesota, Kaufert Lab., 2004 Folwell Ave., St. Paul, MN 55108, USA
e-mail: shri@umn.edu

ΔD	change in coefficient D of a reaction, similar to formula 17
e	stoichiometric coefficient of H_2O (liquid) in the overall gasification reaction 1
E	coefficients of the heat capacity formula
f	stoichiometric coefficient O_2 in the overall gasification reaction 1
g	stoichiometric coefficient N_2 in the overall gasification reaction 1
ΔG^0	standard Gibbs free-energy change of a reaction at 298.15 K, J/kmol
ΔG^0_{fi}	Gibbs energy of formation of component i at 298.15 K, J/mol
$\Delta H^0_{T_0}$	standard heat of reaction at temperature of T_0 (=298.15 K), J/mol
n_i	represents the mole numbers of H_2, CO, CH_4, CO_2, H_2O(g) and C(s), i=1,2,…6
K_0	equilibrium constant at 298.15 K
K_i	equilibrium constants of the three equilibrium reactions 5–7
P_t	the total pressure in the reaction system, Pa
R	ideal gas constant
T_0	reference temperature, T_0=298.15 K
T	reaction temperature, K

Superscript

°	standard state for property values

Introduction

Biomass gasification is gaining increasing attention as one of the prominent thermochemical conversion methods to produce renewable fuels, energy and other products. In addition to producing energy for heat and power, synthesis gas from biomass gasification can be subsequently converted into liquid transportation fuels such as diesel and gasoline, alternative fuels such as methanol and dimethyl ether (DME), ethanol, and other chemicals. This route is referred as the “syngas platform”, or “one carbon platform” for conversion of biomass to biofuels and chemicals, differentiating it from the “sugar platform” where biomass is subjected to hydrolysis and saccharification and then the resulting sugars including glucose, xylose, mannose, etc. are converted into ethanol and sugar-derived building blocks such as 3-hydroxypropionic acid (3-HP), levulinic acid and xylitol, etc., which can later be used to produce various chemicals and materials [1]. The well-known Fischer–Tropsch (FT) synthesis is one of the most important gas-to-liquids (GTL) conversion technologies, which converts natural gas or syngas (CO+H_2) to high-quality liquid transportation fuels (e.g., diesel and gasoline) containing less or no sulfur in a fixed bed or slurry reactor by using iron or cobalt-based or hybrid (composite) catalysts [2–4]. Methanol, a liquid transportation fuel or material for fuel cell, can be synthesized from syngas over the Cu/ZnO catalyst. DME is produced by a two-step process, i.e., synthesis of methanol from syngas and then dehydration of methanol to DME. It can also be directly synthesized from syngas in a single-step process [5] by use of the hybrid catalyst composed of CuO, ZnO, Al_2O_3, and/or Cr_2O_3) for methanol synthesis and an acid function component (such as γ-Al_2O_3, H-ZSM-5 or HY zeolites) for conversion of methanol into DME [6]. In addition, ethanol and other higher alcohols can be produced from syngas with Co–Mo–K catalysts [7].

Coal or oil gasification has been practiced for many years, for example, Sasol’s gasification application in South Africa. There are more pilot scale or demonstration and commercial plants of gasification than those of pyrolysis and liquefaction, using coal or oil as feedstock [8]. In addition, most components for processing of clean syngas are commercial or nearly commercial [9]. The research and development that has been underway in the coal or oil gasification can certainly benefit the future development of biomass gasification [8].

However, there are still apparent differences between biomass gasification and coal and other materials gasification, mostly related to the high level of volatiles (70–75%) in biomass compared to coal (20–25%), the different physical and structural characteristics of the feedstock, and the different char reactivity and particle mechanical properties. Hence, the vast experience with coal and other materials is not directly applicable [8]. Considering this and the fact that biomass gasification is a key process of the future biorefinery, a large number of researchers have been studying it [8, 10–15].

Biomass gasification is rather complex and many researchers have focused on modeling in order to better understand the gasification process and carry out design, simulation, and optimization of gasifiers and perform process analysis. There are many types of biomass gasifiers: fluidized bed (circulating fluidized bed [16], bubbling fluidized bed reactor [17]), fixed bed (downdraft [11, 18–20] and updraft [21–23]), cyclone [24], entrained flow [25, 26], moving-bed gasifers [27, 28], etc. In terms of spatial dimensions, models of gasifiers can be divided into 0-D, 1-D, 2-D, and 3-D models, where D represents dimension. Among these, 1-D, 2-D, and 3-D models contains space variables considering local heat/mass transfer and possibly also fluid flow within the gasifiers. Among these dimensional models, 1-D models were most commonly used, for example, downdraft 1-D models [19, 20, 29, 30] and 1-D bubbling fluidized bed reactor 1-D models [17, 31]. There were a few of 2-D models published, for instances, downdraft 2-D models [32, 33]. Such approaches are more close to the commercial gasification processes than the 0-D (space-independent) model, also referred as thermodynamic equilibrium model. However, the thermodynamic equilibrium model is also imperative due to its ability to predict the maximum possible conversion of biomass during gasification and the theoretical efficiency. It is also important in the optimization of the operating conditions at the equilibrium state and also being a simple tool to estimate the gasification performance for preliminary techno-economic analysis of the whole process.

There are two methods for thermodynamic equilibrium modeling: stoichiometric method based on stoichiometric reactions and non-stoichiometric method based on minimizing the total Gibbs free energy in the system. Up till now, stoichiometric thermodynamic equilibrium models for biomass gasification have been widely applied [34–39]. Most of these have not considered char production in their models. A few of researchers [35, 37] considered the char in their models, but did not establish the modified models for use. Li et al. [40, 41] accounted for char in their model and established the modified models for coal gasification, but, to our knowledge, similar work for biomass gasification considering char and at the same time establishing the modified models has not been reported. The purpose of this paper is to develop a stoichiometric thermodynamic equilibrium model for biomass gasification with and without char, and then develop a modified model to simulate the performance of a downdraft gasifier.

Thermodynamic Equilibrium Model

Overall Reaction and Elemental Balance Equations

The general chemical formula of lignocellulosic biomass, based on 1 atom of carbon, can be expressed in the form of $CH_aO_bN_cS_d$, omitting the other elements such as Cl and traces of metal elements and where a, b, c, d, representing the numbers of atoms of H, O, N, and

S, respectively. The composition of individual elements can be determined from the ultimate analysis of the biomass.

Assuming that the gasification reactions are at thermodynamic equilibrium, and the gasification products contain the gas species of H_2, CO, CH_4, CO_2, H_2O, N_2, and H_2S, and the solid species of solid carbon only, i.e., char only contains solid carbon here (ash is assumed to be inert in the gasification and not considered in the simulation), the overall gasification reaction with steam and air can be written as:

$$\begin{aligned} &CH_aO_bN_cS_d + eH_2O(\text{liq.}) + fO_2 + gN_2 \\ &\quad = n_1H_2 + n_2CO + n_3CH_4 + n_4CO_2 + n_5H_2O(g) + (c/2+g)N_2 + n_6C(s) + dH_2S \end{aligned} \tag{1}$$

From Eq. (1), the elemental balances for C, H and O are easily obtained:

C:

If not considering char (n_6=0),

$$1 = n_2 + n_3 + n_4 \tag{2a}$$

If considering char,

$$1 = n_2 + n_3 + n_4 + n_6 \tag{2b}$$

$$\text{H}: \quad a + 2e = 2n_1 + 4n_3 + 2n_5 + 2d \tag{3}$$

$$\text{O}: \quad b + e + 2f = n_2 + 2n_4 + n_5 \tag{4}$$

Equilibrium Equations

In the downdraft gasifier, there are four zones: drying for removal of moisture, pyrolysis of biomass into oil, char, and volatiles, oxidation of the volatile products of pyrolysis, and gasification of char from pyrolysis [11]. In this paper, only the reaction zone is considered and simulated by the thermodynamic equilibrium model.

There are three main independent equilibrium reactions, which can be used for equilibrium calculations [37]:

Steam methane reforming reaction

$$CH_4 + H_2O = CO + 3H_2 \tag{5}$$

Water–gas shift reaction

$$CO + H_2O = CO_2 + H_2 \tag{6}$$

Primary water–gas reaction

$$C(s) + H_2O = CO + H_2 \tag{7}$$

The three equilibrium constants for the three reactions (5), (6), and (7) are described in Eqs. (8a), (9a), and (10), respectively.

$$K_1 = \frac{n_2 \times n_1^3 \times P_t^2}{n_3 \times n_5} \tag{8a}$$

$$K_2 = \frac{n_4 \times n_1}{n_2 \times n_5} \tag{9a}$$

$$K_3 = \frac{n_2 \times n_1 \times P_t}{n_5} \tag{10}$$

Where K_1, K_2 and K_3 are the equilibrium constants for the reactions (5), (6), and (7), respectively. P_t is the total pressure in the system. According to $\frac{d \ln K}{dT} = \frac{\Delta H_T^0}{RT^2}$, the equilibrium constants can be derived:

$$\begin{aligned}\ln K &= \ln K_0 + \left[\frac{\Delta A}{R}\ln T + \frac{\Delta B}{2R}T + \frac{\Delta C}{6R}T^2 + \frac{\Delta D}{12R}T^3 + \frac{\Delta E}{20R}T^4 - \frac{F}{RT}\right]_{T_0}^{T} \\ &= \ln K_0 + \frac{\Delta A}{R}\ln\frac{T}{T_0} + \frac{\Delta B}{2R}(T - T_0) + \frac{\Delta C}{6R}\left(T^2 - T_0^2\right) \\ &\quad + \frac{\Delta D}{12R}\left(T^3 - T_0^3\right) + \frac{\Delta E}{20R}\left(T^4 - T_0^4\right) - \frac{F}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\end{aligned} \tag{11}$$

Where

$$F = \Delta H_{T_0}^0 - \left(\Delta A T_0 + \frac{\Delta B}{2}T_0^2 + \frac{\Delta C}{3}T_0^3 + \frac{\Delta D}{4}T_0^4 + \frac{\Delta E}{5}T_0^5\right) \tag{12}$$

$$\ln K_0 = -\frac{\Delta G^0}{RT} \tag{13}$$

$$\Delta G^0 = \sum \nu_i G_{fi}^0 \tag{14}$$

$$C_P^0 = A + BT + CT^2 + DT^3 + ET^4 \tag{15}$$

$$\Delta C_P^0 = \Delta A + \Delta BT + \Delta CT^2 + \Delta DT^3 + \Delta ET^4 \tag{16}$$

$$\Delta A = \sum_{\text{products}} nA - \sum_{\text{reactants}} nA \tag{17}$$

With similar definitions for ΔB, ΔC, ΔD, and ΔE.

Thermodynamic Equilibrium Models

Two thermodynamic equilibrium models are taken into account, i.e., Model 1 (not including char) consisting of Eqs. (2a), (3), (4), (8a), (9a), and Model 2 (considering char) consisting of Eqs. (2b), (3), (4), (8a), (9a), (10).

For Model 2, under the given gasification temperature T and pressure P_t, K_1, K_2, and K_3 can be determined by Eqs. (11), (12), (13), (14), (15), (16). Then n_i (i=1–6) are obtained by solving the nonlinear Eqs. (2b), (3), (4), (8a), (9a) and (10), for a specific biomass (a, b, c, d, and e are known) under the given amount of air (f and g are known). Model 1 was solved similarly.

Modified Model—Based on Experimental Compositions

In an actual gasification system, it is always the case that the chemical reactions are not exactly at equilibrium due to the kinetic (including mass/heat transfer) limitations [16]. Therefore, it is necessary to establish the modified model considering the fractional achievement of equilibrium, i.e., the modified models are made by multiplying the coefficient β_1 to K_1 in Eq. (8a), and β_2 to K_2 in Eq. (9a), as seen in Eqs. (8b) and (9b), respectively.

$$\beta_1 K_1 = \frac{n_2 \times n_1^3 \times P_t^2}{n_3 \times n_5} \tag{8b}$$

$$\beta_2 K_2 = \frac{n_4 \times n_1}{n_2 \times n_5} \tag{9b}$$

Where β_1 can be determined by fixing the fraction of CH_4 in the dry syngas at its average value of the experimental data, and β_2 estimated by fixing the fraction of CO in the dry syngas at its average value of the experimental data.

Specifically, modification of Model 1 (not including char) by fixing the fraction of CH_4 only, i.e., $y$$CH_4$ is mainly described by Eqs. (2a), (3), (4), (8b), (9a). This is called M1F1 model. The modification of Model 1 by fixing both $y$$CH_4$ and yCO (fraction of CO) is mainly described by Eqs. (2a), (3), (4), (8b), (9b). This is called M1F2 model. Similarly, the modification of Model 2 (including char) by fixing $y$$CH_4$ only is called M2F1, consisting of Eqs. (2b), (3), (4), (8b), (9a), (10), and the modification of Model 2 by fixing both $y$$CH_4$ and yCO is called M2F2, consisting of Eqs. (2b), (3), (4), (8b), (9b), (10). The resulting nonlinear equations were solved in a similar way as described earlier.

Determination of Deviation Temperature

Model 1 (not considering char) and Model 2 considering char can also be utilized to calculate the deviation temperature between the model and experiment at the same or close to product compositions. Specially, the model temperature was obtained by minimization of the sum of square of residues between the experimental compositions at a specific temperature and simulation compositions. Then the deviation temperature between the model and experiment was determined.

Model Input and Physical Properties

Feedstock Properties and Operating Conditions

The biomass properties and the gasification conditions are shown in Table 1.

Table 1 Properties and the gasification conditions of biomass feedstock.

Biomass	Rubber wood [42]	Sawdust [39]	Biomass Solid waste [39]
Moisture	16	10	16
Ultimate elemental analysis (wt % on dry basis)			
C	50.6	52	51.034
H	6.5	6.07	6.776
O	42	41.55	39.178
N	0.2	0.28	2.642
S	0	0	0.37
Ash	0.7	0.1	0
Operation condition			
Reactor Temp. (T_R), K	1,113	1,073.15	1,073.15
Reactor Pres. (P_R), Pa	101,325	101,325	101,325
Oxidant (Air or O_2 and N_2)			
O_2 flowrate, mol/hr	0.3781	0.3273	0.4647
N_2 flowrate, mol/hr	1.4224	1.2313	1.7482

Physical Properties of Product Species

The coefficients in the heat capacity formula Eq. (15) for gas product species H_2, CO, CH_4, CO_2, H_2O, N_2, H_2S and solid char (C) were taken from a chemical properties handbook [43]. The standard enthalpy of formation, the standard Gibbs free energy of formation, and the standard enthalpy of combustion at 25°C were taken from the process simulator Aspen Plus.

Results and Discussion

Results of Model 1 and Its Modified Models

Figures 1, 2, and 3 show the comparison between Model 1 and its modified models and the experimental data.

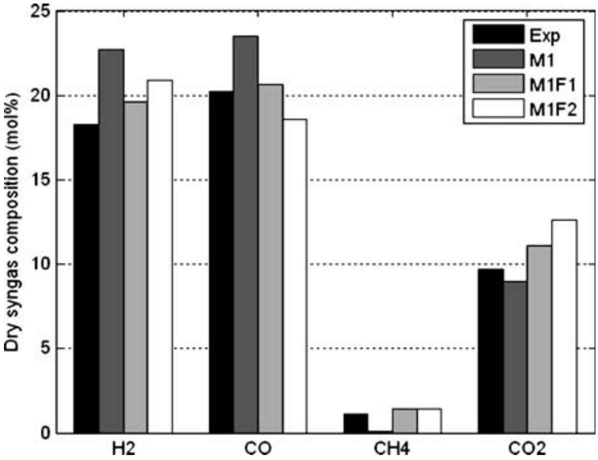


Fig. 1 Dry syngas composition (mol%) of Rubber wood (SSR values of M1, M1F1 and M1F2 are 0.0067, 0.0016, and 0.0035, respectively) Note that M1 is Model 1 (without considering char), and SSR the sum of squares of the residual error between the model predictions and the experiment. SSR represents the model performance. Smaller SSR value indicates a better model performance

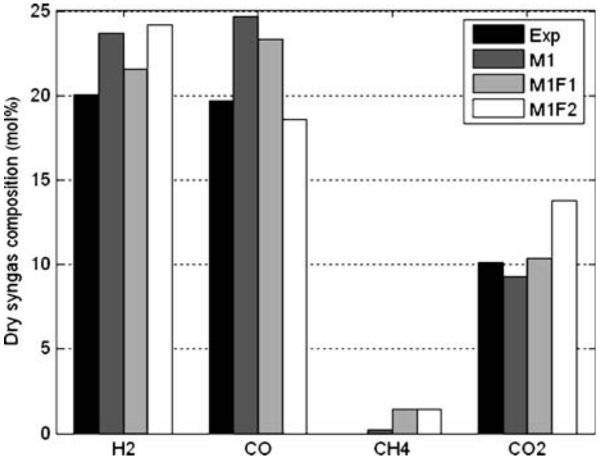


Fig. 2 Dry syngas composition (mol%) of sawdust (SSR values of M1, M1F1 and M1F2 are 0.0102, 0.0063, and 0.0099)

It can be seen from Figs. 1, 2, and 3 that the results of Model 1 (not considering char) are close to experimental data. In addition, the modification of Model 1 by fixing $y\mathrm{CH}_4$ only, i.e., M1F1 can improve the predictive capability. Whereas the modification of Model 1 by fixing both $y\mathrm{CH}_4$ and $y\mathrm{CO}$, i.e., M1F2 lead to poorer predictive capability. This is probably because Model 1 has one unknown variables less than the Model considering char, and thus fixing both $y\mathrm{CH}_4$ and $y\mathrm{CO}$ may become over-estimation.

Results of Model 2 and Its Modified Models

Figures 4, 5, and 6 show the comparison between model 2 (considering char) and its modified models and the experiment data.

From Figs. 4, 5, and 6 it is found that the results of the Model 2 (M2) considering char, are far removed from the experimental data, specifically, the simulation value of $y\mathrm{CO}$ is much higher than that of the experimental data, while the model value of CO2 is much

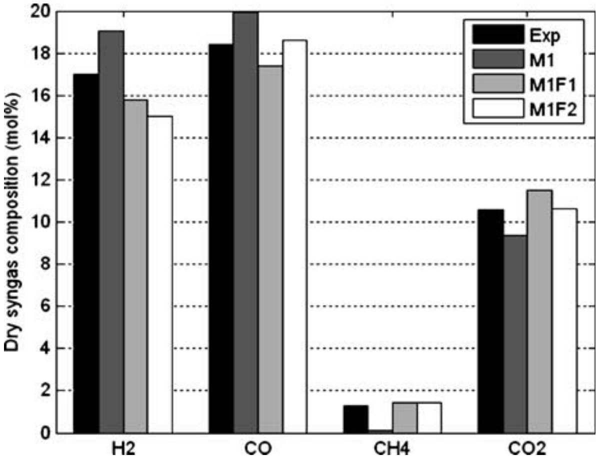
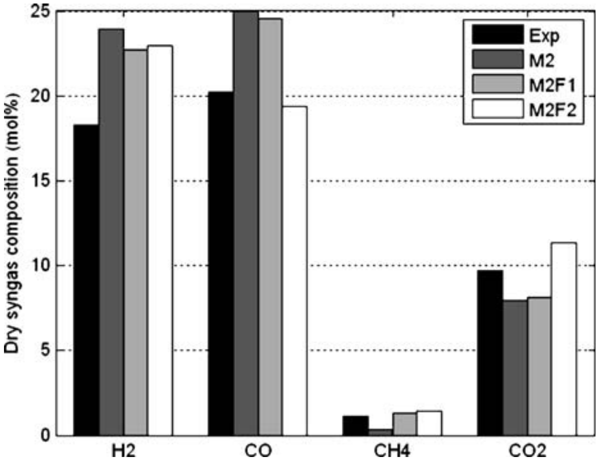


Fig. 3 Dry syngas composition (mol.%) of biomass solid waste (SSR values of M1, M1F1, and M1F2 are 0.011, 0.004, and 0.007)

Fig. 4 Dry syngas composition (mol%) of rubber wood (SSR values of M2, M2F1, and M2F2 are 0.012, 0.010, and 0.006)

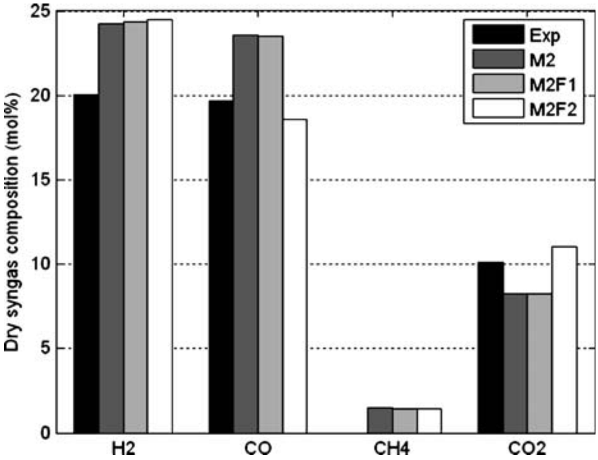


lower than those of experiments. Therefore, the prediction of syngas composition cannot be improved by the modification of M2 by fixing yCH_4 only, i.e., M2F1. Instead, the prediction performance can be improved by the modified model M2F2, which fixes both yCH_4 and yCO. This is possibly due to the increase number of unknown variables for Model 2 considering char compared to the Model without considering char, and thus fixing both yCH_4 and yCO may become more accurate than fixing yCH_4 only.

Deviation Temperature between the Model and Experiment

Table 2 shows that when the model gasification temperature is 125 °C lower than the actual gasification temperature the model results are close to the real data. This temperature deviation also proves that the modified models based on the equilibrium model as described above are significantly necessary.

Fig. 5 Dry syngas composition (mol%) of sawdust (SSR values of M2, M2F1 and M2F2 are 0.010, 0.010, and 0.006)



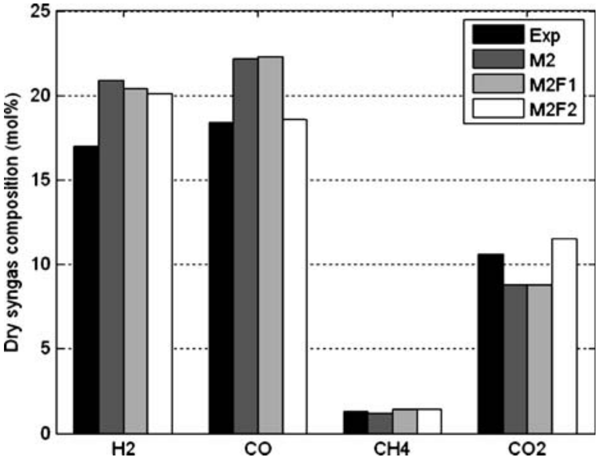


Fig. 6 Dry syngas composition (mol%) of biomass solid waste (SSR values of M2, M2F1, and M2F2 are 0.007, 0.006, and 0.003)

Conclusions

Thermodynamic equilibrium model without considering char, Model 1, reported here can well describe the downdraft biomass gasifier at high temperature when there is no formation of char. Modified equilibrium model matching the yCH_4 in the product gas closer to its average experimentally determined value fits the experimental data very well after a proper choice of beta.

Thermodynamic equilibrium model considering char, Model 2, is obviously more general and widely applicable than Model 1. However, due to the complexities of including char, the equilibrium model predictions do not match well with experimental results. Modified equilibrium model considering char closely matching both yCH_4 and yCO in the product gas can better describe the commercial downdraft gasifier. In addition to equilibrium considerations, local complex fluid flow, heat and mass transfer characteristics and their influence on local equilibrium of an actual gasifier, can be simulated and lumped into the model, as a first approximation, by modifying the model gasification temperature to help improve the model accuracy in prediction of syngas compositions. This provides a viable tool for process simulation such as mass and energy balances and optimization and further development.

Table 2 Dry syngas comp. (mol %) of biomass solid waste (ΔT_R=125 °C).

	Rubber wood		Sawdust		Biomass solid waste	
	Exp [42]	M2	Exp [39]	M2	Exp [19]	M2
H_2	18.3	20.7	20.06	20.46	17	16.39
CO	20.2	24.3	19.7	19.29	18.4	16.88
CH_4	1.1	2.3	0	2.79	1.3	2.18
CO_2	9.7	9.7	10.15	13.37	10.6	12.47
N_2	50.7	43	50.1	44.1	52.7	51.99
SSR	0.008		0.005		0.001	

Where ΔT_R = (Experimental or actual gasification temperature) − (Model gasification temperature)

Acknowledgment The University of Minnesota Initiative for Renewable Energy and the Environment (IREE) is gratefully acknowledged for its financial support.

References

1. Report of Pacific Northwest National Laboratory (PNNL) & National Renewable Energy Laboratory (NREL). (2004). Available from: http://www1.eere.energy.gov/biomass/pdfs/35523.pdf. Accessed at 20 May 2008
2. Bremaud, M., Fongarland, P., Anfray, J., Jallais, S., Schweich, D., & Khodakov, A. Y. (2005). Influence of syngas composition on the transient behavior of a Fischer–Tropsch continuous slurry reactor. *Catalysis Today*, *106*, 137–142. doi:10.1016/j.cattod.2005.07.126.
3. Khodakov, A. Y., Chu, W., & Fongarland, P. (2007). Advances in the development of novel cobalt Fischer–Tropsch catalysts for synthesis of long-chain hydrocarbons and clean fuels. *Chemical Reviews*, *107*, 1692–1744. doi:10.1021/cr050972v.
4. Martínez, A., Valencia, S., Murciano, R., Cerqueira, H. S., Costa, A. F., & Aguiar, E. F. S. (2008). Catalytic behavior of hybrid Co/SiO_2-(medium-pore) zeolite catalysts during the one-stage conversion of syngas to gasoline. *Applied Catalysis A General*, *346*(1–2), 117–125. doi:10.1016/j.apcata.2008.05.015.
5. Ogawa, T., Inoue, N., Shikada, T., & Ohno, Y. (2003). Direct dimethyl ether synthesis. *Journal of Natural Gas Chemistry*, *12*, 219–227.
6. Bae, J. W., Potdar, H. S., Kang, S. H., & Jun, K. W. (2008). Coproduction of methanol and dimethyl ether from biomass-derived syngas on a Cu–ZnO–Al_2O_3/γ-Al_2O_3 hybrid catalyst. *Energy & Fuels*, *22*, 223–230. doi:10.1021/ef700461j.
7. Xiaoming, M., Guodong, L., & Hongbin, Z. (2006). Co–Mo–K sulfide-based catalyst promoted by multiwalled carbon nanotubes for higher alcohol synthesis from syngas. *Chinese Journal of Catalysis*, *27* (11), 1019–1027. doi:10.1016/S1872-2067(06)60053-3.
8. National Non-Food Crops Centre (NNFCC). Report of a DTI Global Watch Mission, 2006. Available from: www.oti.globalwatchonline.com/online_pdfs/36610MR.pdf. Accessed May 19, 2008.
9. Larson, E. D. Biomass gasification systems for electric power, cogeneration, liquid fuels, and hydrogen. gcep biomass energy workshop. 27 April 2004 Available from: http://gcep.stanford.edu/pdfs/energy_workshops_04_04/biomass_larson.pdf
10. Turn, S., Kinoshita, C., Zhang, Z., Ishimura, D., & Zhou, J. (1998). *International Journal of Hydrogen Energy*, *23*(8), 641–648. doi:10.1016/S0360-3199(97)00118-3.
11. Dogru, M., Howarth, C. R., Akay, G., Keskinler, B., & Malik, A. A. (2002). *Energy*, *27*, 415–427. doi:10.1016/S0360-5442(01)00094-9.
12. Jayah, T. H., Aye, L., Fuller, R. J., & Stewart, D. F. (2003). *Biomass and Bioenergy*, *25*, 459–469. doi:10.1016/S0961-9534(03)00037-0.
13. Asadullah, M., et al. (2004). Gasification of different biomasses in a dual-bed gasifier system combined with novel catalysts with high energy efficiency. *Applied Catalysis A General*, *267*, 95–102. doi:10.1016/j.apcata.2004.02.028.
14. Filippis, P. D., Borgianni, C., Paolucci, M., & Pochetti, F. (2004). *Biomass and Bioenergy*, *27*, 247–252. doi:10.1016/j.biombioe.2003.11.009.
15. Radmanesh, R., Chaouki, J., & Guy, C. (2006). *AIChE Journal. American Institute of Chemical Engineers*, *52*(12), 4258–4272. doi:10.1002/aic.11020.
16. Li, X. T., Grace, J. R., Lim, C. J., Watkinson, A. P., Chen, H. P., & Kim, J. R. (2004). Biomass gasification in a circulating fluidized bed. *Biomass and Bioenergy*, *26*, 171–193. doi:10.1016/S0961-9534(03)00084-9.
17. Radmanesh, R., Chaouki, J., & Guy, C. (2006). Biomass gasification in a bubbling fluidized bed reactor: experiments and modeling. *AIChE Journal. American Institute of Chemical Engineers*, *52*(12), 4258–4272. doi:10.1002/aic.11020.
18. Pengmei, L. V., Yuan, Z., Ma, L., Wu, C., Chen, Y., & Zhu, J. (2007). Hydrogen-rich gas production from biomass air and oxygen/steam gasification in a downdraft gasifier. *Renewable Energy*, *32*, 2173–2185. doi:10.1016/j.renene.2006.11.010.
19. Francisco, V. ,Tinaut, A. M., Pérez, J. F., & Horrillo, A. (2008). Effect of biomass particle size and air superficial velocity on the gasification process in a downdraft fixed bed gasifier. An experimental and modelling study. *Fuel Processing Technology*. doi:10.1016/j.fuproc.2008.04.010.
20. Gao, N., & Li, A. (2008). Modeling and simulation of combined pyrolysis and reduction zone for a downdraft biomass gasifier. *Energy Conversion and Management*, *49*, 3483–3490. doi:10.1016/j.enconman.2008.08.002.

21. Di Blasi, C., Branca, C., Sparano, S., & La Mantia, B. (2003). Drying characteristics of wood cylinders for conditions pertinent to fixed-bed countercurrent gasification. *Biomass and Bioenergy*, *25*, 45–58. doi:10.1016/S0961-9534(02)00180-0.
22. Lucas, C., Szewczyk, _D., Blasiak, W., & Mochida, S. (2004). High-temperature air and steam gasification of densified biofuels. *Biomass and Bioenergy*, *27*, 563–575. doi:10.1016/j.biombioe.2003.08.015.
23. Gao, N., Li, A., Quan, C., & Gao, F. (2008). Hydrogen-rich gas production from biomass steam gasification in an updraft fixed-bed gasifier combined with a porous ceramic reformer. *International Journal of Hydrogen Energy*, *33*, 5430–5438. doi:10.1016/j.ijhydene.2008.07.033.
24. Gabra, M., Pettersson, E., Backman, R., & Kjellström, B. (2001). Evaluation of cyclone gasifer performance for gasification of sugar cane residue—part 1: gasification of bagasse. *Biomass and Bioenergy*, *21*, 351–369. doi:10.1016/S0961-9534(01)00043-5.
25. Fletcher, D. F., Haynes, B. S., Christo, F. C., & Joseph, S. D. (2000). A CFD based combustion model of an entrained flow biomass gasifier. *Applied Mathematical Modelling*, *24*, 165–182. doi:10.1016/S0307-904X(99)00025-6.
26. Kobayashi, N., Tanaka, M., Piao, G., Kobayashi, J., Hatano, S., Itaya, Y., et al. (2009). High temperature air-blown woody biomass gasification model for the estimation of an entrained down-flow gasifier. *Waste Management*, *29*, 245–251. doi:10.1016/j.wasman.2008.04.014.
27. Beenackers, A. A. C. M. (1999). Biomass gasification in moving beds, a review of European technologies. *Renewable Energy*, *16*, 1118–1186. doi:10.1016/S0960-1481(98)00469-8.
28. Yu, J., Tian, F.-J., McKenzie, L. J., & Li, C.-Z. (2006). Char-supported nano iron catalyst for water–gas-shift reaction: hydrogen production from coal/biomass gasification. *Process Safety and Environmental Protection*, *84*(2), 125–130. doi:10.1205/psep.05045.
29. Di Blasi, C. (2000). Dynamic behaviour of stratified downdraft gasifiers. *Chemical Engineering Science*, *55*, 2931–2944.
30. Giltrap, D. L., McKibbin, R., & Barnes, G. R. G. (2003). A steady state model of gas–char reactions in a downdraft biomass gasifier. *Solar Energy*, *74*, 85–91. doi:10.1016/S0038-092X(03)00091-4.
31. Mostoufi, N., Cui, H., & Chaouki, J. (2001). A comparison of two- and singlephase models for fluidized-bed reactors. *Industrial & Engineering Chemistry Research*, *40*, 5526–5532. doi:10.1021/ie010121n.
32. Fletcher, D. F., Haynes, B. S., Chen, J., & Joseph, S. D. (1998). Computational fluid dynamics modelling of an entrained flow biomass gasifier. *Applied Mathematical Modelling*, *22*, 747–757. doi:10.1016/S0307-904X(98)10025-2.
33. Gerun, L., Paraschiv, M., Vîjeu, R., Bellettre, J., Tazerout, M., Gøel, B., et al. (2008). Numerical investigation of the partial oxidation in a two-stage downdraft gasifier. *Fuel*, *87*, 1383–1393. doi:10.1016/j.fuel.2007.07.009.
34. Mansaray, K. G., Al-Taweel, A. M., Ghaly, A. E., Hamdullahpur, F., & Ugursal, V. I. (2000). *Energy Sources*, *22*, 83–98. doi:10.1080/00908310050014243.
35. Schuster, G., Löffler, G., Weigl, K., & Hofbauer, H. (2001). *Bioresource Technology*, *77*, 71–79. doi:10.1016/S0960-8524(00)00115-2.
36. Zainal, Z. A., Ali, R., Lean, C. H., & Seetharamu, K. N. (2001). *Energy Conversion and Management*, *42*, 1499–1515. doi:10.1016/S0196-8904(00)00078-9.
37. Mountouris, A., Voutsas, E., & Tassios, D. (2006). *Energy Conversion and Management*, *47*, 1723–1737. doi:10.1016/j.enconman.2005.10.015.
38. Melgar, A., Pérez, J. F., Laget, H., & Horillo, A. (2007). *Energy Conversion and Management*, *48*, 59–67. doi:10.1016/j.enconman.2006.05.004.
39. Jarungthammachote, S., & Dutta, A. (2007). *Energy*, *32*, 1660–1669. doi:10.1016/j.energy.2007.01.010.
40. Li, X., Grace, J. R., Watkinson, A. P., Lim, C. J., & Ergüdenler, A. (2001). *Fuel*, *80*, 195–207. doi:10.1016/S0016-2361(00)00074-0.
41. Mahishi, M. R., & Goswami, D. Y. (2007). *International Journal of Hydrogen Energy*, *29*, 1123–1131.
42. Altafini, C. R., Wander, P. R., & Barreto, R. M. (2003). *Energy Conversion and Management*, *44*, 2763–2777.
43. Yaws, C. L. (1999). *Chemical properties handbook*. New York: McGraw-Hill.